SURFACE ELECTROMYOGRAPHY: BARRIERS LIMITING WIDESPREAD USE OF SEMG IN CLINICAL ASSESSMENT AND NEUROREHABILITATION

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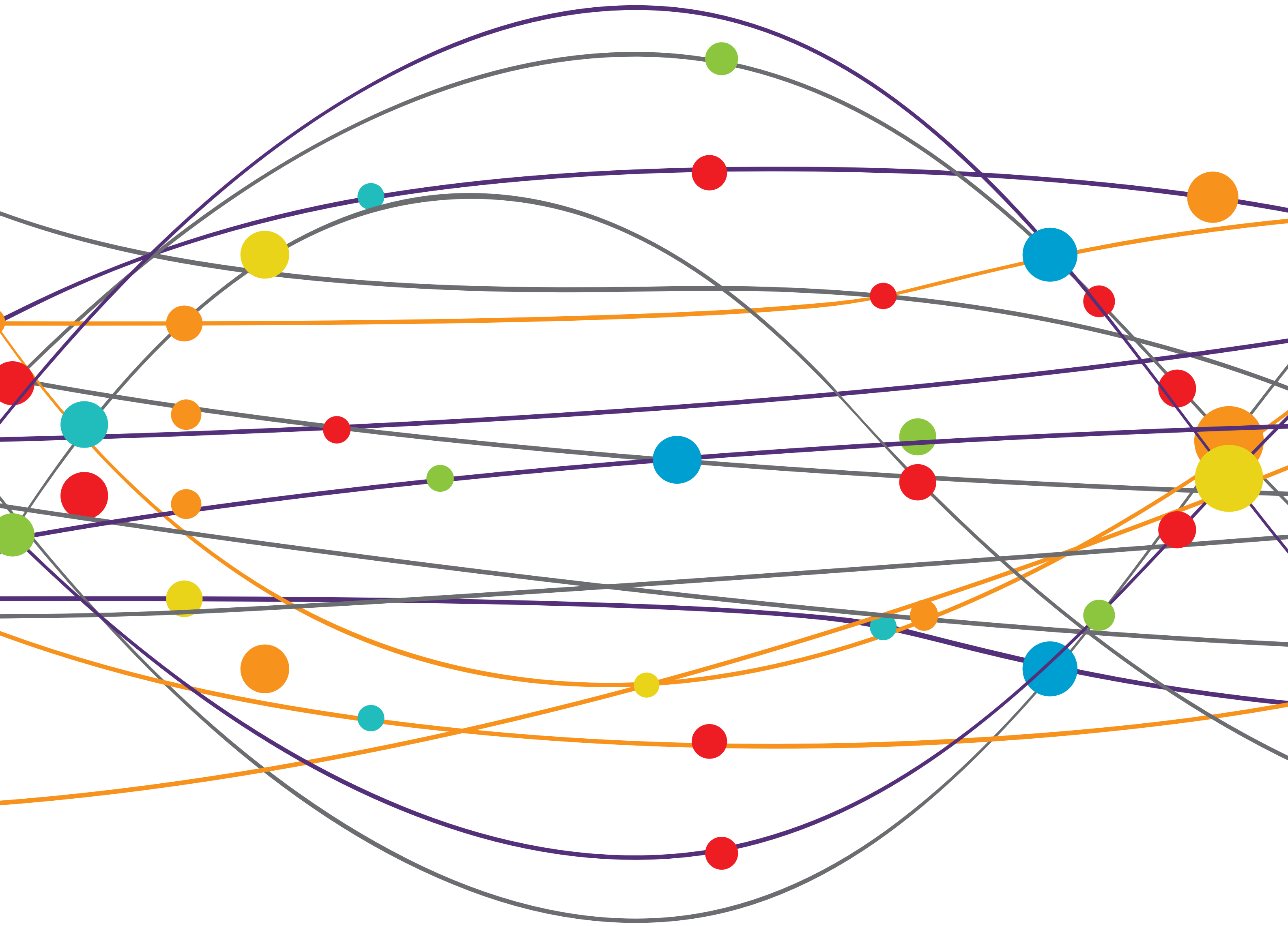

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EDITORIAL
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Editorial: Surface Electromyography: Barriers Limiting Widespread Use of sEMG in Clinical Assessment and Neurorehabilitation

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Keywords: surface electromyography, sEMG, HDsEMG, clinical use, cultural barriers, educational barriers, technical barriers, administrative barriers

Editorial on the Research Topic

Surface Electromyography: Barriers Limiting Widespread Use of sEMG in Clinical Assessment and Neurorehabilitation

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INTRODUCTION

Bioelectric signals provide an extraordinary opportunity to discover and quantify a wealth of phenomena associated with the organs that generate them. In addition, they provide extensive potentially valuable information for medical doctors (MDs), physiotherapists (PTs), occupational therapists (OTs), and movement scientists (MSs), for functional diagnosis, patient path management, evaluation of patient recovery and progress, and to document or quantify the effectiveness of treatments/trainings.

Clinical researchers and engineers have expected that such information would be highly welcomed by clinicians because of the evidence that such information would add to their rehabilitative activity. This has not been the case for surface EMG (sEMG), a fact that motivated this Frontiers project, as well as the publication of a number of tutorials and consensus papers (1–5), and some EU efforts since 1999 (6). A recent Frontiers e-book illustrated sEMG scientific/technical innovations but did not address the "barrier" problem (7).

This Frontiers Project presents 18 contributions from 7 countries and 80 authors (33 engineers, 16 MDs, 18 PTs and OTs, and 13 MSs) who are highly respected experts in the many fields of sEMG. The general problem is addressed in Campanini, Disselhorst-Klug et al., while results of interviews are presented in Manca et al., Feldner et al., and Cappellini et al. as well as the situation in specific countries (Manzur-Valdivia and Joel Alvarez-Ruf; Portero et al.), and teaching/communication experiences (De la Fuente et al.; McManus et al.). Specific clinical applications concerning neurorehabilitation, gait analysis, sport, kinesiology, exoskeletons, occupational medicine, and ergonomics, are discussed in Cappellini et al., Agostini et al., Felici and Del Vecchio, Goffredo et al., Medved et al., Steele et al., Pilkar et al., Campanini, Cosma et al., Ranavolo et al., and Disselhorst-Klug and Williams.

The disciplines listed are not the top branches of medicine in terms of funding and general attention. Their impact is measured in terms of function recovered, improved quality of life or prevented deterioration, and social costs (Ranavolo et al.; Martin and Acosta-Sojo). These "quantities" are not easy to measure. The focus on the clinical impact of quantitative assessments of movement and of the so called "hard sciences" to the rehabilitation field is relatively recent (8–10).

There is general agreement that the barriers limiting the clinical use of sEMG are cultural/educational and technical/administrative.

CULTURAL AND EDUCATIONAL BARRIERS

The education of PTs and OTs varies considerably across countries. France offers a 1+4 year non-academic degree; some countries offer a clinical doctorate (DPT, DOT). Proper interpretation of sEMG requires both technical and clinical competencies. Should these two different types of expertise be merged into a single professional expert, or in two distinct professional figures?

Some universities (TU Delft, Erasmus MC, and LUMC[1]) started training a "clinical technologist" who is a registered healthcare professional carrying out tests and signal processing independently. This new figure has been well-received by the local clinical community (see text footnote 1). Manca et al. indicate that, in reply to their questionnaire, "… the professional figure of 'human motion analyst' was put forward by some respondents as a possible reference to manage sEMG assessments in the clinical setting." Some interviewees in the work of Cappellini et al. made similar propositions.

The alternative option of integrating technical knowledge into the training of PTs, OTs, MSs, and other health operators, finds approval but few implementation efforts. A research group integrating clinicians from Brazil and Chile promoted a Winter School to integrate knowledge about sEMG into the background of clinical operators (De la Fuente et al.). Other authors propose that practical experience working with sEMG should be embedded into education in the form of workshops or course placements to effectively promote its use, and outline a basic tutorial which could be used as a tool for teaching or self-guided learning (McManus et al.). A new medical degree addressing technological issues[2] has been activated in Italy. Masters in Advanced Technologies in Rehabilitation are currently offered by other institutions to MDs, PTs, OTs, and MSs[3,4].

The need for increased technical training of clinical operators and of their educators is generally recognized by all contributors to the project. The publication of open access teaching material[5], as well as tutorials and consensus papers is in this direction [(1, 2, 4, 5); Felici and Del Vecchio]. However, freely available tutorials are still not sufficient, since "publishing our work in journals is essential—but publication of research is not, by itself, sufficient if our goal is to support clinical practice. People follow the lead of other people they know and trust when they decide whether to take up an innovation and change the way they practice!" (11). Lack of knowledge of books and journals in the field is common.

The lack of a Ph.D. degree in Physiotherapy, preliminary to the academic training of professors, the lack of research and publication record by PTs (12), and the poor technical and instrumental education of operators lead to a vicious cycle that is hard to break:

> *No teaching of sEMG applications → No clinical competence in the use of sEMG → Few clinical publications and no grant requests in the field for large clinical studies on sEMG → No experience acquired at the academic level → No academic training of qualified professors → No teaching of sEMG applications. Conclusion: undemonstrated utility of the method.*

Is the user and caregiver perspective a key untapped resource in the design, implementation, and use of sEMG devices as indicated by Feldner et al.? Probably not for clinical measurements but the perspective of clinical operators should be considered (13).

There is general agreement by clinicians about the potential clinical usefulness of sEMG as shown in Table 2 in [Manca et al.; Cappellini et al.; (13)]. The interviews carried out by these authors indicate that sEMG "provides unique information on neuromuscular function that is not offered by other assessment techniques/tools." Large consensus was reached in Manca et al., among 80% to 97% of the 35 respondents interviewed as well as among others interviewed by Cappellini et al. who found that "sEMG use was considered to substantially enhance the quality of patient's assessment." The slow dissemination of this knowledge seems to be a barrier to clinical translation.

Some contradictions are linked to the fact that (as opposed to ECG) visual analysis and interpretation of sEMG is not easy. However, improper muscle coordination and timing (e.g., in gait analysis) can be readily detected visually. Nonetheless, the interpretation of this information requires a thorough comprehension of biomechanics, of the existing boundaries to movement consequent to pathology and, more generally, several years of expertise (Manca et al.; Campanini, Cosma et al.). Lack of time seems to be one of the main reasons behind this barrier (see the section below).

Difficult interpretation of sEMG without specific education/training was reported by 21 out of 28 interviewees (Cappellini et al.) as well as insufficient education/practice during refresher courses (reported by 20/28), and inadequate education and training of PTs and MDs on sEMG (reported by

[1] https://www.tudelft.nl/en/2020/3me/june/clinical-technologists-officially-registered-healthcare-professionals/

[2] https://www.healthcarestudies.com/MedTec-School/Italy/Humanitas-University/ and https://www.humanitas.it/news/24675-medtec-humanitas-university-politecnico-milano-formano-medici-del-futuro

[3] https://www.hunimed.eu/course/master-in-advanced-technologies-in-rehabilitation

[4] https://www.rehabtech.polimi.it

[5] www.robertomerletti.it

17/28). This is another vicious cycle since adequate education, in turn, reduces time for learning and clinical application.

TECHNICAL AND ADMINISTRATIVE BARRIERS

Most clinical research studies involving sEMG have been carried out by engineers and life-scientists in research centers, on small groups of 10–50 subjects. Larger clinical trials are few because they must be carried out within health institutions where engineers are rarely present and clinical operators may lack the competence, the support, and the time to carry them out (Campanini, Disselhorst-Klug et al.).

This is another barrier leading to the undemonstrated utility of the method. The absence of academic positions implies that research in physiotherapy must be carried out in parallel with the very time demanding routine of traditional clinical procedures. The lack of a clinical market is the cited reason for manufacturing equipment being mostly oriented to the much smaller research market. As a consequence, clinical operators consider sEMG technology limited to research, cumbersome to use, time-consuming, and expensive.

Some users suggest that clinical sEMG systems should be inexpensive and simple to use, and incorporate some intelligence for correcting errors of the user by automatically eliminating power line interference, movement artifacts, or other problems. This raises the following interesting question: should technology adapt, with some internal intelligence and higher cost, to the lack of competence of the users, or should user competence be increased so that technology can be simpler, cheaper, better managed, and controlled?

Unquestionably, there is a need for standard protocols based on extensive clinical trials (as was done for ECG and EEG), but the initial effort of the SENIAM project (6) and its extensions (4, 5, 14) did not trigger subsequent clinical initiatives. Preparing guidelines and protocols requires funding, time, and active participation of MDs, PTs, OTs, and MSs.

On another related issue, the number of publications about methodologies for sEMG analysis is overwhelming and confusing. Twenty-four years ago Hodges and Bui (15) tested 27 methods for determining muscle activity onset time. There are many more today. The number of methods to monitor sEMG spectral changes is also huge, ranging from Fourier to wavelet, and from entropy to fractal analysis. Most of these approaches will have limited meaning to clinicians. There is a need to define a limited number of clinically tested reliable algorithms and best practices to use with (or propose to) trained clinical investigators. In addition, the temptation to address complex problems, such as dynamic sEMG, have produced at least as many approaches, generating additional confusion. Perhaps the teacher's attention should first be focused on well-tested methods for studying relatively simple situations, such as the timing of muscle activation during gait in well-controlled conditions (Disselhorst-Klug and Williams) along with the contribution to clinical decision-making (Campanini, Cosma et al.). Scientific societies should address this issue.

Lack of time seems to be a major multifaceted barrier (Feldner et al.; Martin and Acosta-Sojo). The application and connection of electrodes is indicated as time-consuming. This is no longer true with the use of wireless systems but knowledge about proper electrode positioning is required to promote time saving (14, 16–18). Time is needed for PTs, OTs, and MSs to learn and practice these techniques. Formal academic teaching would reduce time spent in the clinical environment, but the lack of leaders/clinicians devoted to full-time teaching and research (doctoral students, researchers, and associate/full professors) is another main barrier.

Administrative issues are also relevant because all clinical activities are coded and reimbursed or documented by the clinician according to such codes. Only gait analysis is coded in a few countries. Most other sEMG-based investigations are not.

Only a few insurance companies reimburse basic sEMG examinations. Institutional stakeholders should outline the fact that muscle assessment for proper treatment selection would likely generate savings, rather than cost increases (Campanini, Cosma et al.).

As indicated by Martin and Acosta-Sojo "…EMG does not provide information about life-threatening conditions, although it can provide useful information about health- or profit-threatening conditions."

Furthermore, in stroke patients "surface EMG would supply information for better assessment of deficits as well as rehabilitation progress and/or efficacy" [Martin and Acosta-Sojo; (19)]. In the (not so) long run, personalized treatment based on personalized assessment (Campanini, Cosma et al.) would reduce the weight of ineffective therapies, increase insurance profits, and reduce costs for national health systems.

CONCLUSIONS

Several negative factors, inconsistencies, and contradictions are outlined in the project. On the one hand, rehabilitation clinicians; (a) recognize the value and need for formal education to enable more rigorous and clear evidence highlighting the benefits of sEMG; and (b) assert that the opportunities to pursue it are inadequate due to administrative and time resource limitations. On the other hand, many textbooks (14) and the abundant free resources available [(1, 2, 4–6); see text footnote 5[6]] are not exploited, either in schools or for continuing education. Increasing their quantity and quality has not been as useful as expected. Vicious cycles can be broken; (a) by extending the number of years required for a clinical degree; and (b) by opening opportunities for higher education and research promoted by scientific associations, the EU, and other national/international bodies.

Removing administrative obstacles is equally important to lighten the workload of clinical operators, leaving time for applying and investigating more recent and well-documented techniques. Doing so would promote experience-based technical improvements, prime virtuous cycles incrementing knowledge,

[6]www.seniam.org

applications, market, and reducing the commercial prices of devices.

Introducing new professional figures such as rehabilitation engineers or clinical technologists (see text footnote 1), alongside clinical operators, would substantially reduce (but would not eliminate) the need for technical training of the latter. As rehabilitation technology is rapidly developing, such figures will become necessary very shortly and early training of these operators is certainly appropriate. The clinical responsibilities of these two professional figures should be defined soon. Finally, a common language for proper communication must be available on both sides to understand the information carried by sEMG.

AUTHOR CONTRIBUTIONS

All authors contributed equally to the preparation of the Editorial.

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HYPOTHESIS AND THEORY
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Surface EMG in Clinical Assessment and Neurorehabilitation: Barriers Limiting Its Use

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This article addresses the potential clinical value of techniques based on surface electromyography (sEMG) in rehabilitation medicine with specific focus on neurorehabilitation. Applications in exercise and sport pathophysiology, in movement analysis, in ergonomics and occupational medicine, and in a number of related fields are also considered. The contrast between the extensive scientific literature in these fields and the limited clinical applications is discussed. The "barriers" between research findings and their application are very broad, and are longstanding, cultural, educational, and technical. Cultural barriers relate to the general acceptance and use of the concept of objective measurement in a clinical setting and its role in promoting Evidence Based Medicine. Wide differences between countries exist in appropriate training in the use of such quantitative measurements in general, and in electrical measurements in particular. These differences are manifest in training programs, in degrees granted, and in academic/research career opportunities. Educational barriers are related to the background in mathematics and physics for rehabilitation clinicians, leading to insufficient basic concepts of signal interpretation, as well as to the lack of a common language with rehabilitation engineers. Technical barriers are being overcome progressively, but progress is still impacted by the lack of user-friendly equipment, insufficient market demand, gadget-like devices, relatively high equipment price and a pervasive lack of interest by manufacturers. Despite the recommendations provided by the 20-year old EU project on "Surface EMG for Non-Invasive Assessment of Muscles (SENIAM)," real international standards are still missing and there is minimal international pressure for developing and applying such standards. The need for change in training and teaching is increasingly felt in the academic world, but is much less perceived in the health delivery system and clinical environments. The rapid technological progress in the fields of sensor and measurement technology (including sEMG), assistive devices, and robotic rehabilitation, has not been driven by clinical demands. Our assertion is that the most important and urgent interventions concern enhanced education, more effective technology transfer, and increased academic opportunities for physiotherapists, occupational therapists, and kinesiologists.

Keywords: surface electromyography, sEMG, rehabilitation, clinical applications, motion analysis, education, physiotherapy, movement sciences

INTRODUCTION

Quantitative Approaches and Measurements in Neurorehabilitation and Physiotherapy

Prevention of injuries and rehabilitation of movement pathologies are among the branches of clinical practice where the impact of technology is leading to improvement of outcomes and to economic benefits. In times of limited resources, the future perspectives and developments of all rehabilitation-related professions will increasingly depend on the evidence supporting the effectiveness of their preventive and therapeutic interventions. This issue has been discussed in a number of scientific contributions and editorials (1–3).

In the last few decades, impressive developments have taken place in many fields providing powerful quantitative approaches toward instrumentation-based assessments in cardiology (ECG, etc.), neurology (EEG, etc.), and biomechanics (inertial sensors, sEMG). Neuroengineering has made available a wealth of investigational techniques and tools, as well as tutorials and textbooks, for understanding mechanisms, implementing prevention, and measuring performance and results of interventions. The proceedings of the International Conferences on Neurorehabilitation (4–8) provide a view of this progress and tools over the last 7 years. A few examples are the devices for the assessment of force, balance, movement, oxygen consumption, and of course, muscle activity. These tools underwent different degrees of translation to the clinics and to the market. This work focuses on surface EMG (sEMG).

As a "muscle activation measuring tool" sEMG has played a growing and important role in neurorehabilitation over four decades (9–19). **Figure 1** shows the increase of international peer-reviewed publications in the sEMG field and **Figure 2** shows an example of the development of sEMG technology since 1950. Equally striking developments have taken place in related fields of neurophysiology, signal processing and extraction of physiologically relevant features from sEMG over the last 50 years (23–30). Moreover, the number of clinical situations compatible with objective measurements of muscular activity, for planning treatment and for pre- and post-treatment assessment, is large and rapidly increasing, as described in section Surface EMG Applications.

Despite this large body of knowledge, literature, and collected research works, the clinical acceptance of sEMG advances among physiotherapists (PTs), kinesiologists and medical clinicians remains low (31). This is in contrast with the history of ECG in cardiology (32, 33) and EEG in neurology (34). Apparently, the potential benefits of sEMG in assessing treatment appropriateness and in determining cost saving are not fully demonstrated in neuromuscular rehabilitation, primarily because they have not been investigated (22). Research has been focused on academic achievements rather than on clinical applications.

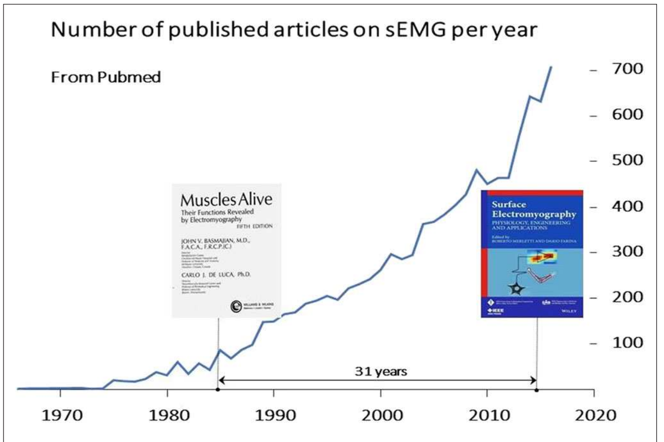

FIGURE 1 | Rate of publication of sEMG articles on international peer-reviewed journals. These articles and more than 20 textbooks (see: https://www.robertomerletti.it/en/emg/material/books/) provide a huge body of knowledge that ranges from technical issues to clinical applications in research labs. A Pubmed search (June 2020, keywords "surface electromyography" OR sEMG) indicated over 5,500 publications (14.8% of the 37,000 publications listed in Pubmed under "neurorehabilitation"). Over 180 review papers are listed by Pubmed in the sEMG field. In most countries, this knowledge is not translated into routine applications for planning treatment, monitoring and assessing outcome in neurorehabilitation.

A number of "barriers" exist limiting the widespread application of sEMG techniques in clinical assessment and in neurorehabilitation. Some barriers are cultural, such as the inappropriate comparison with the diagnostic power of needle EMG (35, 36), or are related to the issue of assessing "function" (with scales and observational descriptions) rather than "impairment" (with measurement of physical quantities), or to the wide-spread diffidence/reluctance with respect to objective measurement, instrumentation, and Evidence Based Practice (EBP) (37–40), or the belief that time spent in assessing results is not productive. There is often a lack of a common language with rehabilitation engineers and many therapists lack the technical background to interpret the sEMG outcomes. Some barriers are technical, like difficulties with the application of sEMG, signal processing and information extraction algorithms which do not directly produce clinically relevant information, or the user-unfriendliness of some equipment. Finally, the cost of the devices, the reimbursement procedures, and the time needed to perform a measurement

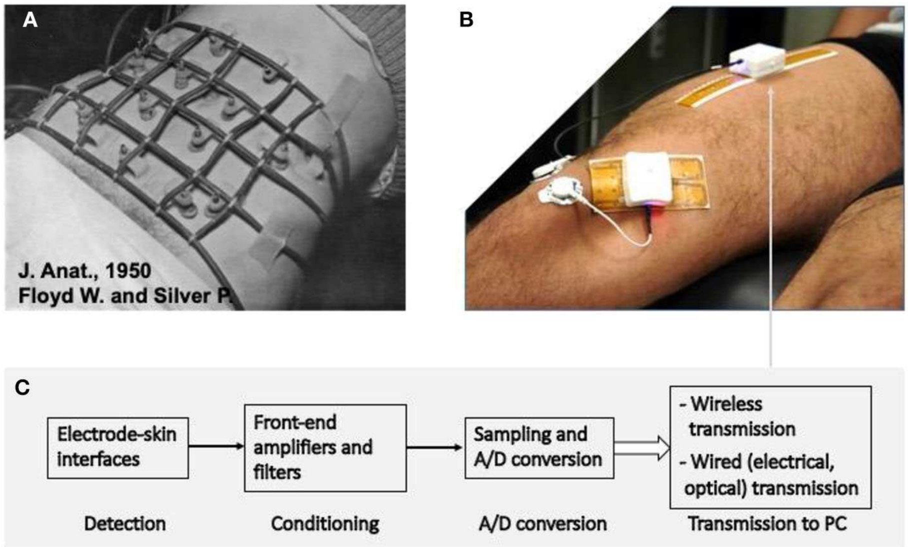

FIGURE 2 | Example of the advances in sEMG detection in the last 70 years. **(A)** The detection system used by Floyd and Silver in 1950 (20) to monitor abdominal muscles. The electronics used for signal conditioning had the size of a suitcase. **(B)** Modern system for detection, condition, A/D conversion, and transmission of signals from sEMG electrode arrays. The white box contains the system described in **(C)** and the rechargeable battery to supply it for a few hours. **(C)** Schematic diagram of the signal detection, conditioning, conversion, and transmission depicted in **(B)**. Two systems, with different detection grids of 32 electrodes each are applied to the rectus femoris and vastus medialis. Up to four such systems can operate simultaneously and provide images of sEMG activity in four locations (21). **(A)** Is reprinted, with permission from Floyd and Silver (20).

and obtain a clinically useful information have also to be taken into account.

It is the objective of this work to discuss these barriers and the options for reducing them.

The Role of sEMG for Monitoring Disorders, Planning Treatments, and Assessing Their Effectiveness

Surface EMG can be used in monitoring neuromuscular pathologies, in prevention of work-related disorders and occupational therapy, and in monitoring neuromuscular changes/progress in acute patients (see section Surface EMG Applications). Information on muscle activation during a movement or effort adds to the clinical evaluation and provides a picture of both impairment and functional alteration. As in other branches of medicine, clinical assessment does not always provide the information needed to design a treatment plan. It is crucial to recognize situations in which added value can be expected from instrumental analysis. Some example of questions which can be answered with sEMG, and which have an impact on designing a rehabilitation plan, are presented in section Some Fundamental Questions. Measurement of muscle activation provides information on the motor unit recruitment/derecruitment capability, on fatigue, synergies, co-contractions, etc. as well as evidence of the efficacy of the rehabilitation plan. Section Surface EMG Applications provides examples of applications.

Physiological and Technological Literacy: The Need for Academic Education and Large-Scale Studies

Physiological and technological literacy is a requirement for medical and health-allied professionals.

The measurement of a physiological quantity (e.g., localized myoelectric manifestations of fatigue) is useless if the recipient does not know its meaning, how to use the information contained in the result and how reliable the measurement is. An ECG does not convey much information to a person knowing little about cardiac electrophysiology. Similarly, information about muscle fiber conduction velocity, sEMG patterns, and amplitude or frequency spectrum, etc. do not inform a person knowing little about muscle electrophysiology and basic signal analysis. The insufficient competence of instrument operators in performing and interpreting such measurements leads to the predictable conclusion that measurements do not contain clinically useful information.

In many countries, the lack of this literacy in physiology/technology leads to the education of physiotherapy and occupational therapy graduates, and future teachers, who serve primarily as professional operators with empirical knowledge mainly (41). This is confirmed, in many countries, by the lack of scientific publications by these graduates (42). In addition, in many countries, the unavailability of PhD degrees in physiotherapy or occupational therapy precludes the evolution of a full academic career and the training of qualified teachers and researchers, perpetuating the situation in its current state. One consequence is that scientists able to conduct large, badly needed, multi-center studies to document the validity of the information obtained from sEMG, do not yet exist. The absence of qualified operators results in an abundance of scientific papers focused on muscle electrophysiology and sEMG technology, in contrast with the lack of studies on the clinical applications of sEMG and on the clinical testing of usability and effectiveness of this technology.

Bioelectric Signals: Basic ECG, EEG, and EMG. General Considerations and History

The most important bioelectric signals are generated by the heart (ECG), the brain (EEG), and the muscles (EMG). The technologies for collecting, reading and interpreting these signals were developed 50–60 years ago and reported in many review papers and books (9, 32–34, 43). ECG and EEG are widely accepted for clinical monitoring of heart and brain functions. They are an important part of the training of cardiologists, neurologists and of the associated health operators and technicians. International standards for the detection and interpretation of these signals have been defined decades ago. In contrast, despite the huge amount of international literature from research labs, sEMG suffers from a wide gap between research and clinical applications. This gap is markedly greater in Mediterranean countries than in North-European countries, USA, Canada, and Australia.

Surface EMG is more than a century old. It started with the pioneer work of Piper, Kugelberg, and Denny-Brown (44–46) and progressed in the second half of last century with the fundamental research of Basmajian, Lindstrom, Gydikov, De Luca (9, 23, 24, 43, 47) and the clinical efforts of Kasman, Cram, Kumar, and many others, leading to the systematization of knowledge in sEMG textbooks (10, 11, 18, 19, 48–52). Some of these books are open-access and free for download.

The sEMG signal is the algebraic sum of the motor unit action potentials (MUAP) generated by the active motor units (MU) and detected over the skin. Like any other signal, sEMG provides quantitative information concerning wave-shape, amplitude, power spectral density, etc. Using such information or those derived by visual observation is a clinical choice/decision.

Traditionally, this signal is detected between two electrodes aligned in the direction of the fibers (bipolar or single differential electrode montage). This "conventional" bipolar sEMG provides ready answers to many important questions in rehabilitation. It is simple to apply on multiple muscles, even by non-technical users, and provides reliable information on the general activation of a muscle or muscle groups and on temporal events of muscular activation (53). Conventional bipolar sEMG is applicable in almost all clinically relevant situations, such as in dynamic movements, in isometric contractions, and in patients with severe movement disorders, adults and children.

Advanced sEMG technologies provide a much larger amount of physiological information than the simple bipolar technique. For example, the use of surface electrode arrays, enables the detection of a so called sEMG "image" that is evolving in time like a movie on the skin [see examples in (52)]. This time-varying electrical image provides indirect information on muscle force, on motor unit (MU) recruitment and de-recruitment strategies and discharge rates, on muscle length, on the location of the innervation zones (IZs), myoelectric manifestations of muscle fatigue, and many other phenomena of interest in neurophysiology, neuropathology, neurorehabilitation, ergonomics, aging, sport, and space medicine (14, 54–60). This technique has been applied in research labs and has been ready for large clinical studies for a few decades. A series of open-access tutorials on this topic is being published in the Journal of Electromyography and Kinesiology (61, 62).

The current applications of sEMG mostly concern physiological investigations, monitoring of neurological disorders, planning of treatments, assessment of interventions and control of prostheses and robots (section Surface EMG Applications). For reasons of space, only a few references are provided here for each area of application. A much more extensive description of applications is provided in chapters 10–20 of Merletti and Farina (18).

SURFACE EMG APPLICATIONS

General Fields of sEMG Application

Like other bioelectric signals, sEMG provides a fundamental added value to the assessment of the organ generating it. The information about muscle activation has different forms (amplitude, timing, morphology, spectral features, muscle fiber conduction velocity, displacement of innervation zone, contributing synergies, muscle coordination, control strategy, etc.) and is relevant in many fields ranging from orthopedics and neurorehabilitation, to movement analysis in exercise and sport, from aging to gnathology, from obstetrics to occupational and space medicine (14, 54–60). Each of the specific assessment methods and techniques listed in **Table 1** and section Overview of sEMG Applications is transversal to most of these medical applications and rehabilitation fields.

Most of the available literature on sEMG concerns methodological issues and proof of concepts, carried out mostly on healthy subjects. Clinical works on large patient groups are few, as well as case studies and case-series on small samples. This does not mean that the developed techniques have no clinical applications or do not answer clinical questions. Rather, it means that there is a huge gap in translating techniques to the clinical environment (see section Barriers to Widespread Clinical Use of sEMG in Neurorehabilitation). Some articles question the diagnostic and therapeutic value of sEMG (35, 36, 63). Conversely, other studies, indicate the use of sEMG as essential in the decision making of functional surgery and in the assessment of spasticity (22, 52, 64–68).

The availability of evidence to support rehabilitation has been a long-standing challenge. The complexity of designing clinical trials to assess the efficacy of rehabilitative treatments has become a topic in the current literature (69). Since sEMG is not a treatment itself, but an instrumental assessment tool that adds to clinical evaluations, specific studies should be designed to assess its impact on (1) the variation in the choice of the rehabilitative pathway and (2) the incremental efficacy of this variation on functional outcomes and on cost/efficacy indicators. A few efforts

TABLE 1 | Applications of sEMG.

	Physiology and basic studies	Neurological rehabilitation	Orthopedic rehabilitation	Gynecological rehabilitation and obstetrics	Prosthesis and assistive devices	Ergonomics	Sport, aging and space medicine	Orthodontics and gnathology
Muscle coordination and activation intervals	x	x	x			x	x	
Primitive synergies	x	x	x					
Spasticity	x	x	x		x			
Muscle over activity		x	x		x	x	x	x
Causes of acquired deformities		x	x		x			
Muscle force estimation	x	x	x	x		x	x	x
Postural control	x	x	x			x	x	
Muscle fatigue estimation	x	x	x		x	x	x	x
Pain	x		x		x	x		
Muscle activity localization	x			x	x	x	x	x
Localization of innervation zones	x			x				
Electrically elicited muscle contractions	x	x	x		x			
Cramps	x	x				x	x	

Rows list topics, methods, and assessment techniques. Columns list large area of medicine in which such techniques are applicable or are applied.

in this direction can be found in the literature for instrumental gait analysis (22, 70–73). Similar specific studies on sEMG are needed. To address this gap, research teams should include sEMG experts, clinical rehabilitation professionals, rehabilitation engineers, experts in research methodology, and in Health Technology Assessment.

The sEMG signal is affected by a large number of factors reflecting the pathophysiology of the muscle and of its control strategy. As such, it provides a window into the muscle, the peripheral (PNS), and central nervous system (CNS). These factors range from alteration of the MUAP propagation along the motor unit fibers to the control of force by recruitment/derecruitment and firing rate of the individual motor units. Unraveling the large amount of information contained in the signal is a major technological challenge and an important field of current engineering, physiological and clinical research (26, 27, 50, 61, 62). The use of large wireless electrode arrays is today possible and relatively simple (**Figure 2B**) so that a fast progress is expected for the next decade. The clinical users of these developments should take a primary role by participating to such progress and orienting it; their education should account for the research instruments of today that will be clinical tools tomorrow (62).

Overview of sEMG Applications

Applications in Physiology and Basic Clinical Studies

Basic and clinical neurophysiology are fields in which sEMG has been extensively applied (12, 17, 74–77). The applications listed below are focused on the pathophysiology of muscles whose knowledge is a pre-requisite for planning clinical interventions and solving clinical problems in the neurorehabilitation field.

Muscle Coordination

It was demonstrated early on that sEMG is suitable for the detection of co-activation of agonist and antagonist muscles, whereby physiological activation patterns could be distinguished from pathological ones (78–80). The clinical relevance of muscular coordination became stronger with the improvement of sEMG techniques (81) and should now be an integral part of any biomechanical analysis of movement (82, 83). The most common use of sEMG to assess muscular coordination is in clinical gait analysis. Here it can be used either in functional diagnosis or in the monitoring of therapeutic outcomes (84, 85). The most prominent fields of application are for neurological impairments like cerebral palsy (CP) and stroke (86), orthopedic impairments, such as back pain (87), anterior cruciate ligament (ACL) injuries (88), and degenerative joint disease (89). However, the interpretation of sEMG signals with respect to muscular coordination requires some caution (90). For this reason, different signal processing methods have been developed in the past to support the interpretation of sEMG signals (91). Currently, the extraction of sEMG primitive synergies is widely used (92, 93). The most recent approaches to categorization take into account biomechanical factors, on which the sEMG signal depends, when determining the physiological or pathological muscular coordination pattern (89, 94).

Extraction of Primitive Synergies

Muscle activation patterns, represented by the sEMG envelopes of a few muscles, can be decomposed into a limited number of "basic" functions or patterns, called "synergies" or "primitives." These primitive patterns can be combined, with different individual weights, and result in the apparent modular organization of multi-muscle activities across different motor tasks. It has been proposed that the nervous system simplifies muscle control through such modularity, using these basic synergies (primitives) to activate muscles in groups. This discovery has had a huge impact on the analysis of motor control and neurorehabilitation since it implies that the CNS generates forces and movements by optimizing the control strategy of either individual muscles or (more likely) muscle synergies (95–101). Research, largely based on sEMG, is focusing on the alterations of these synergies in stroke and other pathologies.

sEMG-Based Muscle Force Estimation

The net torque at a joint is usually produced by a number of muscles, ligaments and other passive structures, and by external forces (e.g., gravity, closed-kinetic-chain forces, orthosis-produced forces). The force contributed by each individual muscle may fluctuate (as does the sEMG amplitude of the muscle) while the total measured torque may remain constant. The estimation of force sharing among synergic muscles by means of sEMG has been reviewed by Perry 30 years ago (102), and more recently, by many other investigators (103–105) but is not yet satisfactorily solved. It is clinically important to realize that one sEMG channel reflects the activity of one (or part of one, or few) superficial muscles while others (including often non-monitored antagonists) may also contribute to the measured torque at the joint. For this reason, care must be taken in associating changes of sEMG amplitude of one muscle to changes of global torque at a joint. At this time, it is rarely possible to acquire the sEMG signal from all muscles acting on a joint. **Figure 3** shows two cases of changing sEMG amplitude in three muscles acting on the elbow during two isometric constant force contractions of the elbow flexors. Brachialis and triceps brachii muscles were not monitored. Although the mechanical contribution of each monitored muscle cannot be estimated, the sEMG amplitude trends suggest that the three contributions are changing in time while the total (measured) torque remains constant. Information of this type should be exploited in sport and rehabilitation medicine to teach or modify the muscle activation patterns.

Myoelectric Manifestations of Muscle Fatigue

The term "muscle fatigue" has many definitions mostly associated with measurements performed during an isometric constant force contraction which is a common and important "bench-test" condition. One definition considers mechanical fatigue as the inability to sustain a given contraction level and is associated with the endurance time (in isometric constant force contractions) or to the inability to perform a task. Another definition refers to "myoelectric manifestations of muscle fatigue" and considers fatigue as the set of changes affecting sEMG features from the very beginning of the contraction. Its main indicator is muscle fiber conduction velocity (CV) which decreases more or less rapidly depending on the level of contraction and is usually measured during isometric constant force contraction. Both types of "fatigue" depend on blood flow and on the stability of the recruited MU pool. Blood flow is blocked, and all MUs are recruited, at contraction levels above about 50% MVC in most muscles (18, 25, 106–110). In this condition many confounding factors are removed (or are constant) so that an acceptable "bench-test" condition is obtained. The reduction of muscle fiber CV causes a compression of the power spectrum of the sEMG toward the lower frequencies and a decrement of the mean and median spectral frequencies that are generally considered as fatigue indicators but that are affected by many additional confounding factors. Measurements of the myoelectric manifestations of muscle fatigue in intermittent or dynamic contractions are very questionable because of many confounding factors (variable blood flow, variable pool of active motor units, etc.) and require considerable competence and caution in defining the specific measurement protocol and the measurement modalities (30, 77, 111).

Muscle Activity Localization

The first use of electrode arrays was described by Gydikov in 1972 (23, 24, 52, 112). Identification of innervation zones using electrode arrays was reported by Masuda et al. in 1985 (113, 114) while the technique of "high density" surface EMG (HDsEMG) was developed 10–15 years later (76, 115–119). The technique is also referred to as sEMG imaging and is used to identify active muscles, the geometry of MUs (e.g., fiber length and orientation), and their innervation zone (IZ). Deep muscles (or deep MUs of a superficial muscle) produce force but their sEMG contributions may be near or below the noise level. Techniques to detect such contributions using HDsEMG are being investigated to obtain a sort of "electromyographic tomography" (120, 121). **Figure 4** shows a large grid (128 contacts, 10 mm apart) displaying the regions of activity of the extensors of the fingers of the right hand. Similar maps may be obtained for other muscles or muscle groups, such as the erector spinae, the trapezius, etc. Biofeedback applications, for correcting muscle involvement while performing a task, are potentially valuable.

Location of Muscle Innervation Zones

A textbook is available with the location of the IZs of 43 muscles (19). Knowledge of the location of the IZs of a muscle is clinically important for (a) proper positioning of a single electrode pair between the IZ and tendon junctions, (b) targeted injection of botulinum toxin (58, 122), and (c) programming surgery in a way that would avoid damage to muscle innervation. The latter application is particularly important for reducing the risk of anal sphincter partial denervation resulting from episiotomy (18, 51, 123–125).

sEMG of Electrically Stimulated Muscles

Neuromuscular electrical stimulation involves the application of electrical stimuli to a nerve, or to the motor point of a superficial skeletal muscle, with the objective of inducing and controlling muscle contractions. The stimulus strength (either current or voltage or pulse width) determines the number of recruited motor units whereas the stimulus frequency determines their synchronized discharge rate. Since all the

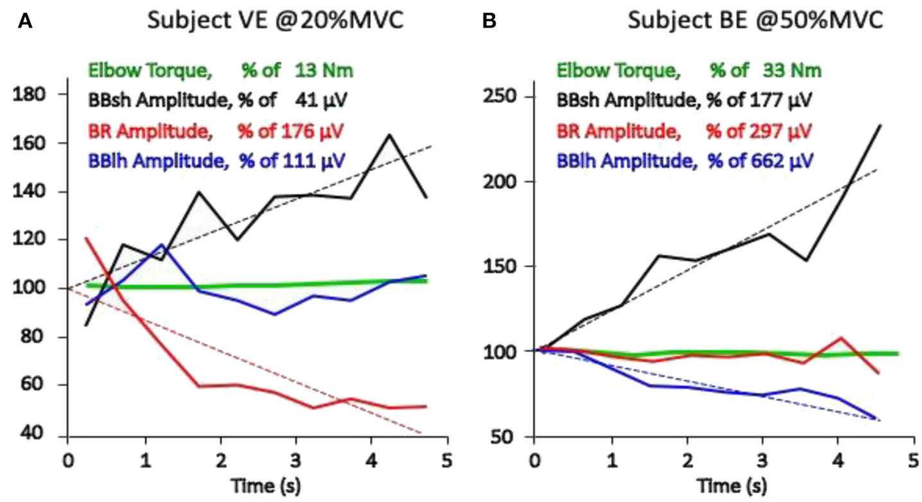

FIGURE 3 | Torque at the elbow and average rectified value (ARV), estimated on epochs of 0.5 s, of the sEMG obtained from three pairs of electrodes placed between the IZ and the tendon endings of the long and short head of the biceps brachii (BBlh, BBsh) and of the brachioradialis (BR) of two healthy subjects (**A** and **B**). All values are expressed as percent of the initial value, which is defined here as the intercept of the linear regression of the experimental values (dashed lines). Results from two 5-s isometric constant torque contractions performed at 20% MVC and at 50% MVC are presented. A progressively changing load sharing among the three muscles is evident and different in the two subjects (**A** and **B**). Different conclusions would have been reached depending on which single muscle had been monitored (unpublished data).

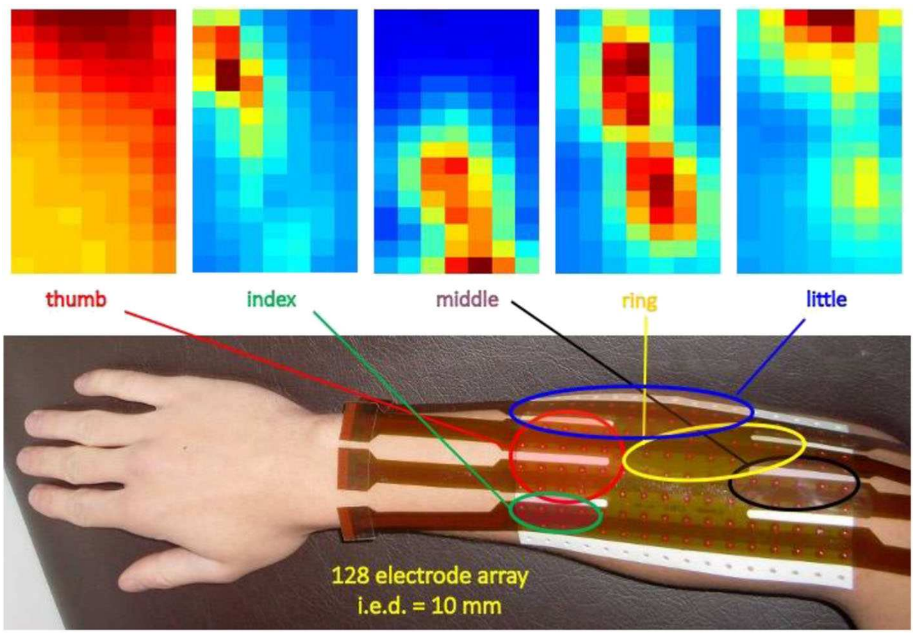

FIGURE 4 | Example of application of a 16 × 8 grid on the dorsal side of the forearm to identify/monitor the regions of activity of the finger extensors. The colors represent the intensity (RMS value) of the longitudinal differential signals (15 × 8 channels). Dark red = strong signal, dark blue = no signal. Interelectrode distance: 10 mm (unpublished data).

recruited MUs are activated synchronously, effectively as a single large MU, the sEMG signal is deterministic rather than stochastic and is referred to as M-wave or Compound Motor Action Potential (CMAP). Confounding factors and the effects of variability of CNS control, present in voluntary contractions, are eliminated and myoelectric manifestations of muscle fatigue are easy to measure. The technique provides a powerful bench-test for the quantitative investigation of a muscle's electrical and mechanical properties (126–128). Finally, functional electrical stimulation (FES) devices may be triggered or controlled by residual sEMG activity of partially paralyzed limb muscles (129).

Applications in Neurological Rehabilitation

Support for the Assessment and Treatment of Muscle Spasticity and Overactivity

The most common definition of spasticity goes back to Lance, according to whom spasticity is "…a motor disorder, characterized by a velocity-dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyper-excitability of the stretch reflex as one component of the upper motor neuron syndrome" and does "not include impaired voluntary movement and an abnormal posture" (130). Beside this definition, spasticity is a term that is firmly but not consistently used in the clinical environment and among pathologies (131). A brief history of the term, of its use and ongoing evolution can be found in the paper from Baude et al. (132). Not only is a generally accepted definition of spasticity lacking, but there is also a lack and a need of objective methods for assessing the level of spasticity (133, 134).

Many different studies have shown that sEMG can quantify alterations associated with spasticity, for example through the extraction of sEMG primitive synergies (93). However, these approaches do not distinguish between spasticity, on the one hand, and dystonia, rigidity or voluntary activation, on the other hand. According to the definition of Lance objective assessment of spasticity should be based on the investigation of the tonic stretch reflex. Several studies carried out in the last decades have consequently used sEMG to investigate the muscle response to stretch in the presence of spasticity (135–138). These studies have shown that sEMG provides the easiest and most reliable way of determining the stretch reflex threshold (133). Quantitative assessment of spasticity (139–141) as well as monitoring of treatment are possible (142) by combining sEMG with biomechanical techniques, measuring stretch velocity and torque. More recent approaches use the increased tonic stretch reflex to quantify the occurrence of spasticity during freely performed movements (143–145). **Figure 5** shows that in the presence of spasticity, a freely performed extension movement of the elbow leads to an increasing muscular activation with increasing movement velocity. This is in contrast to healthy subjects who use a lower muscular activation when the movement is performed with higher speeds.

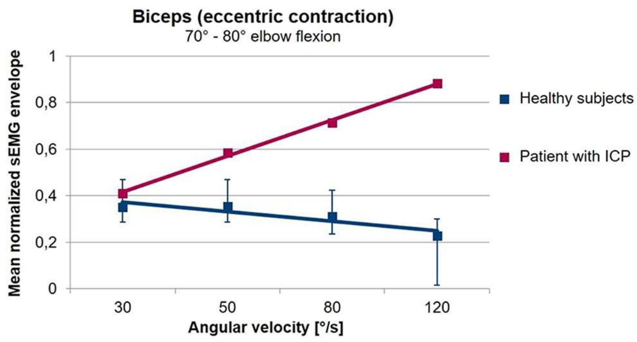

FIGURE 5 | Averaged sEMG envelopes of the Biceps Brachii as a function of the movement velocity during freely performed elbow extension movements. Values are normalized with respect to the 75% of the maximal value of the envelope. The sEMG when the elbow passes an interval from 80 to 70° flexion angle is analyzed. In healthy volunteers (blue), the biceps sEMG envelope decreases with increasing angular velocity. In contrast, in the patient with a spastic movement disorder (red) shown here, muscular activation increases with angular velocity. The gradient of the sEMG envelope–movement velocity relationship is thus a measure for the presence of spasticity during freely performed movements (unpublished data).

Support to the Identification of the Causes of Acquired Deformities and Treatment Selection

Following lesions to the CNS, such as stroke, traumatic brain injury, etc., patients can develop acquired deformities at the lower limb that impair or inhibit walking. These deformities, often termed contractures, are due to a combination of paresis, muscle overactivity, spasticity, along with mechanical barriers, including muscle shortening, increased muscle stiffness and viscosity, and retractions. Other phenomena (e.g., overactivity, spasticity, lack of recruitment) have to be assessed in dynamic conditions, because they may not be detectable during the bedside evaluation, and may be present only during walking, or vice versa (22, 67, 132). The direct assessment of muscle activity with sEMG and indwelling fine-wire EMG for deep muscles allows discriminating between active and passive causes, thus supporting the selection of treatments tailored for each patient (22, 67, 73, 85, 132). For example, in the assessment of the equinovarus foot deformity in stroke survivors, sEMG of the plantar flexors reveals which muscles are overactive during walking (146). This observation supports the clinical decision-making in choosing among focal muscle blockages, non-pharmacological treatments (147), and neuro-orthopedic or functional surgery. It is worth noting that, in stroke patients the triceps surae muscles can be completely silent during swing with equinus (73). **Figure 6** presents data from two stroke patients during walking. Both patients have an equinus foot deformity (i.e., limited dorsiflexion) with the same kinematics. They look equal, based on the visual observation of their gait. Yet, on further analysis of sEMG data, the two equinus deformities have completely different causes, and these are outlined by the sEMG traces (and by sEMG only).

Next, the recruitment of dorsiflexor muscles during walking, regardless of their voluntary activation during tests at the besides, is useful to further tune the surgical plan (e.g., split and transfer of the tibialis anterior tendon) (66, 148). Similarly, sEMG of the quadriceps muscle during walking can be used to support the clinical assessment for selecting the best treatment for stiff-knee gait (22, 65). In stroke survivors, surface EMG can also have a fundamental role in the planning of functional surgery of the upper limb, to support the surgeon's decision about which muscle to lengthen and which muscle insertion to transfer (64). Surface EMG has been used to assess motor function and to support clinical planning of surgical correction of foot deformities in CP children (149). Instrumental gait analysis and sEMG are considered among the fundamental sources of information to drive treatment selection (150).

Surface EMG-derived indices are also used as outcome measures to evaluate the responsiveness to treatments (151). In clinical practice, real-time sEMG can be used by physiotherapists (a) to control if the movement requested to the patient is

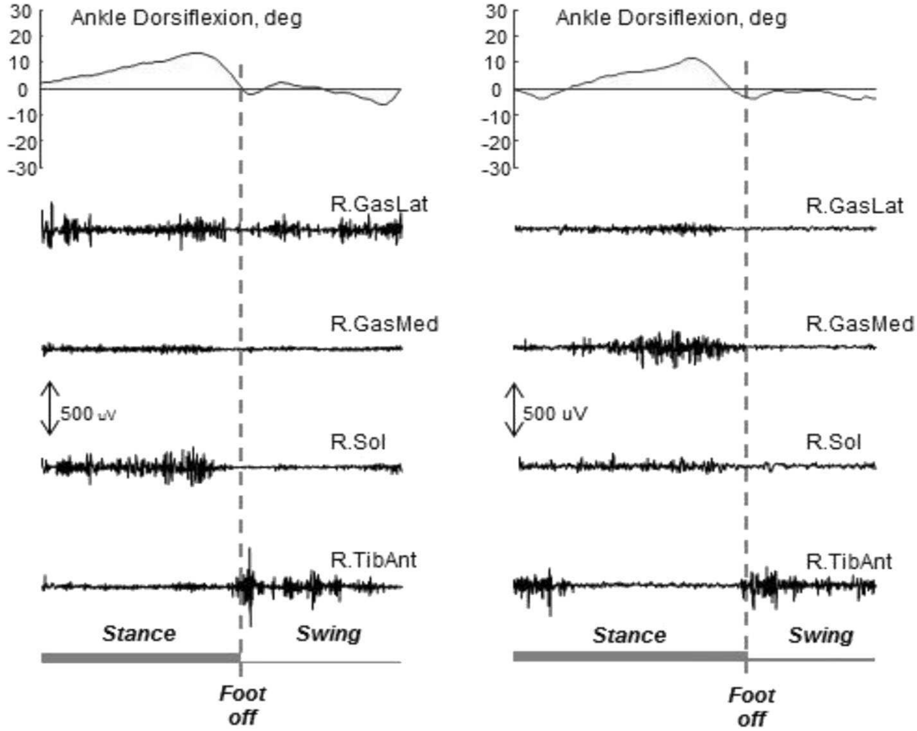

FIGURE 6 | Ankle kinematics and sEMG data from two stroke patients with equinus foot during the swing phase of gait. The same kinematics can be observed, with different underlying mechanisms. In both cases the activity of the tibialis anterior is present at foot off as required to lift the forefoot. On the left, the activity of the gastrocnemius lateralis during the swing phase hinders dorsiflexion. On the right, there is no activity of the triceps surae during the swing phase, and the lack of dorsiflexion is due to the triceps stiffness only. In this situation, sEMG is needed to support the decision-making concerning intervention. Unpublished data acquired in a research project approved by the local Ethics Committee (2017/0123710).

performed by the proper target muscle(s) or by means of compensatory mechanisms, (b) as a direct measurement of variations consequent to mobilization, verticalization, trunk fixation, in acute neurological patients, (c) to assess the effect of different orthoses on muscle activation, which can vary toward or away from the normal pattern (152).

In conclusion, in patients with either acquired CNS lesions (e.g., stroke, traumatic brain injury, spinal cord injuries) or degenerative diseases (e.g., multiple sclerosis), sEMG can be used (1) to better understand the underlying mechanisms of gait deterioration, especially where multifactorial causes coexists, (2) to support the clinical decision making and/or the rehabilitative pathway, and (3) as a marker of disease progression or intervention effectiveness (153). The same considerations are applicable to many other subsections of the neurorehabilitation field, to exercise physiology, occupational, and sport medicine.

Postural Control

Based on the pioneering work of Joseph and Nightingale (154), we now know that many muscles have a postural role that has been investigated by means of sEMG. These muscles oppose the pull of gravity, react to perturbations and allow us to stand, sit, or maintain a desired posture. They achieve this objective by controlling the stiffness of joints (mainly ankle) and by compensating for gravitational forces in either a continuous or an intermittent way. The standing human body is an intrinsically unstable inverted pendulum that requires continuous micro-adjustments to keep the center of mass and the center of pressure within the space defined by the feet.

This mechanism is altered by age and many pathologies and sEMG provides means to monitor such alterations. The role of sEMG is of paramount importance in helping investigators understand how neural regulation contributes to the prevention of falling, by studying the control of posture and the responses to postural perturbations in healthy and pathological subject (155–160).

Applications in Orthopedic Rehabilitation

The majority of rehabilitative treatments delivered by physiotherapists are related to orthopedic pathologies. In this field, the available sEMG-based indices assessing muscle activation, symmetry and localized fatigue can be used to support the selection of the therapeutic exercises and to monitor their effectiveness over time (161). In patients with low back pain (LBP), sEMG has been used as a tool for functional diagnosis and to assess the effectiveness of treatment (162, 163) and manipulation (164). Two systematic reviews are available on this topic (164, 165), which concluded that sEMG-based parameters of amplitude and localized fatigue are useful tools to monitor the effect of different interventions delivered to relieve LBP.

At the shoulder level, alterations in neuromuscular control of the scapular muscles has been proven in subjects with subacromial pain syndrome based on sEMG data (166). The effect on muscle activation of myofascial treatment techniques, such as dry needling, has been described in women with trapezius myalgia (167). Neck muscle dysfunction has been quantitively analyzed in patients with cervical spine pain (168, 169). It has to be stressed that the acquisition of sEMG data from the shoulder and neck muscles requires specific training and adequate instrumentation.

Lower limb orthopedic pathologies, related to either sport activity or injuries, have been widely investigated with sEMG-based techniques. For example, sEMG has been used to compare the activation of gluteal muscles between healthy and injured runners, to quantify thigh muscle imbalance in subjects with patellofemoral pain (170–172), and to investigate the causes of Achilles tendinopathy (173). Moreover, sEMG can be used to evaluate residual muscle function and abnormalities in patients who underwent a total hip or knee replacement and to tailor the rehabilitation programs (174). Considerable literature on this topic is available, inclusive of reviews and meta-analyses (171, 173, 175).

Applications in the Control of Prosthetic and Assistive Devices

Surface EMG detected from the residual muscles of an amputee has been used for controlling the motors of arm/hand prostheses (myoelectric prostheses) for five decades. This technique is limited to 2–3 basic commands and movements, is not intuitive and requires that the subject learns to associate a specific muscle contraction to the desired output. Recently the technique based on "Targeted Muscle Reinnervation (TMR)" has been tested with success in subjects with amputation at the shoulder level. The residual nerves from the amputated limb are surgically transferred to other, previously denervated, muscles that are not used by the subject. Reinnervation of these muscles takes place within 3–6 months. For example, branches of the median, radial, musculocutaneous, and ulnar nerves may be grafted to specific regions of the serratus or pectoralis muscles. Once reinnervated, these muscles act as biological amplifiers of the neural commands meant for the missing muscles and their sEMG can be detected with electrode arrays and decoded, by pattern recognition processes, for the control of the motors of the prosthesis. The command is therefore intuitive, that is the amputee attempts to move the missing arm and the mechanical arm moves as "desired." While some problems need to be solved, this technique is highly promising for specific amputees (176–178).

Applications in Pelvic Floor, Obstetrics, and Gynecologic Rehabilitation

Functional Assessment of Pelvic Floor Muscles

Pregnancy and high-impact sport activity are considered as risk factors for pelvic floor dysfunctions, including urinary incontinence. Surface EMG data demonstrated significant test-retest reliability and significant clinical predictive validity for urinary stress and urge incontinence. Pelvic floor muscle sEMG is reliable and consistently predictive of several important clinical status variables, it can be a useful tool in early detection and prophylactic intervention for muscle laxity. Recent advances in sEMG technology make it cost-effective, convenient and easy to learn and administer by trained assisting staff. This technology is a powerful complementary tool for digital assessment of pelvic floor muscles and should be considered for use in gynecologic practice. Prenatal exercise programs, supported by pelvic floor muscle exercises, should be recommended for pregnant women, especially those who are accustomed to higher exercise intensity (179–181). Surface EMG using intravaginal probes is of widespread use as a biofeedback technique as well as for assessing pelvic floor muscles activity in women. Many muscles are involved and the issue of crosstalk during intravaginal sEMG recordings has been reviewed in Flury et al. (182). A gap in knowledge affecting sEMG investigation methods was identified by these authors. Literature addressing the proper electrode location and the crosstalk problem is scarce and often flawed. Conclusions are regularly drawn from an insufficient basis of evidence. Further research and training of operators is required (182).

High density surface EMG (HDsEMG) signals have been used for mapping the activity of the muscles surrounding the vaginal, the urethral and the anal canals (183, 184). Hacad et al. observed that continent and incontinent male patients presented sEMG changes during the first 6 months after radical prostatectomy that could be justified by the denervation/reinnervation of the external urethral sphincter (185).

Prenatal sEMG of the Anal Sphincter to Predict the Impact of Episiotomy

Although very controversial and discouraged, episiotomy is still a widely performed surgery during child delivery. The techniques described above for the location of MU innervation zones (IZ) provide a tool to estimate the risk of partial denervation of the external anal sphincter (EAS) consequent to episiotomy. An intra-anal probe with a circumferential array of 16 electrodes detects the sEMG activity of the EAS during a voluntary contraction. Proper software identifies the location of the IZs of motor units of the EAS. This information can then be used, at the time of delivery, to guide episiotomy (if necessary) to the right or left side to minimize the risk of EAS partial denervation and possible future incontinence. **Figures 7A,B** show the MUs (and their IZs) detected in one subject at the 34th week of pregnancy and at the 6th week after vaginal delivery with right mediolateral episiotomy. **Figures 7C,D** show the distribution of IZs identified in 86 cases of episiotomy (all performed on the right side and out of 331 deliveries) around the electrodes of the probe. A statistically significant drop of the number of motor units innervated in the right-ventral (RV) quadrant of the EAS as well as the post-delivery reorganization of the EAS motor units are evident in **Figures 7C,D** (123, 125). This technique could be used as a biofeedback modality to retrain the muscle as is done with muscles surrounding the vaginal canal.

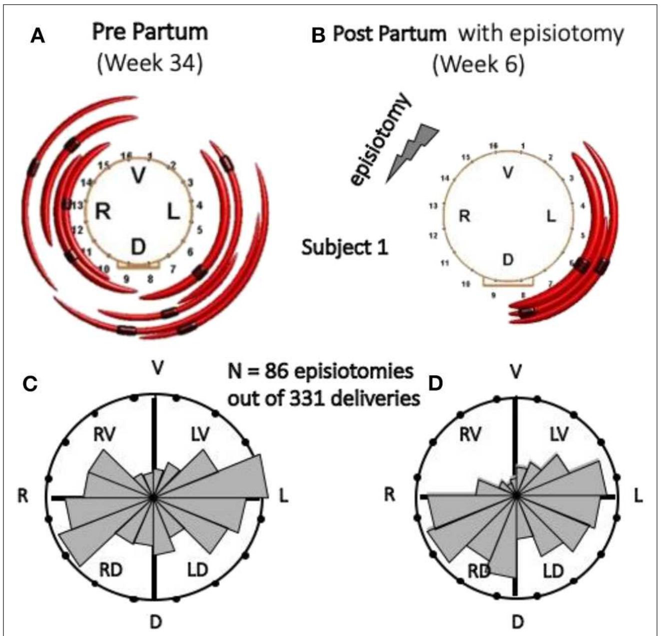

FIGURE 7 | Effect of episiotomy on the EAS innervation pattern. The identified EAS motor units, indicated by red arcs, are not necessarily all the motor units of the EAS. **(A,B)** Identified MUs and their IZs, 4–6 weeks pre-delivery and 6 weeks post-delivery with right mediolateral episiotomy, in one subject. **(C,D)** Circular histograms of the number of EAS IZs pre- and post-delivery in 86 cases of right episiotomy (out of 331 deliveries). Both histograms are normalized with respect to the highest bin. The change in the RV quadrant of the EAS is statistically significant (123). V, ventral; L, left; D, dorsal; R, right. **(A,B)** Reproduced with permission from Cescon et al. (123), **(C,D)** Reproduced, with permission from Di Vella et al. (186).

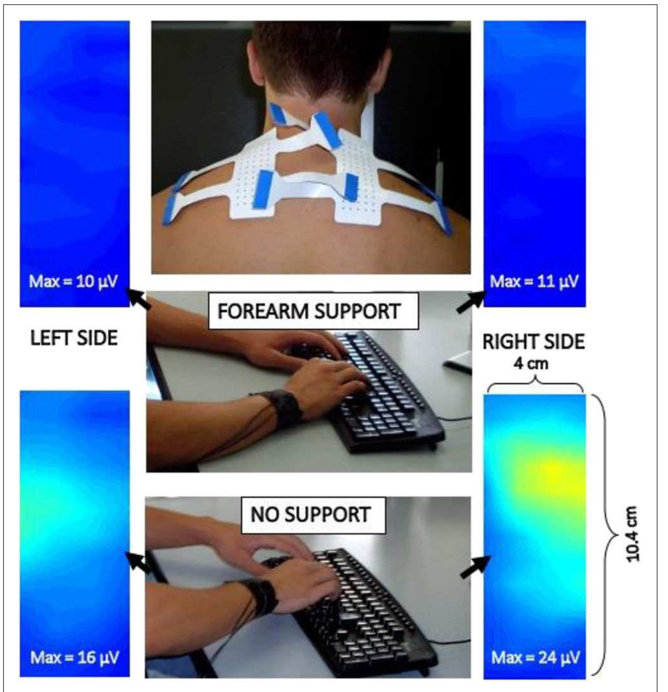

FIGURE 8 | Example of two electrode grids applied to the trapezius muscle to study its activity during typing on a keyboard with and without arm rest on the desk. Images are interpolated and show the sEMG RMS distribution in space (see movies at URL https://www.robertomerletti.it/en/emg/material/videos/f6/ and https://www.robertomerletti.it/en/emg/material/videos/f7/).

Applications in Ergonomics

Surface EMG techniques in ergonomics and occupational medicine for prevention and monitoring of occupational disorders were developed in the 90s (49, 187) and are currently applied for assessing chairs, posture, occupational tasks, fatigue, and risk at work (188–190). As an example, **Figure 8** shows maps of sEMG RMS value (one 0.5 s epoch) of the trapezius muscle of a subject typing with and without forearm rest on the desk. Different activation levels of the upper part of the trapezius are evident while the subject is unaware of them. Teaching correct movements/efforts at work and prevention of work-related disorders are largely based on sEMG applications.

Applications in Exercise Physiology, Sports, and Aging

The literature concerning sEMG applications in sports is very extensive and focused on physiology (191, 192) training, prevention of injury, and recovery after injury (in particular the anterior cruciate ligament injury (193). Many sports have been investigated, in particular golf (194), jumping (195), cycling (196), sprinting (197), volleyball (198), but also strength training (199, 200), back pain in rowers (201), patellofemoral pain (170, 202), and aging (59, 203). The distribution of muscle fiber conduction velocity, related to fiber diameter, may provide insight in muscle structure. Mean/median spectral frequencies are affected by too many confounding factors to be used for this purpose but may be useful, in strictly controlled experiments, to monitor muscle fatigue resistance.

Applications in Gnathology

Temporomandibular disorder (TMD) is a term indicating musculoskeletal disorders in the jaw muscles and/or the temporomandibular joint. Surface EMG analysis has been employed to obtain a better understanding of TMD and is useful to elucidate the masticatory muscle function and adaptation in patients with TMD, using indices of dominance, asymmetry, co-ordination and co-operation of temporalis and masseter muscles during mastication. An association exists linking decreased activity to increased severity and asymmetry between affected and non-affected side in unilateral TMD patients (204–208). The ease-of-use of the sEMG assessment of masticatory muscles during static contractions and/or during chewing, has led to the development of standardized examination protocols and output graphs, which are suited for use in clinical routine assessment.

Other Applications

The above list of sEMG application fields is far from comprehensive. Many other fields take advantage of sEMG as a tool for either investigation, clinical assessment or treatment. These fields deal with the joint use of sEMG and ultrasound (209), the study of muscle deterioration in real or simulated (bed rest) microgravity conditions and the assessment of countermeasures (210, 211), the non-invasive detection of fasciculations (212, 213), the study of cramps (56, 214–216), the use of sEMG in rehabilitation games (217, 218).

BARRIERS TO WIDESPREAD CLINICAL USE OF SEMG IN NEUROREHABILITATION

Current Situation

Section Surface EMG Applications provided a partial overview of the rapidly growing applications of sEMG in neuro-rehabilitation, movement sciences, occupational and sport medicine, and other fields. Many of the thousands of articles in these fields come from rehabilitation engineering groups, quite a few from movement science laboratories, but relatively few from the clinical world. Despite the extremely large number of publications about signal detection, processing tools, and small clinical studies, publications on routine applications in clinical practice are minimal. In addition, sEMG applications in medium/large clinical studies are rare (22, 64, 67, 73, 219). There is a lack of clinical studies (e.g., observational studies) verifying whether patients exposed to an additional sEMG assessment reach better outcomes than patients undergoing standard assessments do.

Hardware and software for sEMG detection and processing/interpretation has been developed mostly by academic researchers whose objective is to develop scientific innovation, and to publish their findings in respected science journals. In these cases, the research questions are typically technical, rather than clinical. The giant step between publishing a method, or developing a prototype, and the design, manufacturing, and marketing of a device for clinical applications is expensive and can be undertaken by companies only if there is evidence of clinical effectiveness and demand from the market. But a demand from the market implies some awareness of the users and their understanding of the potential use and relevance of the new method/device. If the users do not know why measuring muscle activity may be important, they will not be interested in a device or method to measure it. This brings up the issue of information, education and knowledge-transfer, but also other considerations concerning the potential consequences that making such measurement will imply. For example, who is qualified to decide on the measurement, who performs it, and who will use and interpret the resulting information to make decisions? Which balances will be affected, what will the costs or savings be, and who will gain something from doing it? This is important in private health management systems, where the role of insurance companies conditions the market, as well as in national health systems, where the state (that is the community) covers health cost with tax money.

Most of the scientific breakthroughs produced in academia do not routinely result in a marketable product or procedure. Commercialization of emerging technological innovations is difficult to accomplish; Transferring technological knowledge can also be a time-consuming process resulting often in a market failure. This may be because users are not yet competent or did not contribute to the development of the knowledge. On the other hand, academia-based researchers may also not be competent to assess the needs and boundaries of the clinical procedures. This scenario has been conceptualized as a "valley of death" between research and market. To tackle this general problem, major challenges are being analyzed, at the EU and national levels, and in the USA, involving educated/informed Communities of Practitioners (CoPs) in the process of effective transfer of high-value emerging technologies (220).

In addition to this, recent EU grants required the participation of companies as partners of funded projects.

Some Fundamental Questions

To address the barriers to clinical use of sEMG, we believe it is important, together with the CoPs, to try to answer fundamental primary questions and a set of secondary questions which outline the potential added value that can be provided by sEMG-based assessments. Primary questions concern the pathophysiological status of the neuromuscular system as well as the definition/measurement of key characteristic features (e.g., Is the muscle on or off? Does muscle fatigue occur during a task? Is the control strategy changing during a task?). Secondary questions concern when and why the answer to a primary question is clinically important, who should answer the question and how this person should be trained. The list below includes a few examples of the many primary questions that can be answered by a competent analysis of sEMG:

1. Is the muscle active or not at a given time? When does the muscle turn on and off during a task?
2. Is the muscle relaxed or active or progressively changing its activation level? What level of force is produced ?
3. Is muscle activity triggered by muscle lengthening and/or by the velocity of the stretch?
4. What is the level of muscle activation? Is the estimation of force (or force change) of any interest?
5. How are many muscles coordinated and what are the temporal relations between their activations?
6. Is there co-activation of different muscles during a task?
7. Is there a region of a muscle that is more or less active then other regions? Or is there a muscle of a group that is more or less active than other muscles of the same group?
8. What is the strategy adopted for controlling motor unit recruitment and muscle coordination?
9. Where are the innervations zones of the MUs of a muscle located along the muscle?
10. How long are the muscle fibers and how much are they shortening/lengthening during a task?
11. Is conduction velocity of the muscle fibers relevant for the situation at hand? What is its average value? What is its distribution across motor units normal or not?
12. Is muscle fatigue of interest in the situation at hand?
13. Is the number of active motor units of a muscle stable, or changing in time during a task? Are the active motor units rotating, that is are they being de-recruited and replaced by others during performance of a task?

14. What is the fiber size and fatigability of MUs?

The list below includes examples of secondary questions that should be asked and answered in association to each of the primary questions listed above:

1. When and why is the answer to this primary question important?
2. What must be measured to answer the primary question? What instrument should be used?
3. What is the knowledge required to answer this primary question?
4. Who is the competent clinical operator who should perform the measurements required to answer this primary question?
5. What is the knowledge that such operator must have in order to perform the measurement? How can this knowledge be acquired by this operator?
6. Who is the competent clinical operator qualified to interpret the results of the measurement and draw conclusions from them? How can the required competence and expertise be acquired?

The current limited clinical application of sEMG indicates that either type of questions are rarely asked. However, the literature unquestionably indicates that the answers to the primary questions are available and that they are important for understanding the pathophysiology of muscle conditions and motor control strategies. The issue is whether such questions are considered to be relevant, from the clinical viewpoint, by the CoPs, and which barriers prevent answering the relevant ones.

As indicated above and in section Introduction, large studies, and translational efforts from scientific knowledge to clinical application are hindered by a number of barriers a few of which have been previously investigated by other authors and identified as (a) lack of time, (b) lack of skills, (c) misperceptions of EBP (31, 37–40, 221–223). But these barriers go much beyond these issues and much beyond sEMG. They can be roughly grouped in four categories: cultural, educational, technical, and economical.

Cultural Barriers

The cultural barriers limiting the widespread use of sEMG are not specific to this field and are the same that affect many other rehabilitation fields. They are, in general, related to the global approach to measurement in rehabilitation and to the concept of evidence provided by such measurements (39).

The Concepts of Measure and Measurement

In physics, "measurement" is the process of attributing a value to a physical quantity by comparing it to a standard reference quantity called "unit of measurement." In rehabilitation, "measures" can be measurements of physical quantities (e.g., range of motion, 6-min walking test, etc.), ratings of a specific ability based on an ordinal scale with known levels (e.g., Functional Ambulatory Classification for assessing ambulation, etc.), ratings of multidimensional abilities on item scores that are summed up to obtain a total score (e.g., Barthel Index for assessing independence in the activity of daily life), results of questionnaires or aggregations of tests (pass/fail) or ordinal grades, such as very-poor/poor/sufficient/good/very-good, or 0/1/2/3/4/5 (e.g., for assessing force or resistance to stretch). The exact definition of each level of the scale may change from assessor to assessor. On the one hand, all these tools are useful, easy to be administered and represent a key element for both clinical activities and administrative procedures (e.g., reimbursements). Noteworthy, dichotomous variables are the pillar of epidemiological studies (e.g., exposed/non-exposed vs. dead/alive). On the other hand, they may suffer from metrical issues, from construct validity to sensitivity or reliability, and may lead to huge data-analysis problems when ordinal scores (e.g., 1/2/3/4/5) are treated as numbers and averaged or analyzed with parametric statistics and when the effects of a treatment are computed as numerical difference between scores obtained before and after the treatment. Moreover, electrophysiological variables, such as those describing motor control, cannot be assessed by clinical scales and require instrumental measurements. Some well-known textbooks, such as "Measurement in Neurological Rehabilitation" (224) do not even mention measurement of force/torque, or angular velocity, or sEMG and present only scales and questionnaires.

While physical measurements are the foundation of science and associate the change of a quantity as an effect due to some cause, the classification of the patient's current status or functional ability is the main goal of the "measures" in rehabilitation. Surface EMG amplitude (RMS, ARV) and spectral (MNF, MDF) features or timing during movement or tasks, are measurements of muscles signals that in turn reflect and quantitatively describe pathophysiological events or conditions or recovery level. In some cases, the possibility of turning this numerical information into clinically meaningful categories, based on a-priori knowledge and thresholds, would probably support the use of sEMG based examinations (but not of sEMG itself) in the rehabilitation practice.

Technology and Humanity: Communication Gaps and Lack of a Common Language

It has been properly pointed out that the statement "there can be no evidence in rehabilitation" that is so often heard from medical operators who think that their job is more "humanistic" than "scientific," challenges the scientific basis of rehabilitation (3). Such thinking would drive physiotherapy and rehabilitation out of the mainstream of science. Rigorous reasoning and measurement-based approaches require a deep understanding of the physiological mechanisms and quantities being measured, of the instruments being used, and of the design of clinical studies in rehabilitation. Tradition and empirical experience alone are bad teachers (3).

Fundamental concepts of mathematics and biomechanics are associated to sEMG measurements and to the need for a language common to clinicians and rehabilitation engineers. Efforts in this direction are under way (e.g., Tutorials and CEDE consensus papers published in the Journal of Electromyography and Kinesiology) (52, 53, 61, 62). Applications of biomechanics and greater interactions between clinicians and rehabilitation engineers cannot take place without a common language that includes the concept of measurement of physical quantities with proper instruments (31, 38, 40). Rehabilitation medicine and physiotherapy are deeply connected with mathematics, physics and biomechanics. The fact that robotics and advanced technologies are entering the rehabilitation field (4, 6–8) is fear-inducing to some clinicians who consider these advances as job-threatening. Medical students and PTs should be taught to see technology as a tool in their hands. Rehabilitation operators demand more "intelligent," fool-proof, and error-correcting devices to rely on (see section Technical Barriers). For this and other reasons, artificial intelligence, intelligent human-machine interfaces, and self-correcting data acquisition systems, are very important in rehabilitation and must be part of the training of professionals who should use them with proper competence and caution, and never totally rely on them.

Misunderstanding the Purpose of sEMG

Among rehabilitation professionals, there is a tendency to consider sEMG as a therapeutic tool so that the potential benefits of sEMG appear limited to biofeedback applications. In fact, sEMG is much more a monitoring tool, and occasionally, a diagnostic tool. The incorrect view of sEMG as a "therapy" is a barrier to its use.

Educational Barriers

The clinical interpretation of sEMG is based on the timing, amplitude and the morphology (continuous activity, burst-like activity, MUAP shape and firing pattern, etc.) of the signal. Technical aspects related to the type of electrodes, the type of protocol used, the adopted filters, etc., affect the waveform, timing, amplitude, and spectrum of the signal. Also, the modification of the peripheral properties of the muscle and the modification of the central drive have an effect on the morphology of the sEMG signal (225). Although, unlike ECG and EEG, the wrong reading or interpretation of the sEMG tracing may not have dramatic consequences on the patient, it can change therapeutic decisions, surgical options, focal treatment of spasticity, and cost of therapy.

Reading a sEMG recording and linking a pathophysiological and/or biomechanical meaning to its features (that often result from computer processing) requires considerable competences. These are rarely available in the clinical environment. Educational barriers are a bottleneck. Many countries offer a Master in Health Professions (some specifically in physiotherapy). These degrees too often focus on legal, professional and administrative issues and neglect scientific and technical education. Noteworthy, The World Confederation for Physical Therapy (WCPT) advocates that the scope of physical therapist practice is not limited to direct patient/client care, but also includes research (https://www.wcpt.org/policy/ps-descriptionPT). The academic programs in movement sciences often provide a more scientific and research oriented background.

Only a few countries offer a Ph.D. program in physiotherapy and a few more offer a Ph.D. in movement sciences. Where there is no Ph.D., no research fellowships and research positions are available. This precludes the academic career of physiotherapists and has a profound impact on education. A 3-years (or 4-years, as in Belgium and The Netherlands, among other countries) BS program is barely sufficient to train a practitioner, not a contract professor or a clinical researcher able to promote and conduct large-scale studies. In addition, it is unthinkable that a practitioner will acquire this knowledge on his/her own time, in parallel to a heavy burden of clinical work, and publish in qualified journals to achieve an academic status (42). The sEMG field is deeply affected by this situation because of the need for clinical studies that can be carried out only by qualified researchers at the post-graduate level. Moreover, the lack of specific education also prevents the preparation of clinical application guidelines that must become a part of the education of all operators potentially involved in sEMG application.

In countries in which physiotherapy is not a graduate level degree, students are trained to become practitioners rather than clinical researchers. The concept of measuring physical quantities is neglected as well as the fundamentals of physics and biomechanics (from the physical point of view). Moreover, in countries that do not grant a PhD in physiotherapy or movement sciences, teachers of physiotherapy have in general, no or very limited research exposure or international experience. Insufficient continuing education and involvement of teachers in research projects is a barrier to clinical use of all new technologies, and sEMG in particular.

Technical Barriers

Technological evolution led to the development of sEMG hardware that is simple to use and is commercially available. Powerful software can extract sEMG features whose clinical relevance is documented in the available literature. Nevertheless, there is a persistent demand for engineers to build systems that can be easily applied without a high risk of error. Users demand to be technically supported in the interpretation of signals and warned of potential misuse and acquisition error. There is a high demand for artificial expert systems and explanatory components that should be integrated into the sEMG systems and protect the user from errors and misinterpretations. However, no software will correct basic human errors (e.g., electrode misplacement, use of wrong filtering, etc.). This brings up the problem of the degree to which lack of competence can or should be replaced by expert systems, artificial intelligence or automatic devices. This may be a dangerous avenue of research in a field where developers and users have widely different expertise, experience and responsibility. Even if software is subject to the same stringent and reliable regulations as all medical devices, it cannot be fool-proof and cannot replace human expertise and competence. The solution is a more competent operator possibly assisted by a more intelligent machine providing warnings or "suggesting" possible interpretations.

Many researchers made remarkable efforts to (a) introduce sEMG as a tool to integrate biomechanical information for movement analysis, and (b) to provide tutorials and guidelines to clinical operators (29, 61, 108, 226–228). Very important contributions came from the European Project "Surface Electromyography for Non-Invasive Assessment of Muscles (SENIAM)" (226). Additional efforts are under way with the publication of a set of tutorials and consensus papers on the Journal of Electromyography and Kinesiology. These efforts have been designed to increase the competence of sEMG users, but their impact has been limited, suggesting that this may be a necessary but not sufficient step (229).

Economic/Administrative Barriers

The new Medical Device Regulation (MDR) of the European Union requires proof of benefit through clinical studies, based on the Health Technology Assessment (HTA) procedure. This will be difficult to provide for sEMG equipment because of the lack of suitable personnel, creating a vicious circle. In addition, the producers of medical devices will have to maintain competencies in the areas of quality assurance and risk management. This is difficult to ensure, especially for very small companies, and may further hinder the translation of innovative sEMG procedures in the long term. Unresolved reimbursement issues and new regulatory barriers will hinder the development of sEMG systems adapted to clinical needs and their translation into clinical practice.

As mentioned by Duncan and Murray (221) "Whilst the importance of routinely measuring outcomes within the allied health professions is well-recognized, it has largely failed to be delivered in practice. Factors that influence clinicians' ability and desire to undertake routine outcome measurement are bi-directional: they can act as either facilitators or barriers. Routine outcome measurement may only be deliverable if appropriate action is taken at individual therapist, team, and organizational levels of an organization." The European MDR might be such action.

Should sEMG Measurements Be Fast, Simple, Automatic, and Inexpensive?

In most countries, a physiotherapy session lasts 30–60 min and is usually related to treatment, not to measurement of results. This time constraint is mentioned in many articles reporting results of questionnaires or interviews to physiotherapists (38, 40). In their recent work, Feldner et al. (31) reported that "most clinicians (19 out of 22) relied primarily on clinical observation of functional skills … used palpation, manual muscle testing … their choices were often based on time constraints and reimbursement considerations." These authors further noticed that "most clinicians (18 out of 22) reported that they received very little training specific to the use of sEMG systems during their professional curricula…" and "…perceived barriers in "convincing" department administration to invest in technology.…"

In addition, these authors indicated that "Despite barriers, participants were eager to learn about sEMG, noting that it would not replace but enhance their current clinical methods.…" Due to the lack of training, the request is that sEMG equipment and testing should be easy to self-learn, fast and simple to use and inexpensive. The lack of teaching associated to self-teaching by trial and errors or from salespersons only, causes user frustration and is a major barrier to the use of sEMG. This is not so in the case of ECG and EEG (and needle EMG) whose users are provided with proper academic education and training.

Cost of FDA or CE-approved sEMG equipment ranges from about 10 k$ to nearly 40 k$ for wireless systems providing up to 32 channels and processing software. This is in the same order of magnitude of inexpensive to sophisticated ECG, EEG, and needle EMG equipment.

A possible explanation for the differences between ECG, EEG, needle EMG, and sEMG is that the former have a higher diagnostic yield while sEMG only provides information on the functional level, which is associated with prevention, monitoring, assessment, and treatment planning but less to diagnosis. The lower importance attributed to the latter functions with respect to diagnosis is a bias that is hard to overcome and has high social and economic costs.

Coverage by Insurances and National Health Systems

A vicious circle exists between the need to collect more evidence of sEMG effectiveness in assessing results, and the lack of qualified clinical researchers able to do it. This is a clinical activity that should not be left to either the manufactures or to the rehabilitation engineers. It is a clinical activity dealing with, and requiring, studies on patients. Despite the large number of publications on small studies, the evidence does not seem to be sufficient to convince insurance companies or National Health Systems to reimburse the cost of sEMG-based testing for effectiveness of treatments. In North America, sEMG procedures are not routinely reimbursed by insurance, unless they are part of a preoperative protocol, such as used for surgical planning in patients with CP. This is in contrast to diagnostic procedures using intramuscular needles which are done routinely by clinicians for diagnostic reasons.

Research Funding

Evidence supporting the use of sEMG is only partially available because it is limited to small studies. Large studies require substantial funding and competent operators. Competent operators are lacking because of educational barriers. Educational barriers are lower in countries where post-graduate academic degrees are available. Therefore, large-scale studies should be proposed where researchers are available to implement them. Research funding is required to support researchers and pay for equipment and management of large studies.

CONCLUSIONS

Hundreds of publications on peer-reviewed journals (**Figure 1**) provide a consistent body of evidence that the applications of sEMG makes appropriate information available in many medical fields, including the neurorehabilitation and orthopedic areas. Despite these achievements, clinical applications in health delivery institutions remain very limited because of many barriers. Clinicians have ready access to articles, evidence summaries, systematic reviews, and meta-analyses that assess and summarize the state of the art in the field. However, scientific publications are necessary but not sufficient to promote innovation. As indicated in a well-known editorial by A. Jette in 2017 (229) "Publishing our work in journals is essential—but publication of research is not, by itself, sufficient if our goal is to change clinical practice. People follow the lead of other people they know and trust when they decide whether to take up an innovation and change the way they practice!"

In this work, the barriers to a widespread use of sEMG have been classified into four main groups: cultural, educational, technical, and economic. These are strictly linked and interdependent.

Cultural barriers derive from "uneasiness" with technology, from communication gaps, different perceptions and approaches between rehabilitation engineers and clinical operators. These different perceptions hinder technology transfer and generate educational barriers. Overcoming these barriers requires a strongly interdisciplinary educational approach. The lack of a partially overlapping high-level education, involving rehabilitation professionals and engineers, results in different languages, communication gaps, different approaches to common problems, or, in one word, cultural barriers that delay technology transfer. The development of common languages at common institutions would promote the use of sEMG systems and other measurement techniques

To this end it is important to point out and underline the series of open access Tutorials (61, 62) and of Consensus Papers within the "Consensus for experimental design in electromyography (CEDE)" project (53) promoted by the Journal of Electromyography and Kinesiology.

Overcoming educational barriers requires (a) a greater degree of bidirectional osmosis between the clinical and the research environments, (b) funding of translational efforts, (c) use of textbooks and manuals related to the clinical use of sEMG in specific applications prepared by experts (19), (d) design and implementation of large clinical studies. These should rise from (a) simple case-series on the added value provided by sEMG assessment aimed to the selection of a proper treatment, (b) observational studies comparing both pathways and outcomes of cohorts of patients treated in centers with/without sEMG adjunctive assessments, up to RCTs addressing the percentage of modified treatments and the differences in the functional outcomes determined by the use of sEMG-based adjunctive assessments. These activities must be carried out by qualified researchers within post-graduate research programs. This brings up the need for new academic figures merging clinical and physiopathological competences with the capability of understanding and properly using state-of-the art sEMG instrumentation/technology.

The lack of higher academic degrees in physiotherapy and movement sciences prevents (a) the education of qualified researchers able to properly apply the rapidly developing technology and to carry out large clinical studies, and (b) continuing education initiatives in teaching and research to exploit the growing assessment capabilities provided by technology.

Technical barriers are due to (a) sEMG systems considered unfriendly, (b) the lack of familiarity with hardware and signal processing/interpretation techniques, and (c) the demand for fool-proof automatic equipment. The demand for support in the interpretation of signals and automatic warning of potential misuse and acquisition errors cannot be fully satisfied. Automatic expert system are no substitutes for human expertise and competence and may be misleading. No device should be used without knowledge of its performance, limitations and misuse, and without user's critical competence. Education and research should be institutionally planned and provided, like in other fields, at the academic level, by training new figures with a strongly inter- and multi-disciplinary approach. They will, in turn, train a new breed of clinical operators able to manage technology and interact with engineers and manufacturers.

Finally, economical barriers, including cost/benefit analysis, should be seriously considered to identify the most economically rewarding sEMG-based applications, thus turning boundaries into project specifications. This requires fellowships for training researchers and funding for support of large clinical studies whose results will lead to reduction of the economic burden of institutions paying for treatment costs.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Surface Electromyography Meets Biomechanics: Correct Interpretation of sEMG-Signals in Neuro-Rehabilitation Needs Biomechanical Input

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Coordinated activation of muscles is the basis for human locomotion. Impaired muscular activation is related to poor movement performance and disability. To restore movement performance, information about the subject's individual muscular activation is of high relevance. Surface electromyography (sEMG) allows the pain-free assessment of muscular activation and many ready-to-use technologies are available. They enable the usage of sEMG measurements in several applications. However, due to the fact that in most rehabilitation applications dynamic conditions are analyzed, the correct interpretation of sEMG signals remains difficult which hinders the spread of sEMG in clinical applications. From biomechanics it is well-known that the sEMG signal depends on muscle fiber length, contraction velocity, contraction type and on the muscle's biomechanical moment. In non-isometric conditions these biomechanical factors have to be considered when analyzing sEMG signals. Additionally, the central nervous system control strategies used to activate synergistic and antagonistic muscles have to be taken into consideration. These central nervous system activation strategies are rarely known in physiology and are hard to manage in pathology. In this perspective report we discuss how the consideration of biomechanical factors leads to more reliable information extraction from sEMG signals and how the limitations of sEMG can be overcome in dynamic conditions. This is a prerequisite if the use of sEMG in rehabilitation applications is to extend. Examples will be given showing how the integration of biomechanical knowledge into the interpretation of sEMG helps to identify the central nervous system activation strategies involved and leads to relevant clinical information.

Keywords: surface electromyography, biomechanics, neuromechanics, clinical application, rehabilitation

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INTRODUCTION

The coordinated activation of muscles forms the basis for human movement. A frequent consequence of lesions of the central nervous system is muscle paresis accompanied by reduced muscle force and/or the loss of the ability to activate the muscles in a coordinated way. This results in poor movement performance and causes pain and disability. To preserve and restore movement performance is a challenge, and the demand for more effective treatment methods is gaining more importance (1, 2). However, a more patient-tailored rehabilitation therapy would become possible, if the information about the subject's muscular activation is included in the treatment strategy (2, 3).

SEMG technologies allow the pain-free assessment of muscular activation and many ready-to-use technologies are available (4, 5). They enable sEMG measurements in several applications among which rehabilitation is of particular importance. Although sEMG could make an essential contribution to improved rehabilitation it has not yet been routinely translated to clinics (2). This crucial step can only occur, if sEMG achieves high acceptance by physicians and physiotherapists. However, the acceptance of sEMG by clinical users is currently low. Here, the technological challenge is to identify, adjust or develop sEMG tools, signal processing strategies and application procedures which enable sEMG to meet the users' expectations. sEMG can make an essential contribution to many clinical questions, but it also has many limitations. These limitations must be known, understood and integrated into analysis algorithms in order to enable a fast and correct interpretation of the sEMG signal (4, 6).

This perspective report is addressed to clinical users but especially to sEMG developers. The aim is to raise awareness of the importance of biomechanical factors in the analysis of sEMG signals acquired under non-isometric conditions.

Barriers Limiting the Use of sEMG in Dynamic Conditions

One major barrier limiting the use of sEMG in clinical applications is that the correct interpretation of sEMG signals remains debatable (5, 7). Consequently, potential sEMG users will be in a predicament when applying sEMG technologies. The reason for this is that the number of factors influencing the sEMG signal are numerous and interwoven (4, 8). On the other hand, rehabilitative interventions are under increasing pressure to provide evidence of their impact. This is only possible if patient groups can be compared with each other or if individual patients can be matched to a baseline (2). This has been achieved in clinical routine through various tests and scores (9). Information about the amount of muscular activation during functional movement tasks is routinely not included in the assessment. There are various reasons for this and they are related to both educational and practical issues (2). One aspect among others is that in dynamic conditions many factors influence the sEMG signal that are difficult to control (4, 10). This often makes a comparison between subjects, muscles or contractions in dynamic conditions difficult and lowers the clinical potential of the information extracted from the sEMG signals (2).

The challenges sEMG is facing are related to the fact that most applications in rehabilitation are associated with non-isometric conditions. If information about the onset and cessation of muscular activation is to be extracted from the sEMG signal, unambiguous conclusions are possible as long as the sEMG signal can be related to individual movement phases. A particularly clinically relevant example for this approach is the determination of phases of muscular activation during gait (10). Thereby, onset and cessation of muscular activation are set in relation to the gait cycle intervals, which can be easily detected with foot switches. When the informative value is not the timing but the amount of muscular activation, it is necessary to rely somehow on the amplitude of the sEMG signal. However, sEMG amplitude as well as sEMG envelope are influenced by many different factors. Therefore, while the potential of sEMG amplitude is huge, information that can be obtained from it is rarely used in clinical applications. On the other hand, when the majority of factors affecting the sEMG signal are known, controlled and can be unambiguously determined, reliable conclusions can be drawn from the sEMG amplitude (4). This is the case in short duration applications involving isometric contraction. However, in non-isometric applications additional measurement methods are necessary to provide all relevant information needed (11, 12).

Biomechanical Factors Influencing the sEMG Amplitude

The relationship between muscle force and sEMG signal has closely linked the disciplines of biomechanics and electromyography for decades (6, 13–17). Nevertheless, there is unfortunately no simple closed-form or equation that describes this relationship in an adequate manner. From biomechanics, it is well-known that the contraction force of the muscle fiber depends on the fiber length (4, 18–20), as well as on the contraction velocity (4, 13, 16). Both, the muscle fiber force-length relationship (21–23) as well as the muscle fiber force-velocity relationship (24–27) vary non-linearly. Considering in particular the force-velocity relation, it becomes clear that the force generated by a single muscle fiber is greater in eccentric contraction than in concentric contraction (28, 29). Therefore, there is also a dependency of the sEMG signal amplitude on the type of contraction (30–33). On a more macroscopic level, the torque generated by a muscle depends on its biomechanical moment (18, 34, 35), and thus on the joint position (36, 37). In isometric contractions, the moment arm of the muscle and center of rotation of the joint remain constant while in non-isometric applications both change resulting in an altered joint net torque and a modified muscle force (4).

These biomechanical factors affect the number of muscle fibers which must be excited to generate the force necessary to execute the movement. Since the sEMG amplitude depends on the number of excited muscle fibers, it is obvious that in non-isometric contractions sEMG amplitude varies with different biomechanical factors. In addition, agonistic, synergistic and antagonistic muscles generally act on a common joint and produce a resulting total net joint torque (15, 16, 37–41). Due to this redundancy of the musculoskeletal system, the central nervous system's activation strategies for different synergistic as well as antagonistic muscles have to be taken into consideration. These central nervous system control strategies are rarely appreciated in physiological movements and are hard to manage in pathology (42). Consequently, these complex and interrelated factors that underlie the relation between the sEMG amplitude and the force produced by both the muscle fibers as well as the entire muscle have to be taken into consideration when interpreting the sEMG signal in dynamic conditions. **Table 1** summarizes on the effect of the five most relevant biomechanical factors that significantly influence the sEMG signal in non-isometric contractions and therefore require special consideration. All these factors are intrinsic and cannot be directly controlled (4). One possibility here is to learn as much as possible about the movement performed by the use of additional measurement methods and to integrate this knowledge into the analysis of the sEMG signal.

Normalization of the sEMG amplitude to force or torque is frequently used to counteract the high variability of the sEMG signal (43). It allows the comparison between groups, subjects and conditions. However, especially in clinical application, there are reservations regarding amplitude normalization, since it can mask changes related to disease or therapy. This is an important aspect and normalization of the sEMG signal is, therefore, not always the method of choice when analyzing clinical sEMG data associated with abnormal or pathological cases.

sEMG MEETS BIOMECHANICS AND THE RESULTING POTENTIAL FOR REHABILITATION

Many disorders that require rehabilitation are associated with the altered control and activation of muscles by the central nervous system and with the progressive development of rheological modifications in soft tissues, joint deviations and deformities that alter the biomechanics of the system and add mechanical boundaries (44). Prominent examples are stroke, paraplegia or infantile cerebral palsy. Due to the complexity of the analysis of sEMG signals recorded in dynamic conditions, primitive muscle synergies have been successfully applied in recent years to differentiate between a pathologically altered muscular activation and a physiological control of the muscles by the central nervous system (45–48). The concept of muscle primitive synergies aims to reduce the complexity of motor control. The drawback of this reduction in complexity, however, is that it is often difficult to attribute specific changes in muscle synergies to individual symptoms such as spasticity, rigidity or compensatory patterns. This requires a more detailed analysis of the control strategy used by the central nervous system.

In order to be able to determine for each patient specifically, which individual alterations the activation strategy occur during the execution of movements, the physiological activation pattern of the muscles involved should be used as a baseline (49, 50). However, the amount of muscular activation and the resulting sEMG signals depend significantly on the biomechanical factors described in **Table 1**. A promising way to establish comparability and reproducibility between groups or different test sessions, when determining the amount of muscular activation, is to limit the analysis to near-isometric epochs (4). In terms of biomechanical factors, a near-isometric epoch means that only those sEMG signal segments are compared that are derived from the same contraction type as well as at similar muscle lengths, leverage conditions and contraction velocities.

Von Werder et al. referred to the separation of the sEMG signal into near-isometric epochs as categorization (51). They used the categorization approach to investigate the effect of movement velocity on the central nervous system's control strategies. Muscular activation of the elbow flexors and extensors was investigated during elbow flexion and extension tasks against a constant external torque over the full range of motion. Fifteen healthy subjects were included and movement tasks were performed with different self-selected movement velocities. sEMG was recorded from biceps, brachioradialis and triceps. By rectification and smoothing, the sEMG envelope was built and normalized to 75% of its maximal value. In addition, the elbow flexion and extension angle was determined using 3D motion analysis and the angular velocity was calculated by differentiation with respect to time. A total of 40 categories were formed, with each category being characterized by the three biomechanical factors: contraction type (concentric or eccentric), joint angle interval (25°-44°; 45°-64°; 65°-84°; 85°-104°, and 105°-125°) and angular velocity interval (30°/s-49°/s; 50°/s-69°/s; 70°/s-89°/s; 90°/s-110°/s). To identify near-isometric epochs in the sEMG signal, each sample of the normalized sEMG envelope was assigned to the category, which corresponds to the biomechanical situation at that point in time when the sample was taken. Afterwards, all sEMG envelope samples that belonged to a near-isometric category were averaged. Detailed description of the categorization approach can be found in Von Werder et al. (51) and von Werder and Disselhorst-Klug (42).

Figures 1A,B show the effect of movement velocity on the sEMG envelope. In accordance with the force-velocity relation, the force that a single sarcomere can produce in concentric contraction decreases with increasing contraction velocity. Thus, if the external torque remains constant, concentric contraction requires more muscle fibers to be activated as the movement velocity increases. As a consequence, in concentric contraction the sEMG envelope increases with increasing movement velocity in all three muscles (**Figures 1A,B**).

In contrast to concentric contractions, the force that a single sarcomere can produce in eccentric contractions increases as the velocity of muscle stretch increases. Based on this biomechanical consideration, the sEMG envelope should decrease with increasing movement velocity during eccentric contractions. However, this can only be noticed in the biceps (**Figure 1A**). The sEMG signals of brachioradialis and triceps clearly show an increased envelope with increasing velocity in eccentric contractions (**Figures 1A,B**). These results can be better explained by control strategies via the central nervous system rather than by muscle biomechanics.

Particularly in rehabilitation, there is a great demand to be able to evaluate functionality in everyday situations (9). This is why the concept of including biomechanical knowledge in the analysis of the sEMG signals becomes more crucial for rehabilitation. A clinically relevant example, is spasticity. According to Lance spasticity is characterized by a velocity-dependent increase in tonic stretch reflexes (52) and does not include impaired voluntary movement and an abnormal posture (53). Although more recent publications differentiate the term spasticity (54), the definition introduced by Lance of

TABLE 1 | Biomechanical factors that significantly influence the sEMG signal in non-isometric contractions.

	Biomechanical factor	Effect
1.	Muscle length	According to the force-length relation, the muscle fiber generates different forces at different sarcomere lengths. Sarcomere length changes with joint position.
2.	Contraction velocity of the muscle	The muscle fiber generates different forces at different contraction velocities due to the force-velocity relation. Contraction velocity is related to the angular velocity of the joint.
3.	Lever arm of the muscle	The angle at which the tendon attaches to the bone depends on the joint position. Since the resulting contraction force acts parallel to the tendon, the lever arm of the muscle varies with joint position.
4.	Type of contraction (concentric or eccentric)	The force-velocity relation is either increasing or decreasing depending on whether the muscle shortens or lengthens during contraction.
5.	Redundancy of the musculoskeletal system	Besides the agonist, antagonists and other synergistic muscles also contribute to the net joint torque.

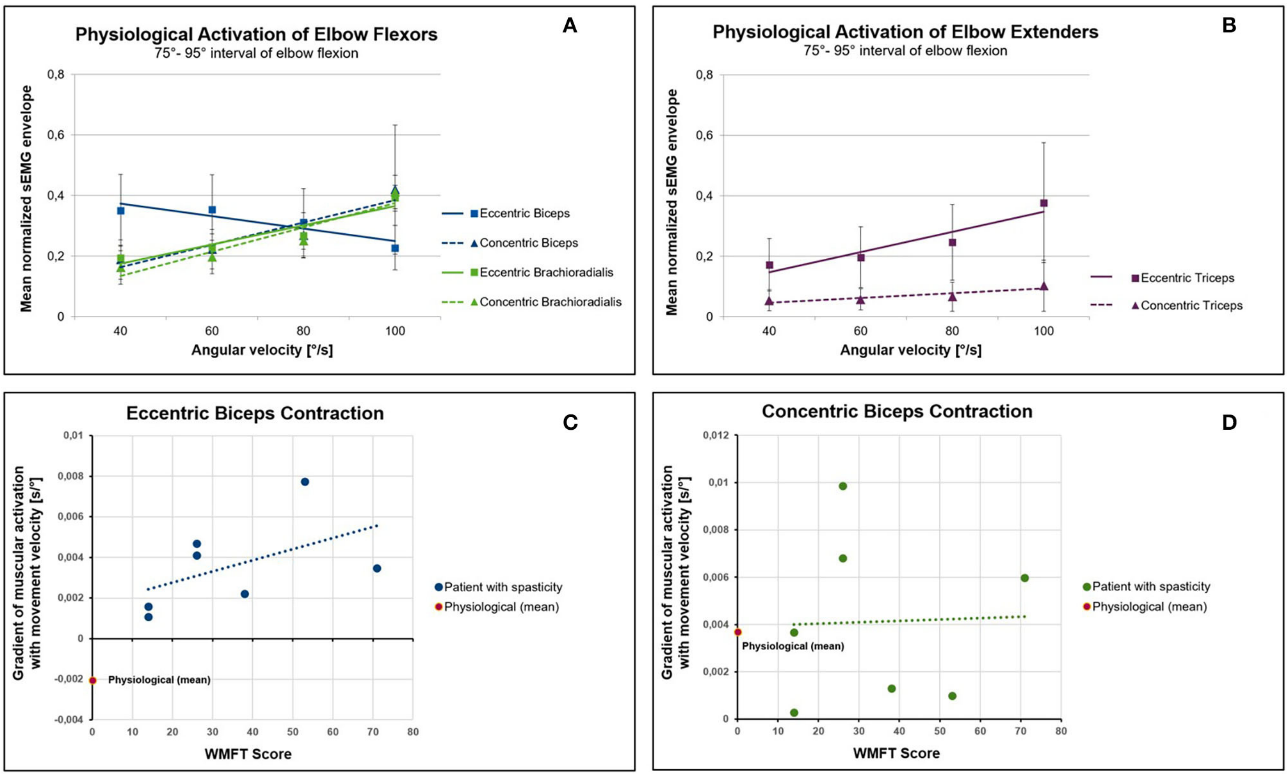

FIGURE 1 | Effect of movement velocity on muscular activation in physiology and in patients suffering from spasticity. **(A)** Mean normalized sEMG envelope of the elbow flexors biceps and brachioradialis during concentric and eccentric contraction. In contrast to the biceps and to the force-velocity relationship, the muscular activation of the brachioradialis increases with increasing angular velocity. **(B)** The muscular activation of the triceps increases with increasing velocity of movement both in eccentric and concentric activation. **(C)** Relation between the severity of upper limb impairment (WMFT score) and the gradient of the normalized sEMG envelope with the movement velocity. A higher WMFT score means a more severe impairment related to spasticity. In patients with spasticity, the eccentric contraction of the biceps causes an increase in muscular activity with increasing movement velocity (positive gradient). This is in contrast to the physiological baseline, which is characterized by a negative gradient. **(D)** No differences could be found between patients and controls in concentric contractions.

the velocity dependence of the increase in the stretch reflex remains unchanged. Therefore, in the assessment of spasticity sEMG is commonly used to investigate the muscles' response to stretch (55–58). Although the investigation of muscles' response to stretch provides fundamental information about spasticity, it does not provide any indication of the occurrence or severity of spasticity during intentionally executed movement tasks relevant for patients' daily lives (55). In addition, muscular coordination is often investigated during gait analysis of patients suffering from disorders accompanied by spasticity (49, 59–65). In this case it is usually not possible to distinguish between spasticity and the voluntary compensatory activation needed to counteract for weakness. Although the assessment of spasticity is important for clinical management (54), it still lacks objective assessment methods to quantify the level of spasticity during intentionally executed movement tasks (9, 55, 58, 65–70).

Since, according to the definition of Lance, stretch velocity dependency is a characteristic property of spasticity, the question arises whether the integration of biomechanical knowledge might support a distinction between voluntary muscle activation and spasticity. As discussed before, to achieve comparability between physiological and spastic muscular activation patterns in dynamic conditions, near-isometric epochs of the sEMG signal have to be compared. **Figures 1C,D** compare the gradient of the normalized sEMG envelope against the movement velocity of healthy subjects with that obtained for 7 patients suffering from spasticity of the biceps muscle with different degree of severity. Study design and sEMG post processing were identical to the procedure described above. The gradient of the sEMG envelope with angular velocity was calculated and averaged over all joint angle intervals. This was done for each patient separately. Upper limb motor ability was clinically assessed using the Wolf Motor Function Test (WMFT).

As in healthy subjects, the biceps' sEMG envelope increases in patients with increasing contraction velocity during concentric contractions. This relationship is reflected by a positive gradient (**Figure 1D**). However, this is in contrast to eccentric contractions (**Figure 1C**). While healthy subjects show a negative gradient in eccentric contractions (**Figure 1A**), patients show an increase in the amount of muscular activation with increasing movement velocity. This positive gradient can neither be explained by the force-velocity relation nor does it correspond to a physiological central nervous system's control strategy. Thus, a positive gradient of the muscular activation with movement velocity in eccentric phases of muscular contraction can be interpreted as a sign of spasticity. When the magnitude of the gradient is compared to the WMFT score (**Figure 1C**), it becomes apparent that a more severe spasticity (higher WMFT score) tends to be associated with a higher gradient.

DISCUSSION: BRINGING sEMG TECHNOLOGIES TO CLINICAL USE

The sEMG signal is significantly dependent on various biomechanical factors and it can be assumed that an interpretation of the sEMG signal with respect to amplitude becomes more accurate when these biomechanical factors are taken into account. Hence, isometric measurements, in which these factors can be controlled, are still widely used. In rehabilitation, however, isometric contractions usually play a subordinate role. Here, the analysis of intentionally executed movement tasks is of primary importance. This complicates the interpretation of the sEMG signals, if beside the timing, the magnitude of the muscular activation is of interest. The consequences are often contradictory results both between individual studies and between follow-up measurements. This is fatal for the translation of the sEMG into clinical application, as it essentially weakens the users' confidence in the methodology.

Among others, Bogey et al. emphasized the clinical relevance of an integrated analysis of timing and relative magnitude of the sEMG signal (10). Consequently, new ways have to be found to increase the reliability the information gained from the magnitude of sEMG signal in dynamic conditions. The consideration of at least the essential biomechanical factors could lead to an improved informative value of the sEMG signals. This leads to two consequences:

1. When analyzing non-isometric conditions, additional measurement methods must be applied synchronously to the sEMG signal, which provide information about the execution of movements, such as movement cycle intervals, joint positions, movement velocities and external forces. This approach is already successfully applied in clinical gait analysis (71) and needs to be extended to other scenarios.
2. On the basis of current biomechanical knowledge, information about the execution of the movement must be merged with the sEMG signal. This will probably only be reliable if the analysis is broken down into near-isometric epochs. Appropriate algorithms that make this possible must be developed in the future.

The two examples given show how the consequent implementation of this strategy leads to new insights important for rehabilitation. They give a representative of the potential of integrating biomechanical principles into the interpretation of the sEMG.

In conclusion, there is an increasing demand in rehabilitation for objective methods, which on one hand provide evidence and on the other hand enable a therapy tailored more to the individual patient. sEMG has the potential to contribute significantly to this goal, even in dynamic conditions (2). However, biomechanical factors should be more integrated in the analysis of sEMG signals in the future. This becomes more urgent when sEMG signals are recorded in dynamic conditions. New and innovative sEMG processing and information extraction strategies are needed to make this approach clinically applicable. These challenges cannot be solved by isolated research labs. A multi- and inter-disciplinary network is needed, which will collectively work toward the development and establishment of sEMG procedures to meet the demands and acceptance of physicians and therapists.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: The copyright for the data belongs to the Department of Rehabilitation and Prevention Engineering; Institute of Applied Medical Engineering; RWTH Aachen. Requests to access these datasets should be directed to Catherine Disselhorst-Klug, disselhorst-klug@ame.rwth-aachen.de.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethik-Kommission der Medizinischen Fakultät an der RWTH Aachen. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CD-K elaborated the relationship between the surface EMG and the biomechanical factors, identified the barriers for translation into clinical application, developed the measures necessary to overcome them, reinterpreted the data from the presented studies, and wrote the manuscript. SW conducted an extensive literature research on the context of the manuscript, involved in the reinterpretation of the study data, assigned the results to the state of the art, and revised the manuscript. All authors contributed to the article and approved the submitted version.

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PERSPECTIVE
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Surface Electromyography in Physiotherapist Educational Program in France: Enhancing Learning sEMG in Stretching Practice

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Surface electromyography (sEMG) is a non-invasive method, which may be used in France by health practitioners without medical degree, such as physiotherapists, who are taught in Institutes of physiotherapy. However, very few hours are devoted to sEMG teaching in physiotherapist educational programs, especially in a form of practical work. In order to motivate using sEMG in physiotherapy to the students, we propose an example of sEMG practical work, applied to muscle stretching. Passive stretching exercises are often used by physiotherapists to maintain or improve range of motion. During a passive stretching session, subjects are given specific instructions to relax and not to activate their muscles during the procedure. In the proposed practical work, the sEMG is used to study the plantar flexor activation level during passive stretching. Therefore, this work may provide students with deeper understanding of physiology and biomechanics, trigger an interest in sEMG as a tool, and give knowledge about good sEMG practice, according to SENIAM and other recommendations. The integration of Institutes of physiotherapy in the University system may provide an opportunity to revisit the physiotherapist educational program and to provide students with more practical courses on sEMG application.

Keywords: surface electromyography (EMG), stretching, biofeedback, *triceps surae*, physiotherapy

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INTRODUCTION

The clinical use of EMG in France for neuromuscular diseases diagnosis is performed by medical doctors using needle EMG only. However, according to French Common Classification of Medical Acts [CCAM, (1)] nomenclature, "sEMG can provide useful information different from the needle EMG technique, since it is an authorized method, which may be applied according to the physiotherapist's choice without increasing overall cost of the physiotherapy act, refunded by National Insurance [(2) and following, concerning physiotherapists, giving them the liberty of technic choice]. sEMG is a non-invasive technique, which may be used by health practitioners without medical degree, such as physiotherapists.

Starting from 2015, physiotherapist educational program duration in France is 4 years in Institutes of physiotherapy, preceded by 1 year of either medical study, sport-science studies or natural/formal science bachelor programs, i.e., overall education time is 5 years after high school (3, 4). The students of these programs, who successfully passed the ranking, can enter one of 46 (as for 2017 according to French Association of masseur-physiotherapists) public or private Institutes of physiotherapy, according to their ranking (5). All the private institutes are independent structures, affiliated with a University by an agreement. Nevertheless, some public Institutes of physiotherapy are integrated with Universities (Paris-Est Créteil, Orléans, Limoges, Grenoble). Graduating from Institutes of physiotherapy provides a student with a national diploma, which is not an academic degree. After graduating, physiotherapists can continue their studies by applying for a master science program in movement science, kinesiology, or biomechanics, which may be also organized in the format of double diploma (master science – physiotherapy).

The recommended educational program for Institutes of physiotherapy contains a course about the theories, models, methods, and tools in physiotherapy with a total volume of 40 h of lectures and 40 h of tutorials. This course is conducted during four first semesters. EMG is cited among the other methods, like motion capture, force plate and gauge, inertial sensors as the methods recommended to be presented in this course.

To our knowledge based on the inquiry among French Institutes of physiotherapy, the time devoted to teaching musculoskeletal EMG is little (among seven institutes that we contacted only two give a class on EMG without practical work, and the others do not give a specific class on it).

One of the main parts of physiotherapist practice is to recover or maintain the maximal range of motion which may be performed by passive mobilization or stretching, performed by a physiotherapist or a patient under the supervision of the

FIGURE 1 | Wall stretching; **(A)** standing position. Differential electrode placements are schematically shown for gastrocnemius medialis (GM), gastrocnemius lateralis (GL), soleus (SOL), and tibialis anterior (TA) muscles. Ground electrode placements are indicated by GND. In this example, an individual ground electrode was used for each pair of differential electrodes. Goniometer placement sites are indicated by α_1 and α_2. **(B,C)** Show the ventral and the dorsal view of the leg with placed electrodes correspondingly.

former. The ability to move efficiently through a large range of motion (ROM) is essential for the successful completion of numerous tasks in daily living, work, and sports. Stretching exercises are often advocated to maintain and improve ROM (6). Optimal passive stretching techniques require the muscles to be inactivated as much as possible. This state involves a physiological muscle resting state, which is challenging to reach for the subjects.

LABORATORY STUDIES SHOWING THE MUSCULAR ACTIVATION DURING STRETCHING

There is a number of studies, aimed to quantify the muscle activation level during stretching, when the subjects were asked to maintain a relaxed state (7–9). For that purpose, sEMG is often measured from the plantar flexor muscles and the root mean square (RMS) of the signal is usually normalized to signal RMS during isometric maximal voluntary contractions (MVC) of these muscles. These studies show that during an initial stretch produced by individuals who have not stretched for long time, sEMG responses above 2% of MVC RMS appear for joint angle starting from 80% of the maximal range of motion. These sEMG responses increase as the joint angle approaches the maximum tolerated stretch amplitude. The sEMG can vary between 2 and 15% of MVC RMS and is more frequently observed in the older adult. With repeated stretching, this activity usually decreases considerably below 2% of MVC RMS.

The recent study (9) has quantified the muscle mechanical changes, when the muscles were voluntarily activated at 1, 2, and 5% of MVC RMS, with reference to "relaxed" conditions, where the subject was asked to produce no voluntary activation. During the experiment, the ankle was dorsiflexed using isokinetic dynamometer, and the participants were asked to produce low muscle activation using a visual feedback of sEMG amplitude at 1, 2, and 5% of maximal sEMG or to stay fully passively relaxed as possible during stretching. The results show a significant increase in joint torque (+ 33%) and muscle shear modulus (+ 55, + 38, and + 100%, for *gastrocnemius medialis, gastrocnemius lateralis*, and *soleus,* respectively), when the participants activated their muscles at 5% activation during slow dorsiflexions of the ankle. Nevertheless, even at a lower activation level of sEMG amplitude (2%) the change in joint torque was significant (+14%).

EDUCATIONAL APPLICATION

One of the main stretching methods commonly used in clinical practice is called "wall stretching" (**Figure 1**). Wall stretching is performed by placing the foot at a distance from the wall, with the subject leaning forward, keeping the knee in extension, which leads to stretching the TS muscle (10).

We propose to integrate the practical work on sEMG into the physiotherapist educational program in order to demonstrate the interest on sEMG application in practice related to force application on passive structures.

This work may be performed in pairs: one student in a role of an experimental subject and the second one as an investigator. The investigator places the surface electrodes and the goniometers as shown in **Figure 1**. The electrodes are placed on *gastrocnemius medialis, gastrocnemius lateralis,* and *soleus* muscles (GM, GL, and SOL), which are plantar flexors, forming *tripces surae* muscles, and on *tibialis anterior* muscle (TA) according to SENIAM recommendations (11). The goniometers are placed above ankle and knee joints. The investigator asks a subject to lay down and records the sEMG in rest. Next, the subject is asked to stand up in front of the wall in a position,

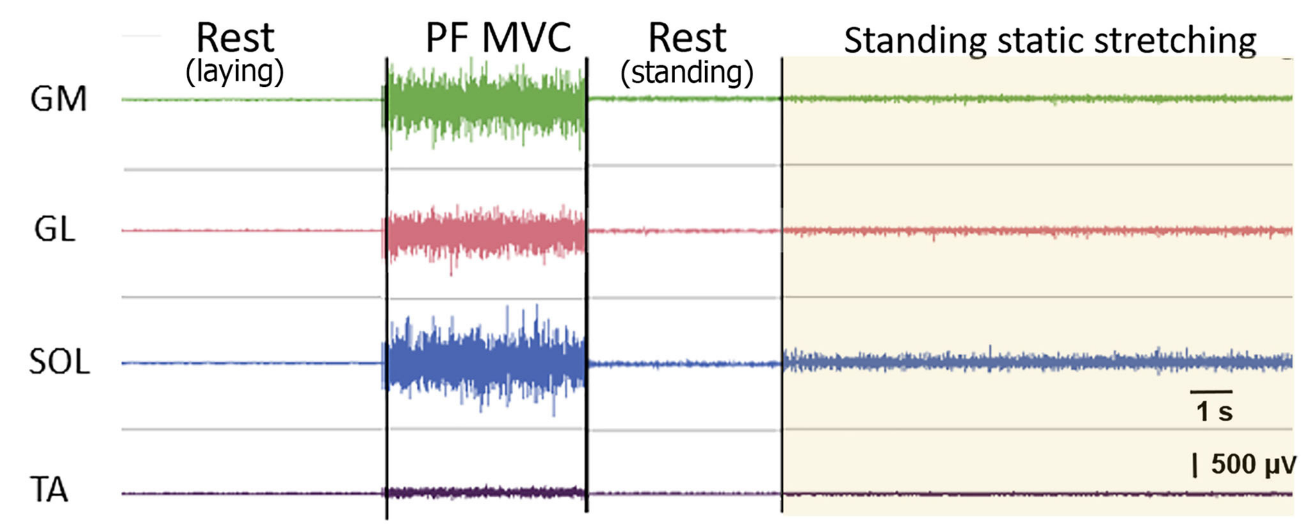

FIGURE 2 | Typical raw electromyogram signals of gastrocnemius medialis (GM), gastrocnemius lateralis (GL), soleus (SOL), and tibialis anterior (TA) muscles during different stages of the proposed protocol: at rest, during a plantarflexion maximal voluntary contraction (plantar flexor MVC), and during a static stretching. A slight signal recorded from TA can be either an activity of this muscle or a crosstalk from *triceps surae* muscles.

shown in **Figure 1A** to measure the RMS of sEMG during plantar flexor MVC. After a resting period (at least 5 min) a subject is asked to perform a passive wall stretching protocol for 30 s at 80% of maximal ROM of the ankle and full knee extension. The corresponding angles are measured with goniometers and displayed to the subject. The typical signals, recorded from the sEMG electrodes during all stages of the protocol, described above, are shown in **Figure 2**. An involuntary activity of the muscles, forming *tripces surae* muscles may be noticed during passive stretching phase. A slight signal recorded from TA can be either an activity of this muscle or a crosstalk from *triceps surae* muscles. After completing the protocol, the roles of investigator and experimental subject can be inverted.

The questions asked to the students are:

- Which muscles are activated during stretching?
- What was the observed activation level of stretched muscles in percentage of root-mean-square of sEMG from corresponding muscle during MVC?
- Was the stretching completely passive?

The main limitation of this work is the availability of the experimental setup. If only one set of measurement equipment is available, this session may be performed in 2 h by two pairs if the roles are switched or by five pairs without switching the roles. At the end of the session, the pairs are encouraged to share the results and discuss them before writing the group report.

CONCLUSION AND PERSPECTIVES

In this paper we propose an example of a practical work which is aimed to provide physiotherapists students with a deeper understanding of the neuromuscular physiology and biomechanics of stretching. This work also shows the value of sEMG as a biofeedback, which is an informative tool, not widely used in neuromuscular rehabilitation in France. Finally, this work might make the student familiar with the recommendation about the sEMG procedure, such as SENIAM recommendations (11) and CEDE project (12). These skills may be used by future physiotherapists not only in a given stretching example, but also in other applications.

The recent extension of the physiotherapist studies in France (from 4 to 5 years) might give an opportunity to develop the educational programs in scientific areas. Due to this educational reform, relevant sEMG application courses may be integrated into the French physiotherapist academic programs. Currently (13), French Health Ministry and Ministry of Higher Education and Research start an experimental educational program, including some universities, in order to approach French Institutes of physiotherapy with Universities. This integration may be also used to revisit the physiotherapist educational program and to provide students with more practical courses on sEMG application.

At the same time, further development of sEMG equipment could improve its usability, such as textile-based electrode arrays, which do not require precise electrode placement; capacitive electrodes, which do not require skin treatment; wireless sensors, which do not restrain movement. We believe that improving the usability of sEMG, together with available professional training program will lead practitioners to use of sEMG in their practice.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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CASE REPORT
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Added Value of Dynamic EMG in the Assessment of the Equinus and the Equinovarus Foot Deviation in Stroke Patients and Barriers Limiting Its Usage

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Equinus (EFD) and equinovarus foot deviation (EVFD) are the most frequent lower limb deformities in stroke survivors. The equinus component can be triggered by a combination of dorsiflexor deficits, plantar flexor overactivity, muscle stiffness, and contractures. The varus component is typically due to an imbalance between invertor and evertor muscle actions. An improvement in identifying its causes leads to a more targeted treatment. These deformities are typically assessed via a thorough clinical evaluation including the assessment of range of motions, force, spasticity, pain, and observational gait analysis. Diagnostic nerve blocks are also being increasingly used. An advantage of dynamic electromyography (dEMG) is the possibility of measuring muscle activity, overactivity or lack thereof, during specific movements, e.g., activity of both ankle plantar flexors and dorsiflexors during the swing phase of gait. Moreover, fine-wire electrodes can be used to measure the activity of deep muscles, e.g., the tibialis posterior. An impediment to systematic use of dEMG in the assessment of EFD and EVFD, as a complimentary tool to the clinical evaluation, is a lack of evidence of its usefulness. Unfortunately, there are few studies found in literature. In order to fill this void, we studied three pairs of patients suffering from chronic hemiparesis consequent to a stroke, with EFD or EVFD. At the initial evaluation they all displayed the same clinical traits, very similar walking patterns, and an overlapping gait kinematics. However, the patterns of muscle activity differed considerably. dEMG data acquired during walking provided information that was not available from the sole clinical assessment. The contribution of this information to the subsequent clinical and rehabilitation process was discusses along with the barriers that limit the use of dEMG as a routine tool in neurorehabilitation.

Keywords: dynamic EMG, surface EMG, stroke, gait analysis, rehabilitation, equinus deformity, equinovarus deformity, physiotherapy

INTRODUCTION

Following an upper motor neuron lesion, patients may develop acquired deformities in the lower limbs that impair or inhibit walking. The most frequent lower limb acquired deformities in stroke survivors are the equinus (EFD) and the equinovarus foot deviation (EVFD) (1). They are characterized by a downward deviation and an internal rotation of both the ankle and foot (2, 3). Both are often associated with clawed toes. Ankle dorsiflexors (DF), plantarflexors (PF), invertor, and evertor muscles and toe flexors and extensors control ankle-foot movements and are typically involved with EFD/EVFD in various ways. These deformities are caused by several factors that are found in the different combinations of paresis, overactivity, and altered motor control (paresis, co-contractions, spasticity, dystonia, and other manifestations of muscle overactivity), changes in soft tissues that gradually result in stiffness, contractures and secondary joint limitations due to disuse (4, 5).

The combination of these phenomena is different in each patient and results in joint alterations during gait, which must be evaluated in dynamic conditions because they may not be detectable and measurable by a clinical evaluation. Clinical evaluation and observation of a patient's gait may not be sufficient to establish the causes responsible for the observed deviation and walking alterations. The contribution of gait analysis (GA), and in particular dynamic EMG (dEMG), can be used to discriminate between different causes and thus support the decision-making process in order to formulate the most appropriate therapeutic program (5–9). The presence/absence of EMG activity and the type of activation (e.g., continuous, with bursts) detected (9–15) leads to different choices in terms of focal neuromuscular blocks, non-pharmacological treatments, and neuro-orthopedic surgery.

Failure to use dEMG and GA during the decision-making process could be due to the presence of some barriers (13, 16). In this manuscript we tried to overcome this issue. We will present six patients with very similar gait patterns and different dEMG that provides information not available by the sole clinical assessment.

MATERIALS AND METHODS

Patients and Clinical Assessment

Six subjects with stroke and EFD or EVFD during gait and showing clinical and kinematic overlapping patterns were selected from the authors' databases.

Written informed consent was obtained from the patients for the publication of any potentially identifiable images or data included in this article.

Based on the clinical assessment we extracted the following variables from the patients' records: age, sex, affected side, time elapsed from stroke and its etiology, maximum passive ankle dorsiflexion measured with the knee both extended and flexed, score of the Modified Ashworth Scale at the triceps surae and the soleus and Functional Ambulation Category score (FAC), along with the subsequent rehabilitative choices (17).

Instrumental Assessment

From the patients' GA we collected lower limb kinematics and dEMG activity. GA was acquired during walking at spontaneous speed on a level surface. At least five strides per subject were considered. Markers for kinematic analysis were placed according to Conventional protocol (18). Surface electrodes (2 cm interelectrode distance) were placed on the lower limb muscles at specific positions, defined as the minimum crosstalk areas (19, 20). Fine wire electrodes were inserted based on the anatomical landmarks in accordance to recommendations by Perotto et al. (21) and further confirmed by ultrasound guidance (22). Their proper placement was then verified by electrical stimulation. One laboratory was equipped with a BTS-Smart system for 3D motion capture and a BTS FreeEmg device (BTS Bioengineering, Italy). The other laboratory was equipped with a Bonita Vicon system (Vicon, United States) and ZeroWire electromyograph (Cometa, Italy). Data were analyzed using the EMG Easy Report software (MerloBioengineering, Parma, Italy). Both laboratories had been previously cross validated for GA (23).

Interpretation of dEMG

Muscles that could play a role in EFD and EVFD deformities are summarized in **Table 1**, which shows, for each muscle, the different combinations of paresis (a lack of voluntary motor command), overactivity (such as spasticity, tension-dependent muscle involuntary activation, out of phase muscle activation, and a reduced ability to relax muscles), soft tissue contracture (especially muscle shortening and joint retraction), and increased stiffness (a reduction of muscle elasticity and extensibility) (24) that could result in foot deviation during both the stance and the swing phases.

Table 1 was used as reference in the analysis of the cases presented in this study. This was developed by the authors throughout years of clinical and instrumental practice and was also based on available literature (2, 9, 11, 13, 25). For all cases, we discussed the causes of EFD and EVFD based on the dEMG patterns and presented the refinement of the intervention proposal. Finally, the added value of dEMG during walking to clinical decision-making and to physiotherapy has been discussed, along with the barriers that currently limit its use.

RESULTS

Subjects #1 and #2 (**Figure 1**) exhibited a gait with foot supination and equinus, reducible during stance, and a hyperextended knee in Mid Stance (MSt) and Terminal Stance (TSt). Clinically, both patients had the same slightly reduced passive ankle mobility that is usually compatible with a modest shortening of PF, a marked weakness of DF and PF and a reflex overactivity of PF, the latter more pronounced in Patient 1. Following clinical evaluation and in the absence of significant signs of contracture the treatment hypothesis for both was the use of a posterior orthosis to support the weakness of DF and a generic PF inhibitory focal treatment. However, when dEMG assessment was performed, the two subjects showed different

TABLE 1 | dEMG-based interpretation of EFD and EVFD causes.

Plantarflexor and dorsiflexor muscles	EMG pattern (classification) and effect	
	Stance phase	**Swing phase**
Flexor digitorum longus (FDL)	Premature in LR/Prolonged in PSw (overactivity) **E, V**	Out of phase (overactivity) **V**
Flexor hallucis longus (FHL)	Premature in LR/Prolonged in PSw (overactivity) **E, V**	Out of phase (overactivity) **V**
Gastrocnemius medialis (GAM)	Premature in LR/Prolonged in PSw (overactivity) **E** Absent or minimum continuous activity (contracture, stiffness) **E**	Out of phase (overactivity) **E** Minimum continuous activity (stiffness, contracture) **E**
Gastrocnemius lateralis (GAL)	Premature in LR, prolonged in PSw (overactivity) **E** Absent or minimum continuous activity (contracture, stiffness) **E**	Out of phase (overactivity) **E** Minimum continuous activity (stiffness, contracture) **E**
Soleus (SOL)	Premature in LR/Prolonged in PSw (overactivity) **E, V** Absent or minimum continuous activity (contracture, stiffness) **E, V**	Out of phase (overactivity) **E, V** Minimum continuous activity (stiffness, contracture) **E, V**
Tibialis posterior (TP)	Premature in LR/Prolonged in PSw (overactivity) **V** Absent or minimum continuous activity (contracture, stiffness) **V**	Out of phase (overactivity) **V** Minimum continuous activity (stiffness, contracture) **V**
Tibialis anterior (TA)	Prolonged in MSt-TSt (overactivity) **V** Absent in LR and in PSw (weakness) **E, V**	Absent during whole swing (weakness) **E** Absence of the second peak in TSw (weakness) **E, V** Continuous (overactivity without EDL activity) **V**
Extensor digitorum longus (EDL)	Absent in LR and in PSw (weakness) **E, V**	Absent during whole swing (weakness) **E, V**
Extensor hallucis longus (EHL)	Prolonged in MSt-TSt (overactivity) **V** Absent in LR and in PSw (weakness) **E**	Absent during whole swing (weakness) **E** Absence of the second peak in TSw (weakness) **E** Continuous (overactivity) **V**

***E**, Equinus; **V**, Varus; LR, Loading Response, that includes initial contact, MSt, Mid Stance; TSt, Terminal Stance; PSw, Pre-Swing; TSw, Terminal Swing.*

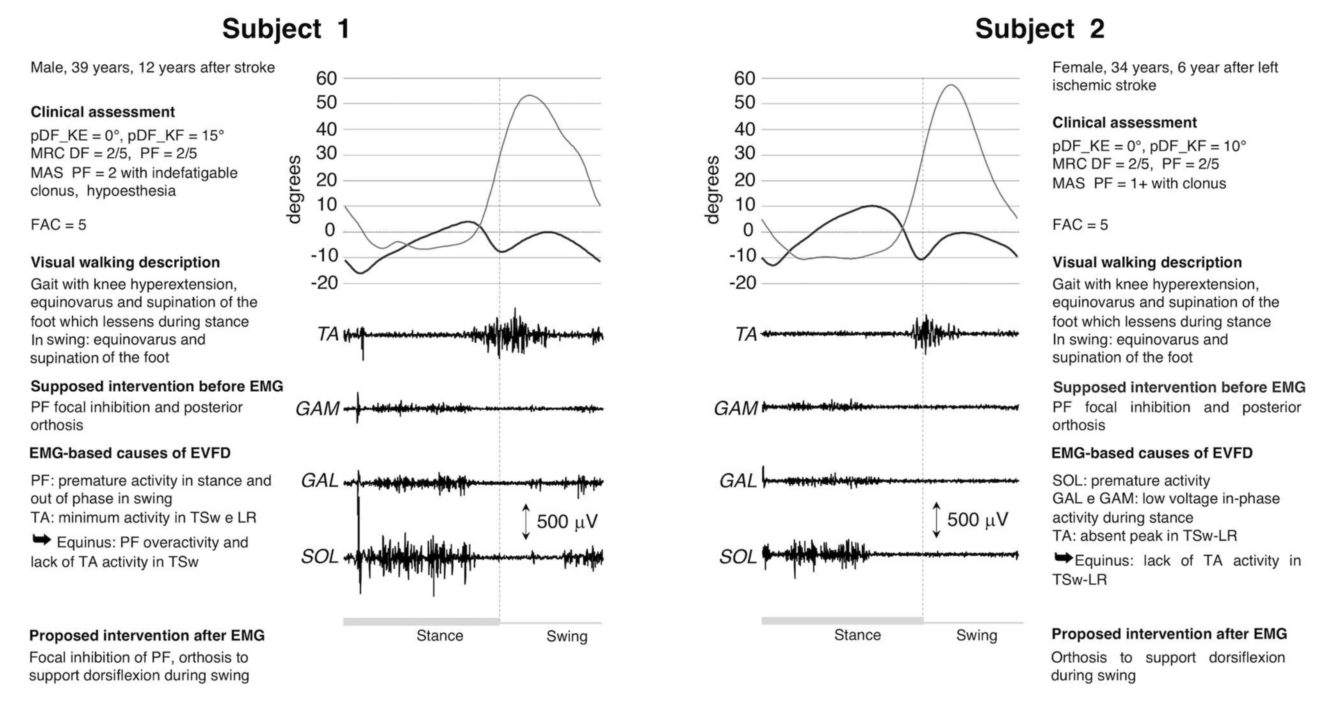

FIGURE 1 | dEMG, knee and ankle kinematic during a gait cycle for two post-stroke patients presenting similar clinical characteristics and very similar kinematics. Clinical assessment included: maximum passive ankle dorsiflexion measured with the knee extended (pDF_KE) and flexed (pDF_KF); plantarflexor (PF) and dorsiflexor (DF) muscles force measured with the Medical Research Council scale (MRC), PF spasticity scored with the Modified Ashworth scale (MAS), and the walking ability measured with the Functional Ambulation Category scale (FAC). See **Table 1** for muscle-related acronyms.

dEMG patterns during swing. In Patient 2, the use of focal inhibition was excluded because of the absence of overactivity during gait, while it was confirmed in Patient 1.

Subjects #3 and #4 (**Figure 2**) had a gait with EVFD, with reducible equinus during stance, a hyperextended knee in MSt-TSt and a knee flexion deficit in swing. Clinically, both cases

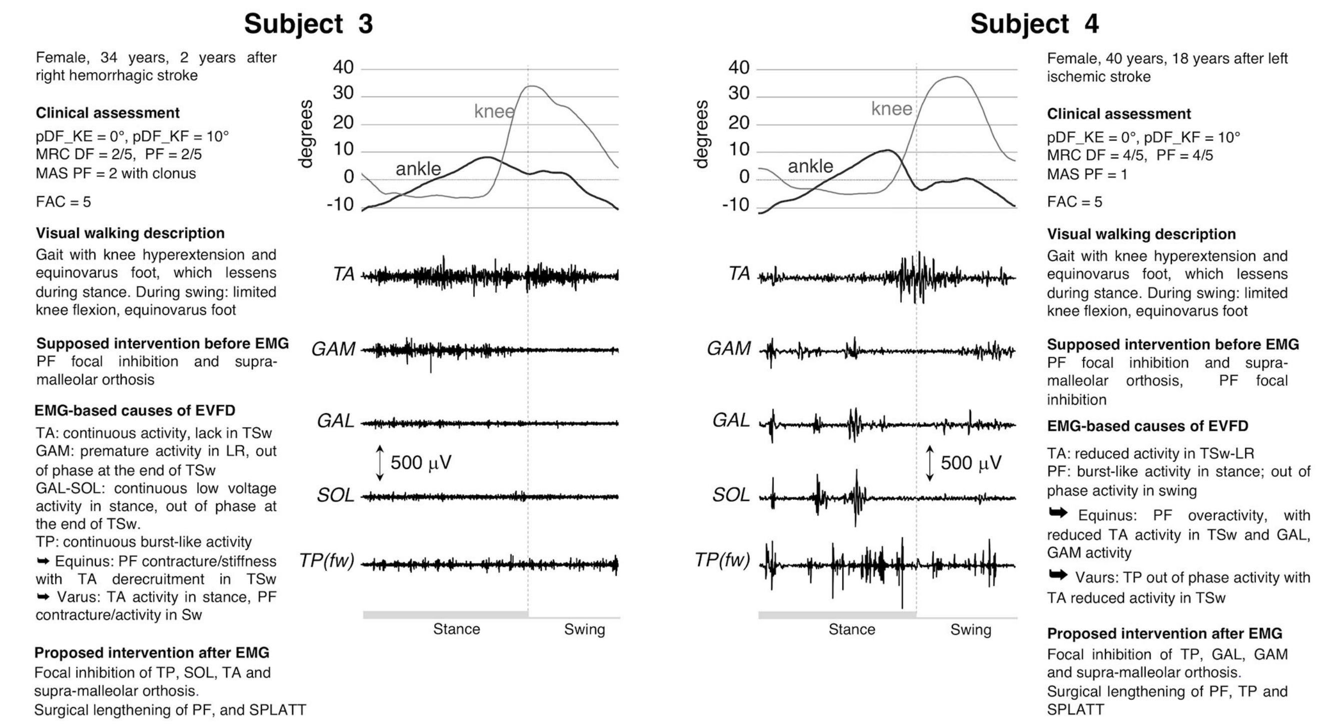

FIGURE 2 | dEMG, knee, and ankle kinematic during a gait cycle for two post-stroke patients presenting similar clinical characteristics and very similar kinematics. See caption in **Figure 1** and **Table 1** for acronyms. In these two subjects the dEMG of the tibialis posterior muscle was recorded using fine wire electrodes [TP(fw)].

exhibited slightly reduced passive ankle mobility, which is consistent with a modest shortening of PF. In Patient 3, there was PF spasticity and muscle force reduction of both PF and DF. Following a clinical evaluation, the treatment suggested was the use of orthosis (to compensate for the DF deficit in swing and to contain the varus attitude) and a generic focal inhibition of PF muscles. The dEMG assessment showed completely different dEMG patterns for the two subjects, which suggested modifications of interventions (**Figure 2**). The EMG morphology seen in Patient 3 is typical when an increase in PF stiffness is present. Because of this passive resistance, during swing TA failed to lift the foot and decreased its activity in terminal swing (TSw). The continuous activity of TA could explain the varus during stance and contributed to the varus during swing, along with the contracture/stiffness of SOL. Therefore, in this subject, the focal inhibition was only aimed at correcting the varus component determined by a combination of SOL, TP, and TA. In addition to this, there is a surgical possibility of lengthening the whole PF muscle-tendon unit and of performing a split anterior tibialis tendon transfer procedure (SPLATT) to provide a balanced foot dorsiflexion, the latter being supported by the appropriate activation of the TA muscle. In Patient 4, the lack of dorsiflexion during swing was caused by a combination of out-of-phase activity of PF and reduced activity of TA in TSw. In this patient the orthosis and the focal inhibition of the GAM, GAL and TP muscles, but not the SOL, were confirmed. In addition, the surgical lengthening of the PF, TP muscles and SPLATT could be a viable option.

Subjects #5 and #6 (**Figure 3**) exhibited EVFD during stance and supination during swing, knee extended during the entire stance phase and knee flexion deficit during swing. Clinically both patients had the same functional ability and a significantly reduced passive ankle mobility that is compatible with PF retraction. In both cases there was a marked weakness of TA and a spasticity of PF, the latter was more pronounced in Patient 5, who also has less residual strength and clones at the bedside assessment (see **Figure 3**). Following the clinical evaluation, the treatment suggested was the use of orthosis and the possible focal inhibition of the PF muscles. The dEMG of these patients showed two completely different patterns. In Patient 5, the total absence of DF and PF activities led to favor surgical lengthening of PF, rather than opting for focal inhibition. In this case, surgery would be aimed only to restore a proper foot placement on the ground. In Patient 6 the continuous activity of TA was counteracted by the premature and out-of-phase activity of PF in LR and swing, respectively. The continuous activity of TA could explain the varus component during stance and contributed to the varus in the swing phase along with the activity of SOL and the lack of EDL activity. The pulling action of EDL, in normal subjects, compensates the varus component of TA during dorsiflexion. The presence of continuous PF activity during walking (see **Figure 3**) confirmed the appropriateness of focal inhibition to all PF muscles and advocated for an intervention to

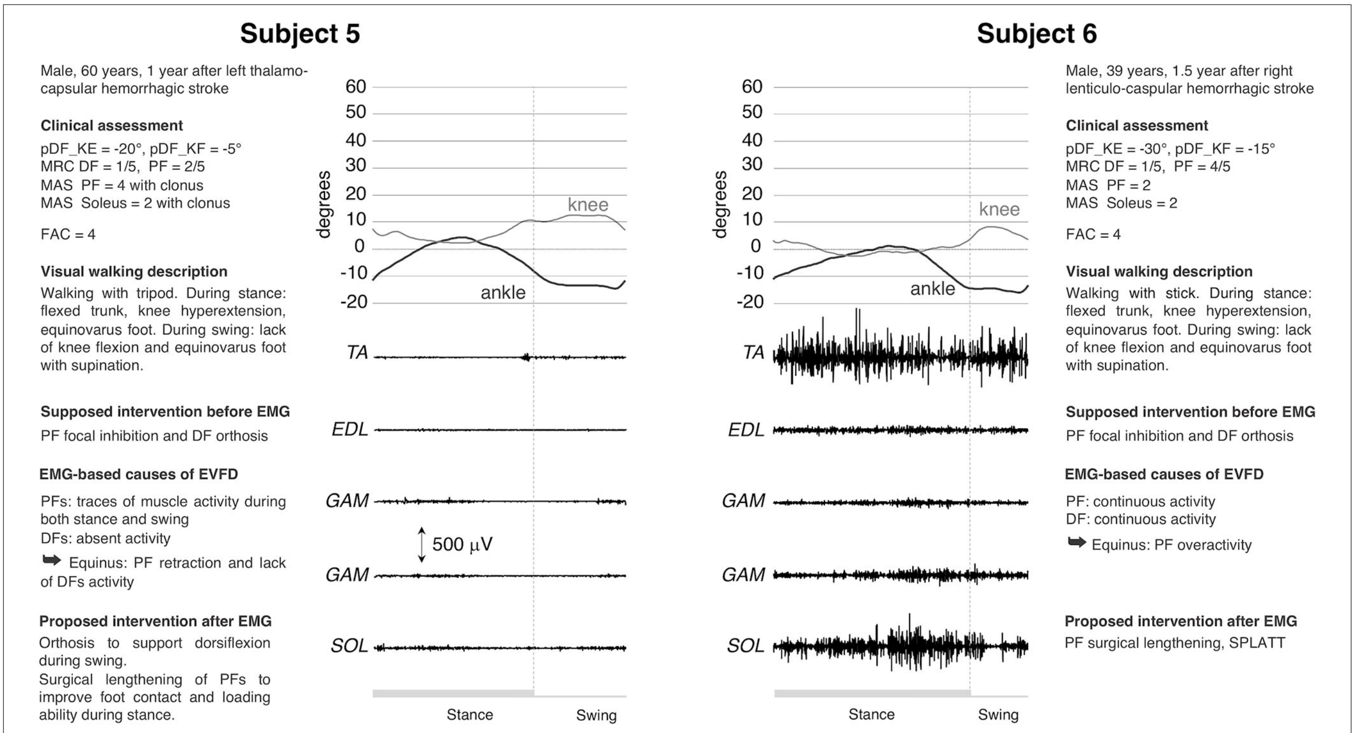

FIGURE 3 | dEMG, knee and ankle kinematic during a gait cycle for two post-stroke patients presenting similar clinical characteristics and very similar kinematics. See caption in **Figure 1** and **Table 1** for acronyms. The completely different muscle activation pattern underlying the same lower limb kinematic is evident.

lengthening them. The presence of important TA activity without EDL supported the SPLATT procedure.

The use of dEMG also addresses the physiotherapy aspect of a treatment. For example, in cases 1, 2, and 4, TA had a proper recruitment of muscle motor units (as proven by interferential signal) that allowed for foot dorsiflexion. This was missing in TSw. Therefore, TA failed either to overcome the tension of the contracted and hyperactive PFs (cases 1 and 4) or the stiffness (cases 2 and 3). Physiotherapy should increase the ankle range of motion for all patients, the tolerance to PF lengthening in cases 1 and 4 and augment the strength during lengthening in cases 2 and 3. Any strengthening of the dorsiflexors would be meaningful only after PF recovers proper extensibility, without hindering passive movements and without responding to stretching maneuvers during gait.

Even for case 6, TA did not require treatment: MRC score was only 1/5 at the bedside evaluation, but EMG signal was properly represented during walking (correct recruitment and derecruitment of many motor units leading to an interferential signal), thus enabling foot dorsiflexion. In case 5, physiotherapy would not be appropriate given the substantial absence of muscle recruitment in the leg muscles.

DISCUSSIONS

The limited availability of literature regarding the impact of dEMG on the choice of the rehabilitative treatments and on the subsequent patient outcomes is probably the main barrier to its systematic use. To start addressing this issue, we presented data from six patients in which the added value provided by dEMG was evident. In 5 out of 6 cases, the suggested treatment was revised following dEMG assessment.

dEMG enables professionals to understand what the primary cause of EVFD is, showing what combination of paresis, activation, overactivity, stiffness, contracture/shortening is present in a specific patient. In all the patients examined, three aspects can be emphasized:

- Despite clear similarities in their main impairment, observational gait assessment, and joint kinematic, relevant differences in muscular behavior were present (13);

- EMG assessment led to a change in the therapeutic treatment with respect to focal muscle inhibition, also favoring targeted surgical proposals. This aspect has already been reported by other authors (6, 7, 26–28);

- Physiotherapy treatments can benefit from the information provided by dEMG. Timing, amplitude and morphology of the dEMG signal can shed light on the residual level of motor control, muscle recruitment, interference of both muscle overactivity and non-neural components (6). Actually, knowing the causes for an alteration in the gait pattern of a patient, allows to set specific targets tailored to the patients' impairment, integrating the predefined physiotherapy protocols that are often used in everyday practice (29). Tailored physiotherapy should include intensive motor training, daily stretching at high load and exercises characterized by maximal amplitude rapid alternating movements (30).

Our comments on the added value provided by dEMG in the assessment and treatment selection in neurological patient are in line with the results of similar studies, where dEMG was used to quantify the different forms of muscle overactivity, including spasticity (7, 31–33) and to support the design of neuro-orthopedic surgery (27, 28). A thorough review of the applications of sEMG in neurologic rehabilitation can be found in a study by Campanini et al. (13).

How to Use dEMG in the Choice of EFD and EVFD Treatments

The numerous combinations of paresis, muscle shortening, imbalance and overactivity that might result in EFD or EVFD have been summarized in **Table 1**. Generally speaking, the presence of PF overactivity and/or of bursts-like activity during stance and out-of-phase activity during swing promotes focal inhibition. Moreover, dEMG reveals which muscles are specifically involved. In addition, the characteristics of the dEMG signal (i.e., timing, amplitude, and morphology) could provide useful information when choosing the type of inhibitory pharmacological treatment (nerve block or inoculation of botulinum toxin). The absence of EMG activity and/or the presence of a very reduced and continuous activity, excludes the usefulness of focal inhibitions. In this case the main cause of EVFD is PF muscle shortening and/or increased stiffness. The presence of preserved, or partially preserved recruitment of PF muscles during stance supports the choice of surgical lengthening. In this case the propulsion provided by PF muscles should result in an improvement of functional walking (speed, fluidly, and energy cost) in addition to the mere correction of the foot. The absence of DF activity indicates the need for an orthosis, and this need will remain even after PF lengthening. Moreover, in functional surgery, the presence of TA interferential signal during swing is a pre-requisite for DF tendon transfer (as in the case of Subject 6).

From the physiotherapist's point of view, GA and sEMG can provide optimal treatment protocol (34). The type of signal recorded on DF and PF can indicate whether and how to treat these muscle groups in the presence of EVFD. When the TA signal is interferential and phasic, the recovery of PF length should be targeted. If PFs have a bursts-like signal, the patient could benefit from a treatment to recover muscle extensibility and decrease linear resistance caused by an increase in transverse collagen fibers and a decrease of the slide between muscle and fascia, respectively (35). This could be achieved by stretching exercises and exercises characterized by maximal amplitude rapid alternating movements to prevent contracture, to improve joint range of motion and flexibility and by muscle strengthening (30, 36–43). Soft tissue manual treatments could be helpful too (35, 44).

Barriers to the Use of dEMG in Clinical Practice

The void between the clinical usefulness of a dEMG assessment in patients with EVFD and its limited use in the clinical and physiotherapy fields led us to share the cases presented in this work. While the added value of dEMG, when working with neurologic patients is confirmed among experienced users (45), it is not known to most professionals (16). This is reasonably due to the scarcity of clinical literature, and especially of clinical trials, which could demonstrate greater benefits for patients when the treatments are selected by integrating clinical assessment with dEMG (46).

A further barrier to the use of dEMG lies in the difficulty of properly performing and interpreting the results. The analysis of the dEMG signal (15), its interpretation from the physiopathological point of view, the relationship between an altered signal and an observed deviation, and the choice of therapeutic treatment in light of the instrumental data require specific knowledge. In addition, technical skills are necessary, such as the ability to recognize (and not comment on) artifacts and the knowledge that the effects of technical variables (e.g., gain, filters, etc.) has on data (15). Indwelling EMG requires for a time-consuming prepping and provides data that can be corrupted by large motion artifacts. All these steps require time, teamwork, in depth knowledge of physiopathology, and an appropriate setting. In our opinion, the skills necessary to conduct and interpret a dEMG examination and the availability of the necessary equipment are not suited for the daily practice. However, these are available at a motion analysis labs (MAL), where specialized staff received specific training and over the years collected hundreds or thousands of case data. These structures, where available, represent a valuable asset for other rehabilitative services in the local area. Since the learning curve to carry out and interpret an exam correctly takes years, it seems crucial that the operators involved in a MAL should be the one to handle this topic. The selection of the teaching staff, inclusive of physiotherapists, motor scientists, medical specialists in rehabilitative medicine, neurologists, and biomedical engineers, is also fundamental. At least 5 years of practical experience with dEMG techniques are suggested to qualify in order to be able to teach and train dEMG to clinical neurorehabilitation professionals (45).

Technical and cultural barriers could be overcome by enriching the university curricula to include rehabilitation classes and lectures by the professionals who work with walking biomechanics and instrumental evaluation (13). In addition, further efforts are needed to develop courses on how to interpret dEMG signal, leading to a greater consistency of data interpretation among the different centers.

Limitations

This manuscript is part of a Special Topic relating to "Surface Electromyography: Barriers Limiting Widespread Use of sEMG in Clinical Assessment and Neurorehabilitation." Therefore, it focuses on the added value of sEMG without providing details on the complete clinical assessment of patients, on the individual's pathophysiology of spasticity, on the functional assessment of walking by means of clinical scales, and on gait biomechanics as provided by GA (47). Similarly, it does not compare the effectiveness of treatments when designed based either on the sole clinical evaluation or with the contribution of dEMG.

CONCLUSIONS

This paper is a presentation of anecdotal cases that show the usefulness of dEMG during clinical decision-making and physiotherapy. Both technical and knowledge-related barriers determine its current limited used in the clinical practice. Adequate training during university, further literature on the topic, along with strategic communication and reliable opinion leaders, are needed to overcome these barriers.

DATA AVAILABILITY STATEMENT

Inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Ethical review and approval was not required for this educational paper on human participants in accordance with the local legislation and institutional requirements. Written informed consent to clinical and instrumental data publication was provided by all subjects.

AUTHOR CONTRIBUTIONS

IC: concept and design, study coordination, selection of the cases, interpretation of data, preparation of manuscript, and review of manuscript. MC: concept and design, selection of the cases, interpretation of data, and review of manuscript. MM: concept and design, interpretation of data, and preparation of manuscript. AM: concept and design, preparation of manuscript, and review of manuscript. All authors contributed to the article and approved the submitted version.

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Clinical Relevance of State-of-the-Art Analysis of Surface Electromyography in Cerebral Palsy

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Surface electromyography (sEMG) can be used to assess the integrity of the neuromuscular system and its impairment in neurological disorders. Here we will consider several issues related to the current clinical applications, difficulties and limited usage of sEMG for the assessment and rehabilitation of children with cerebral palsy. The uniqueness of this methodology is that it can determine hyperactivity or inactivity of selected muscles, which cannot be assessed by other methods. In addition, it can assist for intervention or muscle/tendon surgery acts, and it can evaluate integrated functioning of the nervous system based on multi-muscle sEMG recordings and assess motor pool activation. The latter aspect is especially important for understanding impairments of the mechanisms of neural controllers rather than malfunction of individual muscles. Although sEMG study is an important tool in both clinical research and neurorehabilitation, the results of a survey on the clinical relevance of sEMG in a typical department of pediatric rehabilitation highlighted its limited clinical usage. We believe that this is due to limited knowledge of the sEMG and its neuromuscular underpinnings by many physiotherapists, as a result of lack of emphasis on this important methodology in the courses taught in physical therapy schools. The lack of reference databases or benchmarking software for sEMG analysis may also contribute to the limited clinical usage. Despite the existence of educational and technical barriers to a widespread use of, sEMG does provide important tools for planning and assessment of rehabilitation treatments for children with cerebral palsy.

Keywords: cerebral palsy, abnormal development, muscle pathophysiology, surface electromyography, spinal locomotor output, rehabilitation, clinical application

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INTRODUCTION

Cerebral palsy (CP) is the most common form of motor disability in childhood. It describes a group of permanent disorders of movement and posture, caused by disturbances in the fetal or infant brain (1). The clinical manifestations of CP vary greatly in the type of movement disorder and the degree of functional disability. It is often characterized by impaired coordination, muscle weakness, spasticity, hyperreflexia, hypertonia, clonus, spasms and co-contraction (2, 3). Children with CP have a variety of symptoms and CP is often accompanied by other disorders such as cognitive dysfunction, communication problems, deficits of vision, epilepsy, etc. (4, 5). Currently there are multiple symptomatic treatments being used, such as physical therapy (e.g., therapeutic exercises according to Bobath or Vojta; constraint induced therapy) and orthotics (e.g., foot, ankle-foot, knee-ankle-foot, hip-knee-ankle-foot orthoses), pharmacologic treatments (systemic medications: e.g., oral baclofen, diazepam, tizanidine, dantrolene, local intramuscular injection of botulinum toxin A), neurosurgical procedures (e.g., selective dorsal rhizotomy, deep brain stimulation), surgical neuro-orthopedic interventions that may include muscle tendon lengthening to correct retractions, interventions for re-establishing muscle balance through tendon transfer, rotational osteotomies for correcting bone deformities of the spine or lower limbs (6–12). Instrumentation-based assessment of functional disability is essential both for understanding the mechanisms of impaired movement control and for evaluation of treatment.

In recent decades, significant developments have occurred in many electrodiagnostic studies that provide powerful quantitative approaches to instrumentation-based assessments in cardiology (electrocardiology), neurology (electroencephalography), skeletal muscle functioning (surface electromyography, sEMG). In this work we will specifically focus on sEMG. It can be used for evaluation of the integrity of the nervous system in neurological disorders with motor deficit, playing an important role in neurorehabilitation and predicting the outcome of neuromuscular disorders (13–17). Multi-muscle sEMG recordings provide information on muscular recruitment/de-recruitment capability, fatigue, synergistic activation, co-contractions, as well as contribute to the evidence for the efficacy of the rehabilitation plan (18, 19). Quantitative sEMG can be used as a practical, relatively simple and non-invasive tool and a screening method adopted by medical doctors and physiotherapists. However, although sEMG study is an important tool in neurorehabilitation, the limited clinical use and almost no teaching in the physical therapy schools of most countries represent a contradiction (20).

This article specifically reports the potential clinical value of techniques based on sEMG in neurorehabilitation medicine of children with CP and addresses the barriers limiting a widespread clinical usage of sEMG for this patient population. In the first section, we will briefly consider the motor impairments that result from a lesion occurring in the developing brain and describe sEMG applications for the assessment of neurological impairments and for performing interventions/treatment in children with CP. In the second section, we will present the results of a survey directed to the physiotherapists, neuro-developmental disorders therapists and medical doctors of a department of pediatric rehabilitation related to the barriers limiting a widespread clinical use of sEMG techniques in clinical assessment and neurorehabilitation of children with CP.

MOTOR IMPAIRMENTS AND SEMG APPLICATIONS IN CP

Motor Impairments

One of the most widespread and used classifications of CP is that proposed by Surveillance of Cerebral Palsy in Europe. According to their criteria, all CP subtypes have an abnormal pattern of movement and posture and classification is applied in a hierarchical manner using the predominant type of muscle tone and movement abnormality, resulting in the following categories: spastic, dyskinetic and ataxic (21). The most common type of CP, on terms of motor control, is spastic CP, which affects ∼70–80% of the population of children with CP and results in impaired sensory-motor control, muscle weakness and muscle hyper-resistance (22). Objective functional scales have been employed to assess individuals with CP such as the Gross Motor Function Classification System (GMFCS) for assessing functional mobility and motor skills related to both lower and upper limbs. Parallel classification scales have been developed for assessing upper extremity function in CP, such as the Bimanual Fine Motor Function Scale (BFMF) and the Manual Ability Classification System (MACS) (22).

Comprehensive descriptions of motor impairments in children with CP have been reported in numerous studies both for lower and upper limbs. Children with CP may develop various motor dysfunctions, including dystonia, contractures, hyperreflexia, muscle weakness, lack of coordination (23, 24), increased passive musculotendinous stiffness (25), increased cocontraction of antagonists (26, 27), structural changes in muscle fibers and connective tissues (28–32).

Gait impairments in CP are also typical (33). In particular, children with CP show difficulties in gait maturation and a lack of some major features of adult gait (pendulum mechanism of walking, foot trajectory control), frequent problem of foot drop associated with impaired ability to dorsiflex the ankle, difficulties in hip extension and ankle joint plantarflexion at end stance, excessive leg muscle co-activation, increased proprioceptive reflexes, and delayed or impaired maturation of the spinal pattern generation output (27, 34–38). Some characteristic features of gait are illustrated in **Figure 1**. In line with the general hypothesis of delayed maturation (39), many idiosyncratic features of gait in older children with CP resemble those in typically developing (TD) children at the onset of independent walking (37), for instance, the noticeable single-peak foot lift (**Figure 1B**) and a lack of stereotyped vertical trunk displacements resulting from the pendulum mechanism of walking. The adult two-peaked foot trajectory, representing an accurate endpoint control with a minimum at midswing (40–42), is usually not observed in children with CP; instead, a single peak of the foot lift, typical for TD toddlers, can be frequently seen across all sampled ages in CP (37) (**Figure 1B**).

Since any reflection on functional disability in CP should consider the mechanisms and methods of their assessment, sEMG monitoring may be useful for assessing and treatment of motor impairments and various examples will be considered below.

sEMG Applications

Background

Since the discovery of sEMG in 1912, myoelectric activity measurements provided many examples of normal and pathological skeletal muscle function, improved our knowledge about the neural control of movement and contributed to the

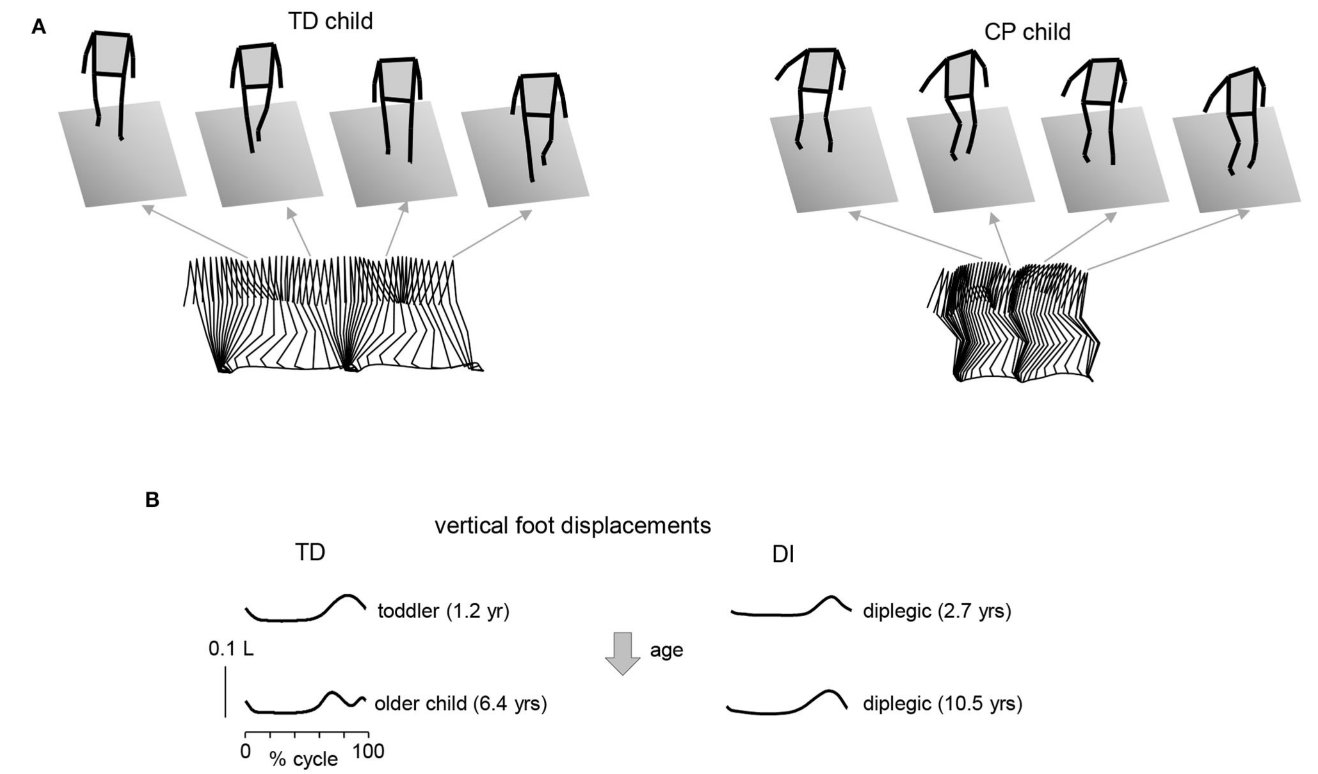

FIGURE 1 | Gait impairments in children with cerebral palsy. **(A)** Stick diagrams (3D, sagittal on the bottom) of 2 consecutive strides in one TD child (5.7 yrs) and one diplegic child (6.3 yrs). Note typical two peaked profile of vertical hip position during one stride in TD child (pendulum mechanism of walking) and variable pattern in child with CP. **(B)** Vertical foot displacements averaged across 45–60 strides during overground walking at self-selected speed for two TD children (1.2 and 6.4 yrs) and two diplegic children (2.7 and 10.5 yrs). Vertical foot displacements are expressed in relative units (normalized by the limb length L). Patterns are plotted vs. the normalized gait cycle. Adapted from Cappellini et al. (37).

development of clinical applications (43). sEMG registers the electrical potential at the surface of the skin associated with the summation of multiple action potentials of individual muscle fibers during their contraction and thus provides a direct measure of muscle contraction/relaxation activity controlled by the nervous system. One can record muscle activity by placing one or more pairs of electrodes on the skin over a muscle and sEMG can be used to estimate the global net firing of spinal motoneurons (MN) innervating that muscle, since it increases fairly linearly with the sum of rectified motor unit action-potentials at least over the physiological range of 0–50% contraction levels (44–46). The amplitude and spectral characteristics of the sEMG signal depend on the anatomical and physiological properties of muscles and subcutaneous tissue thickness. Surface EMG-derived indices have an important role as outcome measures to evaluate the responsiveness to treatments (47, 48). In some cases, the visual inspection of sEMG traces is easy to perform and data are easy to interpret, as in the case of a complete lack of muscle activity (paresis). In many clinical applications (e.g., support to the surgical planning) there is no need for algorithms and raw data may support the clinical decision making [e.g., (49, 50)]. However, some performance indicators, factors and processing methods, such as the determination of the onset/offset of sEMG bursts or amplitude normalization (43), require attention and agreement between the users, and in particular, the interpretation of sEMG signals with respect to muscular coordination requires some caution (51). For this reason, to support the interpretation of sEMG signals, different signal processing methodologies were developed (52).

Standard measurements and processing procedures of the sEMG signals are in great demand for a better understanding of neuromuscular control and are important for various biomedical applications and clinical diagnosis. In clinical practice, real-time sEMG can be used by physiotherapists as control if the movement requested is performed by the proper target muscle or by means of compensatory mechanisms, as a direct measurement of variations consequent to mobilization, verticalization, trunk fixation, or to assess the effect of different orthoses on muscle activation, which can vary toward or away from the normal pattern. Below we consider examples of using sEMG in children with CP for assessing neurological impairments and performing interventions.

Assessing Muscle Activity and Motor Dysfunctions

Walking is typically considered one of the most essential activities of daily living (53, 54). Clinical gait analysis is therefore useful and can get insights into the complexity and deficits in the control of pathological gait, and be integrated into the clinical decision-making of individuals with gait disorders (55). Motor problems in children with CP can be associated with excess symptoms such as hypertonia, spasticity, spasms, hyperreflexia, and deficiency symptoms such as muscular weakness, apraxia, ataxia, loss of selective activation of muscles (56). The latter feature is an important determinant of motor control in children with CP and can be used to monitor gross motor function progress over time (57). sEMG recordings may provide a quantitative assessment of coactivation and the degree of selective activation of muscles rather than using subjective estimates of muscle coordination with a low sensitivity (58). Moreover, sEMG is suitable for the detection of coactivation of agonist and antagonist muscles, so that physiological activation patters could be distinguished from pathological ones. Management and rehabilitation processes of children with CP can be improved using electromyographic techniques (59). Particularly, sEMG analysis in children with CP can also be used for surgical planning (60).

It is worth noting that the muscles are often weak and atrophic in children with CP, resulting in significantly reduced volumes in leg muscles and in bone changes (28, 29, 31, 61, 62). Therefore, interventions increasing muscle length or strength are beneficial. For instance, sEMG can be used to monitor and accomplish targeted muscle contraction in children with CP in order to prescribe exercise programmes for muscle strengthening and their effectiveness (63).

sEMG is commonly used to assess muscular coordination in clinical gait analysis but could also be used in functional diagnosis or in the monitoring of therapeutic outcomes. In particular sEMG could be useful for the assessment of the "paretic component," i.e., defective activation of peripheral muscle effectors on most affected side of hemiplegic children. Reduced and insufficient speed dependent modulation of the ankle dorsiflexors' activity (e.g., tibialis anterior, TA) around foot contact at end swing (and to a lesser degree at end stance) can significantly affect the ankle dorsiflexion torque and consequently the foot trajectory in children with CP (**Figure 2**) (64). The TA activity frequently demonstrates only one major peak at lift-off at the onset of swing (on the most affected side of hemiplegic and on both sides in diplegic children) with respect to two prominent peaks in TD children [**Figure 2**, see also (37)]. This TA pattern is likely associated with impaired foot trajectory control. Other intrinsic and extrinsic foot muscles contribute to flexion/extension of the ankle and metatarsophalangeal joints as well (65) and their impaired activity might also limit ankle dorsiflexion and foot varus deviation in children with CP. However, a registration of sEMG activity of intrinsic foot muscles is challenging (e.g., due to crosstalk) and was not systematically performed for clinical gait assessments. Furthermore, there is a lack of important age-related changes of sEMG characteristics in children with CP. For instance, in TD children, there is a progressive reduction of sEMG burst durations with age and corresponding spatiotemporal characteristics of the spinal motor pool output, likely reflecting an essential developmental aspect of muscular control optimization (37). In children with CP, these characteristics of motoneron output are similar to those at the early stages of development in TD children (**Figure 3A**).

Functional corticospinal connectivity in CP can be assessed by estimating the oscillatory drive of the motor cortex to the spinal cord using coherence analysis of sEMG signals within and between muscles. Indeed, in children with CP, there is a frequent problem of foot drop associated with impaired control of the ankle dorsiflexors (**Figure 2**) and reflected also in reduced TA sEMG-sEMG coherence in the beta and gamma frequency bands associated with impaired functional corticospinal connectivity (68). Such sEMG-sEMG coherence assessment can be used for monitoring of therapeutic outcomes. For instance, 4 weeks of intensive training of walking on the inclined surface can reduced foot drop and significantly improve the ankle joint control in children with CP along with improved functional corticospinal connectivity and increased beta and gamma oscillatory drive to motoneurons (69).

Hyperreflexia

Hyperreflexia is a frequent feature in neurological disorders characterized by a velocity-dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyper-excitability of the stretch reflex (70). sEMG examination is indispensable for detecting the presence, contribution and interference of the spastic component with walking pattern, augmenting motor unit recruitment, enhancing stretch responses during walking and coactivating muscles during specific phases or through the whole gait cycle (23, 71). Accordingly, hyperreflexia can significantly influence the locomotor movements, assist joint/segment stability or impede movements during muscle lengthening, limit ranges of angular motion, and may necessitate extra efforts or reorganization of muscle responses to compensate for these abnormalities. There is growing consensus that it is important to distinguish different contributions to joint hyper-resistance, i.e., non-neural originating from passive tissue properties, and neural originating from background muscle activity and stretch hyperreflexia. sEMG provides a mean to identify the contribution of muscle activity to muscle hyper-resistance (72).

Clinical analysis of muscle activity is thus necessary for deciding whether to intervene or not and in particular for determining the degree of post-treatment reduction of the spastic component. Experiments and data analysis using muscle models confirmed a tight coupling between kinematics and motor output in children with spastic diplegia, for instance, during the phases of lower limb muscle lengthening in the gait cycle (73). In particular, atypical stretch responses were more easily produced around the time of foot ground contact during lengthening contractions than at other moments of the gait cycle. The above findings point toward an essential role of sEMG measurements in the clinical evaluation, understanding of spastic muscle dysfunction in children with CP and improving the outcomes of neurorehabilitation (71).

Muscle Fatigue

Children with CP might have higher levels of activation in specific muscles and/or large amounts of coactivation of agonist

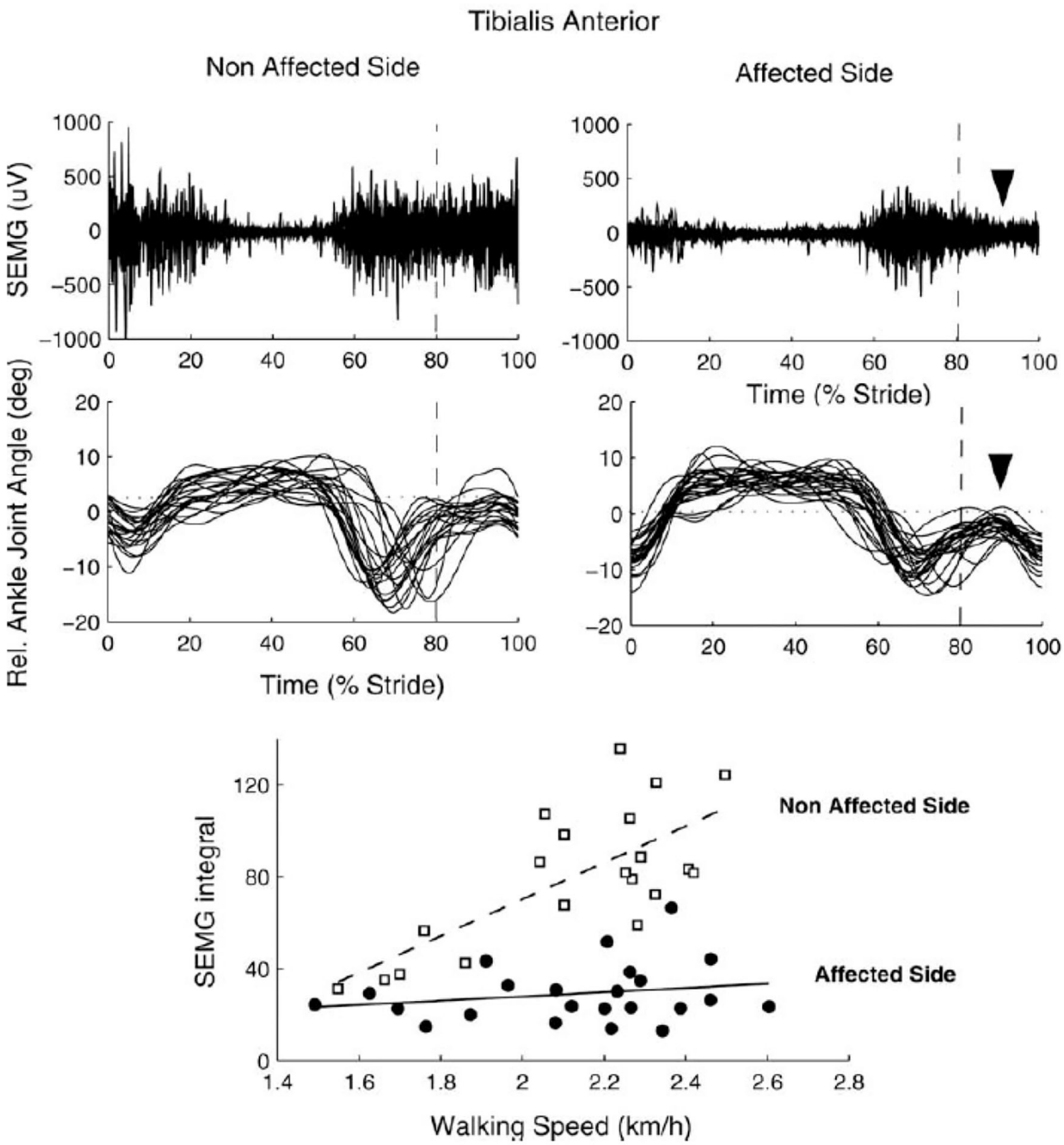

FIGURE 2 | sEMG of tibialis anterior muscle during walking in one 8 yrs child with congenital hemiparesis. Upper panels: examples of sEMG plotted vs. the normalized gait cycle. Middle panels: ankle joint angles of individual strides. Lower panels: speed-dependent recruitment of TA (quantified as sEMG integral or the mean amplitude of rectified sEMG over the period) on the affected and non (least) affected side. Note reduced paretic component of TA around foot contact at end swing along with reduced foot dorsiflexion (upper and middle panels) and insufficient up-scaling of TA activity with speed (lower panel) on the affected side [reproduced from Frigo and Crenna (64) with permission].

and antagonist muscles in the same joint, which could increase muscle fatigue. Mechanical manifestations of muscle fatigue are defined as a reduction in the force-generating capacity of the neuromuscular system, which occurs during sustained activity (74). Muscle fatigue is usually divided into peripheral and central fatigue (75). Peripheral mechanical fatigue is generally a loss of force-generating capacity due to processes distal to the neuromuscular junction, whereas central is described as progressive reduction in voluntary activation. sEMG could be used to assess these changes in neuromuscular activation associated with peripheral fatigue.

Typically a decrease in frequency and an increase in root mean square of sEMG signals are interpreted as myoelectric manifestations of muscle fatigue (76, 77). Fatigue itself is not a physical variable. Its evaluation requires the definition of indices based on physical variables that can be measured,

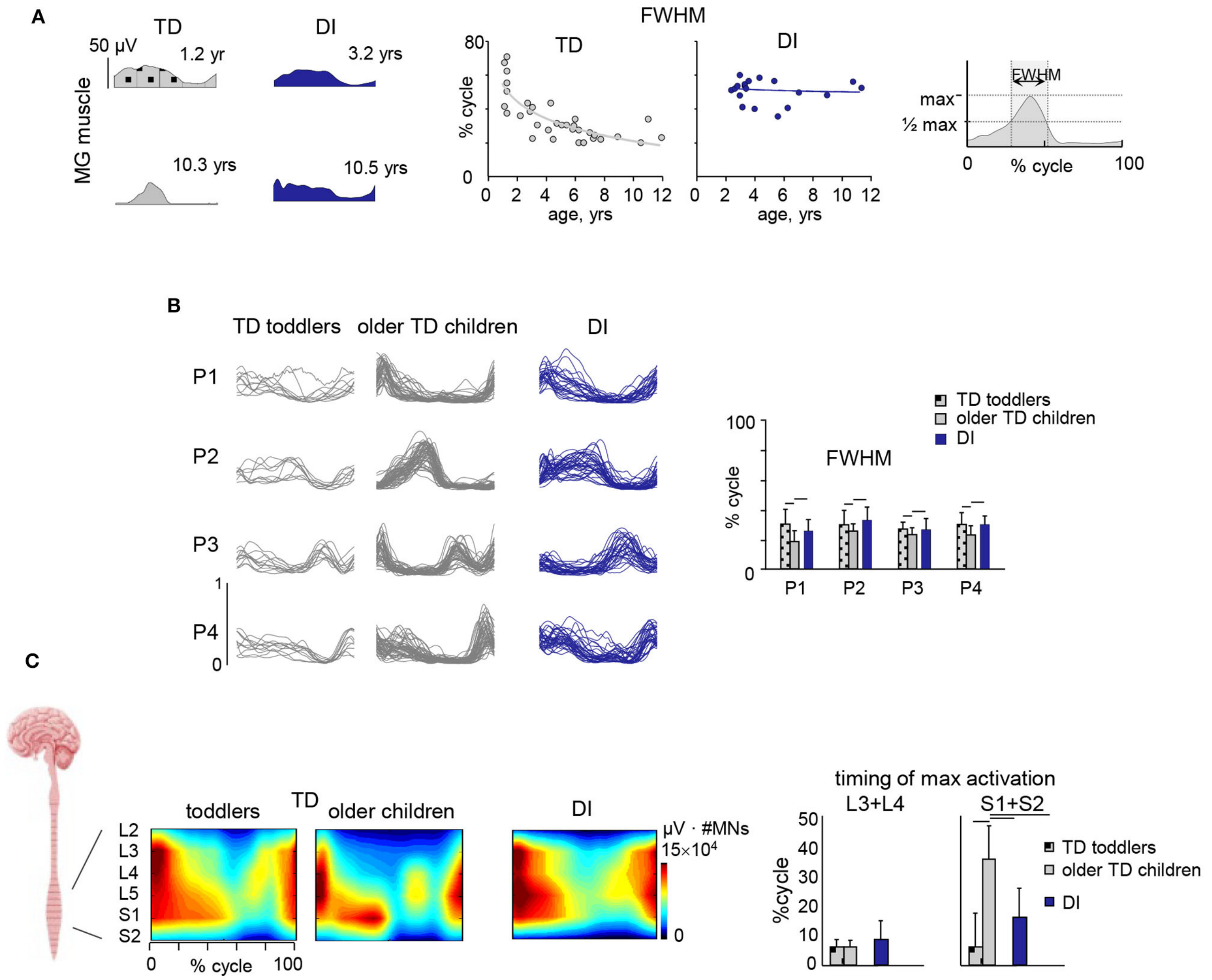

FIGURE 3 | Muscle activity locomotor output and its impairments in children with CP. **(A)** Developmental trend for the duration of muscle (medial gastrocnemius, MG) activity. From left to right: examples of MG activity in two TD children (1.2 and 10.3 yrs) and two diplegic children (3.2 and 10.5 yrs), and duration of MG activity (full width at half maximum, FWHM, see right panel) as a function of age (continuous lines represent exponential fittings). Note significantly wider sEMG activity in CP, independent of age. **(B)** Statistical analysis of sEMG patterns: basic activation patterns P1–P4 consistent across individual children. Right panel – mean (+SD) FWHM of P1–P4. TD toddlers aged 1–1.2 yrs, older TD children aged 2.1–11.8 yrs and DI children aged 2.3–11.1 yrs. Modules were ranked based on their best similarities. Note significantly wider patterns in CP. **(C)** Segmental motoneuronal (MN) output in TD toddlers, TD older children and diplegic children estimated by mapping sEMG activity patterns of 11 simultaneously recorded lower limb muscles onto the approximate rostrocaudal location of the motor pools of the corresponding muscles (averaged across children and normalized to the mean number of MNs in spinal segments L2–S2) and plotted as a function of gait cycle. Output pattern for each segment L2–S2 was reconstructed by averaging all rectified sEMGs corresponding to that segment [for details, see (66)] and plotted in a color scale. To visualize a continuous smoothed rostrocaudal spatiotemporal activation of the spinal cord, we used a filled contour plot. To account for size differences in MN pools at each spinal level, this segmental activity value (in µV) was then multiplied by the segment-specific number of MNs, taken from Tomlinson and Irving (67). Right panel shows timing (+SD) of maximum activation of sacral (S1 + S2) and lumbar (L3 + L4) segments. Significant differences with respect to older TD children are indicated by lines over bars. Adapted from Cappellini et al. (37).

such as, for example, force or torque, power, angular velocity of a joint, or variables associated with the single motor unit, such as the conduction velocity, or with the sEMG signal, such as amplitude, spectral mean or median frequency. The conduction velocity is the main index, it decreases more or less rapidly depending on the level of contraction and is generally measured during isometric constant force contraction. The measurement of muscle fatigue in CP using sEMG reveals differences relative to the age-matched controls (78, 79).

Neuromuscular Electrical Stimulation

Neuromuscular or functional electrical stimulation (FES) is an example of the appropriate usage of temporal characteristics of sEMG recordings for determining the application of multi-channel electrical stimuli to superficial skeletal muscles in order to control, compensate and/or correct their contractions (80–85). In addition to a physiotherapy programme, it emphasizes task specificity, motor learning, and positive effects (86). It provides input while the child is engaged in a motivating, goal-directed activity. The decision about which muscles to stimulate is based on the biomechanics and required sEMG patterns during effective performance of the action. The child is an active participant and is encouraged to initiate movement. A single-case study reports that a boy aged 6.7 years learned to perform a number of tasks, including tying his shoelaces, after 24 sessions of stimulation to wrist extensors, finger flexors and extensors, with resisted exercises and task training (87). A period of wearing a dorsal wrist splint made of orthoplast was included to help him with his task practice. This study shows that such intervention is feasible with children and can be remedial. More recent studies of functional electrical stimulation applied to wrist extensor muscles found improvements in hand use (88–90). Other studies of children with diplegia found an increase in walking speed and muscle strength (80, 91, 92).

Electromyographic Biofeedback

Some studies used electromyographic biofeedback as a non-invasive, safe, and effective treatment for children with CP (93–95). Children with bilateral and unilateral CP may benefit from sEMG biofeedback therapy for various tasks including both upper and lower extremities. sEMG biofeedback treatment is an active rehabilitation training capable of detecting the signals of muscle contraction through auditory and/or visual feedback for motivating child's involvement and stimulating the recovery or improvement of the limb control (96). Some previous studies demonstrated the positive clinical effects of using sEMG biofeedback in improving upper limb dysfunction in persons with CP (94, 97, 98), the motor outcomes at the ankle joint, the strength of muscle contractions, range of motion, and walking speed (93, 99, 100).

Characterization of Multi-Muscle Activity Regularities (Basic Muscle Modules)

To perform a movement, the central nervous system (CNS) should engage many muscles and control corresponding forces exerted around joints involved. Furthermore, muscles differ in the fiber composition (slow, fast) and structure (pinnate, parallel fibers, etc.), may be divided into compartments and comprise quite different number (thousands) of motor units. During locomotion or other movements, tens of muscles are active and need to be coordinated simultaneously. The idea that the CNS can control the complexity of interactions to promote a certain motor act by adopting a modular decomposition and therefore a limited number of primitives has recently received a lot of attention (101). In the last years researchers showed evidence that muscle activation patterns, represented by the sEMG envelopes of a few muscles, can be decomposed into a limited number of "basic" functions or patterns, called "synergies" or "primitives" (37, 102–104). These primitive patterns can be combined, with different individual weights, and produce the corresponding compound task-related muscle activations to perform the movement. It has been hypothesized that the CNS simplifies muscle control through modularity, using these basic synergies (primitives) to activate muscles in groups (105).

This approach has had a large impact on the analysis of motor control in the field of neurorehabilitation since it implies that the CNS generates forces and movements by optimizing the control strategy of either individual muscles or (more likely) muscle synergies (106). Concerning application of this approach to neurorehabilitation of children with CP, several studies evaluated impairments in the modular organization of multi-muscle activity patterns and alterations of muscle synergies (37, 100, 107–120). The multi-muscle activity analysis through non-negative matrix factorization revealed that sEMG activity regularities and patterns can be adequately captured and represented by a small number of temporal components during walking in children with CP and in TD children (**Figure 3B**). Such analysis showed a comparable spatiotemporal organization of the motor output in both groups, but noticeably wider temporal basic activation patterns in CP, similar to the patterns of younger TD toddlers (**Figures 3A,B**) (37). Reduction of dimensionality (fewer muscle synergies) reported in some studies [e.g., (107, 109, 110)] may depend on the relatively small number of analyzed muscles (121–123) and/or the method used to define the minimum number of modules (37, 124, 125). Moreover, the observed phenomenon of widening seems to be a characteristic feature of CP gait and does not depend on the number of modules used in the sEMG decomposition procedure (126).

Spinal Segmental Motoneuron Output

The final neural output of spinal locomotor circuitry is represented by the spatiotemporal activation of α-motoneurons (MN). It can be evaluated indirectly by using sEMG recordings from a large number of lower limb muscles and mapping their activity patterns onto the approximate rostrocaudal location of the motor pools of the corresponding muscles in the lumbosacral enlargement (66, 127, 128). The implicit assumption is that the rectified sEMG provides an indirect estimate of the net firing of spinal MNs innervating that muscle (44–46, 127). In essence, to reconstruct the motor-pool output pattern of any given spinal segment innervating limb muscles, all rectified sEMG-waveforms corresponding to that segment are averaged using appropriate weighting coefficients (66, 127). In general, each muscle is innervated by several spinal segments, and each segment supplies several muscles (129), so that one may estimate the segmental MN output by adding up the contribution of each muscle to the total activity in each spinal segment according to the published myotomal charts of segmental innervation in humans. The analysis of motor pool activation using multi-muscle sEMG can also be complemented by a statistical analysis of the muscle activity profiles and their decomposition into a small set of so-called muscle modules or common basic activation components (see the previous section) as a means to look backward from the periphery to the spinal cord motor programming and output (130, 131). There are now several studies that evaluated the spinal locomotor output, its spatiotemporal organization and impairment in children with CP (37, 100, 107–120).

Figure 3C illustrates the spinal maps of MN activation during walking and typical features of motor output impairment in children with CP compared to TD children obtained using the averaged rectified sEMG profiles of multiple leg muscles as an indirect measure of the net MN firing in the spinal cord. TD children show a notable functional reorganization and maturation of the MN output with increasing age, consisting in more narrow loci of MN activity and a progressive shift of the timing of maximum activation of sacral segments toward later stance (**Figure 3C**). By contrast, this developmental trend in children with CP is lacking. They show very limited reduction in the muscle activity pattern durations with age and limited changes in the timing of lumbar and sacral motor pool activation over the gait cycle (37), in line with the idea that early injuries to developing brain substantially affect the maturation and functioning of the spinal pattern generation circuitry.

RESULTS OF A SURVEY ON CLINICAL RELEVANCE OF SEMG IN A DEPARTMENT OF PEDIATRIC REHABILITATION

A number of "barriers" exist limiting the widespread application of sEMG techniques in clinical assessment and neurorehabilitation of children with CP. We aimed at examining these barriers by gathering information from the clinicians involved in pediatric rehabilitation to generate opinion on the current use of sEMG and its clinical utility. We think that getting some background views and perspectives will help our understanding of the current applications of sEMG in neurorehabilitation of children with CP as well as of the potential obstacles to its use in the clinical setting in this particular area. To this end, we conducted a survey directed to the physiotherapists, neuro-developmental disorders therapists and medical doctors related to the barriers limiting a use of sEMG techniques in clinical assessment and neurorehabilitation of children with CP.

Participants

An online survey involving the personnel of the Department of Pediatric Neurorehabilitation of the IRCCS Santa Lucia Foundation was conducted. Of the 36 invitations sent, 28 invitees completed survey questionnaires. Professional background was varied, with 16 (57%) physical therapists, 7 (25%) medical doctors, and 5 (18%) neuro-developmental disorders therapists (**Figure 4A**, left panel).

Survey Questionnaire

We have prepared a 34-item (**Table 1**) online survey. To address the barriers to clinical use of sEMG, we included in the survey questions about the potential added value that could be provided by sEMG-based assessments but also the reasons of the minimal use in the clinical practice. The questionnaire also included information about participants: self-reported knowledge about the sEMG techniques obtained during studies at the university and/or refresher courses, self-reported level of knowledge of the sEMG usage, and self-reported usage of sEMG in their own clinical practice. Participants were invited to participate via an e-mail and an online survey (using *Google Forms*) was used to collect the answers electronically. They were requested to respond to the questionnaire by selecting one of the answers to each statement (**Table 1**).

Results of Survey

Background and Self-Reported Usage of sEMG by Participants

All clinicians that completed survey questionnaires (7 medical doctors, 5 neuro-developmental disorders therapists and 16 physiotherapists, **Figure 4A**) were highly involved in pediatric neurorehabilitation though their self-selected level of knowledge and usage of sEMG varied. Not all clinicians reported learning the sEMG technique at the university or refresher courses (**Figure 4A** middle panel). While some respondents (12/28) reported "good" or "very good" level of knowledge about the use of sEMG (**Figure 4A**, right panel), nevertheless, most participants do not use sEMG in their clinical practice (**Figure 4B**, right panel).

The survey (**Table 1**) also included two major sets of questions related to the usefulness (**Figure 4**) and barriers (**Figure 5**) to the clinical usage of sEMG. We describe the results of the survey below.

Usefullness of sEMG

Twelve (43%) contributors totally agree with the statement that sEMG is rarely used in clinical neurorehabilitation (**Figure 4B**, left panel), the majority of participants agree that sEMG is currently more relevant for researchers than clinicians and also that sEMG provides information on neuromuscular function that is not provided by other assessment techniques/tools in neurorehabilitation (**Figure 4B**, right panel). While most participants have limited practice with sEMG, they nevertheless expressed willingness to use sEMG to improve their own capacity for neurological assessments (**Figure 4B**, right panel).

Regarding the role of sEMG in muscle functioning assessment in children with CP, the majority of participants agreed that sEMG may be useful to: outline the abnormal timing of muscular actions during movements (e.g., gait, motor tasks), evaluate muscular fatigue, evaluate the appropriateness of muscle activation in specific motor acts, identify pathological patterns of motor unit behavior, evaluate maximal voluntary activation, characterize involuntary muscle activations (e.g., dystonia, ataxia, spasticity), and characterize muscle fiber conduction velocity (**Figure 4C**, upper panel). Nevertheless, many of them were also "neutral" or disagreed with these assessments (e.g., for stretch reflex anomalies, etc.).

Regarding the usefulness of sEMG for decision making or performing invasive intervention/treatment, more than half of participants expressed themselves in favor of the sEMG usage in the following circumstances: treatment of hypertonic muscles with botulinum toxin, personalized therapy, selective dorsal rhizotomy, decision on surgical acts or rehabilitative interventions that involve bandages or constraints on joints, FES, functional surgery such as elongation or transpositions of tendons/muscles in order to change or improve their function (**Figure 4C**, lower panel). On the other hand, about half of them were uncertain or disagreed with these sEMG applications.

In sum, although the participants believe that the application of sEMG in the field of rehabilitation is useful (**Figure 4C**) and

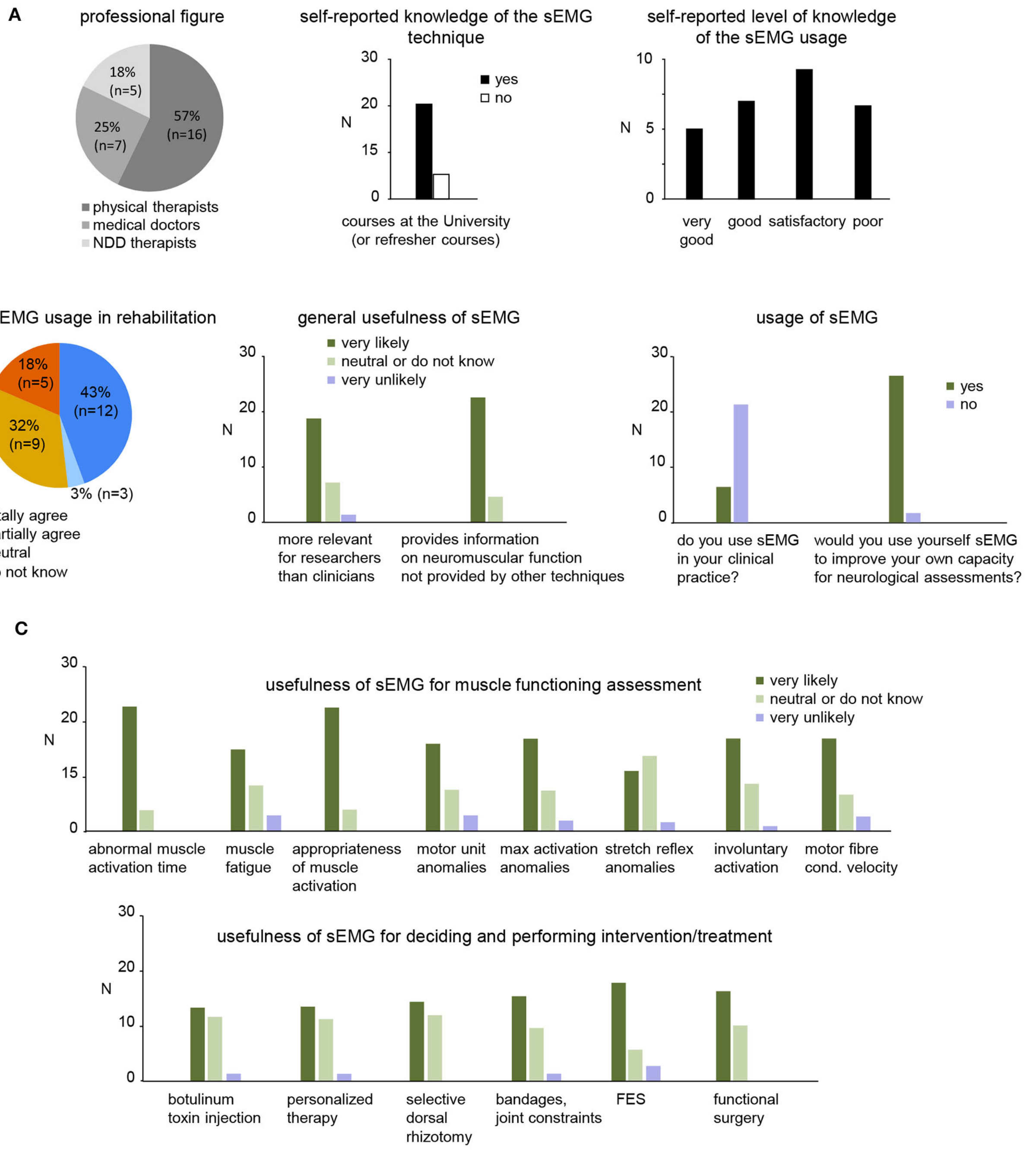

FIGURE 4 | Results of survey to address the usefulness of sEMG in clinical practice for children with CP. **(A)** Pie chart showing the number and percentage of each group of participants that completed the survey (twenty-eight returned completely survey questionnaires: 7 medical doctors, 5 neuro-developmental disorders (NDD) therapists and 16 physiotherapists) and self-reported knowledge of the sEMG techniques and usage. **(B)** General assessment of the sEMG usage in rehabilitation. Left panel: pie chart showing the percentage of the participants that agree or disagree of rare sEMG use in clinical neurorehabilitation. Middle panel: general relevance of sEMG for research and clinical usage. Right panels: usage of sEMG and willing to use by participants of the survey. **(C)** Usefulness of sEMG for functional assessment (upper panel) and performing/defining an intervention (lower panel).

provides information on neuromuscular function not provided by other techniques, many of them were still uncertain about its usefulness (for instance, they consider sEMG to be more relevant for researchers than for clinicians, **Figure 4B**, middle panel).

Barriers to the Clinical Use of sEMG

We also specifically asked the participants about potential barriers to the clinical use of sEMG in neurorehabilitation of children with CP (**Table 1**, last section). More than

TABLE 1 | Survey items of the questionnaire to address the usefulness of sEMG in clinical practice for children with CP.

Statement	Possible answers (one answer for each statement)
Self-reported knowledge of the sEMG technique: did you address this topic during your studies at the university and/or refresher courses?	yes no
Self-reported level of knowledge of the sEMG usage	very good good satisfactory poor
sEMG is rarely used in clinical neurorehabilitation	totally agree partially agree neutral do not know
General usefullness of sEMG in the field of neurorehabilitation 1. sEMG is currently more relevant for researchers than clinicians 2. sEMG provides information on neuromuscular function not provided by other techniques	very likely neutral/do not know very unlikely
Usage of sEMG and willing to use by participants of survey 1. do you use sEMG in your clinical practice? 2. would you use yourself sEMG to improve your own capacity for neurological assessments?	yes no
Usefulness of sEMG for muscle functioning assessment. sEMG can be useful to: 1. outline the abnormal timing of muscular actions during movements (i.e., gait, motor tasks) 2. evaluate muscle fatigue 3. evaluate the appropriateness of muscle activation in specific motor acts 4. identify pathological patterns of motor unit behavior 5. evaluate anomalies of maximal voluntary activation 6. characterize the stretch reflex 7. characterize involuntary muscle activations (e.g., dystonia, ataxia, spasticity) 8. characterize the motor fibres' conduction velocity	very likely neutral/do not know very unlikely
Usefulness of sEMG for deciding and performing intervention/treatment. sEMG can be useful in the following cases: 1. treatment of hypertonic muscles (gastrocnemius, soleus, hamstrings, adductor) with botulinum toxin 2. personalized therapies 3. selective dorsal rhizotomy 4. decision on surgical acts or rehabilitative interventions that involve bandages or constraints on joints 5. functional electrical stimulation (FES), for instance, for ankle dorsiflexors (TA) stimulation during gait 6. in the most serious cases, functional surgery can be used for elongation of targeted muscles or transpositions of tendons/muscles in order to change their function	very likely neutral/do not know very unlikely
Several factors may limit the widespread usage of sEMG in clinical neurorehabilitation. Based on your experience and knowledge, please score the relevance of the following elements as potential barriers to the clinical use of sEMG: 1. lack of widely accepted evidence that the use of sEMG in neurorehabilitation helps the selection of treatments 2. lack of widely accepted evidence that the use of sEMG improves treatment effectiveness 3. lack of normative data for evaluation of children with CP based on sEMG 4. insufficient education/practice for professionals in neurorehabilitation at refresher courses 5. insufficient or lack of education on sEMG at the university 6. limited relevance of sEMG as a clinical tool (sEMG has more theoretical relevance) 7. high cost of sEMG equipment 8. sEMG data analysis/interpretation is difficult to perform without specific education/training 9. sEMG software/device not easy to use or not friendly enough for clinicians 10. time consuming 11. discomfort for children with CP 12. no multidisciplinary team available 13. clinical aim is to associate symptoms to therapy and not to investigate the pathological mechanisms using sEMG 14. EMG measurements do not improve the outcome of treatment	very relevant neutral/do not know not relevant

50% of the participants very likely consider the following elements as potential barriers (**Figure 5**): difficult interpretation of sEMG data without specific education/training (21/28), insufficient education/practice during refresher courses (20/28), and inadequate education and training for physiotherapists and medical doctors on sEMG at the university (17/28). Less than 50% of the participants consider the following elements as potential barriers to the clinical use of sEMG: high cost of sEMG equipment (13/28), time-consuming for sEMG measurements/assessment (11/28), lack of evidence that the use of sEMG improves treatment effectiveness (10/28), limited relevance of sEMG as a clinical tool (9/28), need for a multidisciplinary team (9/28), lack of evidence that the use of sEMG helps the selection of treatments (7/28), lack of normative data for evaluation of impairments in children with CP based on sEMG (6/28), sEMG device/software not easy to use by clinicians (4/28). Nevertheless, only few participants agreed that sEMG measurements should not be used to investigate the pathological mechanisms or do not improve the outcome of treatment (**Figure 5**, bottom).

Discussion

In the first section ("Motor impairments and sEMG applications in CP"), we described motor impairments resulting from a lesion occurring in the developing brain and corresponding sEMG applications. The use of sEMG signals through state-of-the-art and advanced methodologies is becoming essential in rehabilitation engineering and in clinical neurophysiology. Many publications in peer-reviewed journals provide various arguments and examples related to the current clinical applications of sEMG showing the information available for neurorehabilitation of children with CP (17, 19, 36, 55, 59, 63, 64, 69, 73, 93–96, 99, 100, 116, 132–136). Recent studies have recommended using a combination of electromyography and biomechanical measurements as a more accurate method of evaluating impaired motor function in individuals with brain damage, such as cerebral palsy (25, 37, 69, 100, 102, 135, 137, 138). The use of sEMG is essential in the decision making of functional surgery and in the assessment of spasticity (133). Moreover, monitoring sEMG signals is beneficial for detecting voluntary muscle activation that may interfere with the identification of reflex responses and evaluation of corticospinal and neuromuscular connectivity (134). The uniqueness of this technology is that it provides information on neuromuscular function not provided by other techniques, assists for intervention or muscle/tendon surgery acts, and evaluates more integrative functioning and impairment of the nervous system based on multi-muscle sEMG recordings. sEMG can be helpful for monitoring neuromuscular modifications and progress in children with CP, integrating the clinical evaluation and providing a picture of both impairment and functional alteration.

Despite these successes and evidences, clinical applications remain very limited because of many barriers acknowledged by the end-users (therapists and medical doctors). In addition, publication of clinical results in the experimental papers or state-of-the-art reviews is necessary but far from being sufficient pointing to the important issue of disseminating rehabilitation innovations and evidence-based practice (139). The results of a survey showed a lack of the sEMG usage in clinical practice and generally limited competence of clinicians in its usage for rehabilitation of children with CP (**Figure 4B**). A number of barriers limiting the widespread application of sEMG techniques were considered (ranked according to their greatest relevance in **Figure 5**); among the most relevant – "difficult interpretation" and "insufficient education."

One limitation of our survey is that the results are for a single center. Nevertheless, the sample of responders was relatively large ($n = 28$) and included experts in pediatric rehabilitation: physical therapists, neuro-developmental disorders therapists, and medical doctors (**Figure 4A**, left panel). It is also worth noting that many of the barriers for the sEMG use were acknowledged for other populations of patients as well [see, for instance, other articles in this research project: (140–145)]. Therefore, a general need for this innovative technology suggests that "*specific education should be part of the rehabilitation professionals' curriculum*" (142).

Some barriers are related to the lack of confidence or knowledge when comparing the results of sEMG with the diagnostic power of needle EMG (146, 147), or are related to the problem of assessing "function" (with scales and observational descriptions) rather than "impairment" (with measurement of physical quantities) (148, 149). There is often a lack of a common language with rehabilitation engineers and many therapists and medical doctors lack the technical background to interpret the sEMG outcomes. They may believe that time spent in assessing sEMG is not "productive" because it provides limited or incomplete information about pathology. However, this opinion may be related to several reasons including a lack of knowledge of the subject. Some barriers are technical, like difficulties with the application of sEMG, time consuming, signal processing and information extraction algorithms, which do not directly produce clinically relevant information. Among technical problems associated with certain applications of sEMG in children with CP, one could also mention difficulties in normalization of sEMG amplitude to maximum voluntary contraction or distinguishing involuntary stretch reflex activation from voluntary activation. For instance, children with CP demonstrate significantly larger intensity of MN activity of the lumbosacral enlargement during gait than TD children (37). However, it is difficult to evaluate the amount of excessive muscle activation for personalized assessments since differences in "non-normalized" sEMG intensity may reflect potential differences in subcutaneous tissue thickness between subjects. Using reference (rather than maximum) contractions for sEMG normalization may be used in some cases although the order of motor unit recruitment, differences in muscle fiber composition in children, difficulty to activate a particular muscle in isolation and crosstalk from neighbor muscles affect sEMG normalization. One should also keep in mind that it is often difficult to obtain reference muscle contractions in infants at risk of developing motor disorders [e.g., (150–152)]. Finally, the cost of the devices, the reimbursement procedures, and the time needed to perform a measurement and obtain a clinically useful information have also to be taken into account.

These perceived reasons for the potential barriers (**Figure 5**) do suggest a necessity for additional training sEMG courses and/or need to add specific education in graduate degree courses of physiotherapists and medical doctors. The participants agreed that the sEMG analysis may be difficult to execute without such knowledge and specific training. Moreover, the lack of specific education also prevents the preparation of clinical application guidelines that must become a part of the education of all

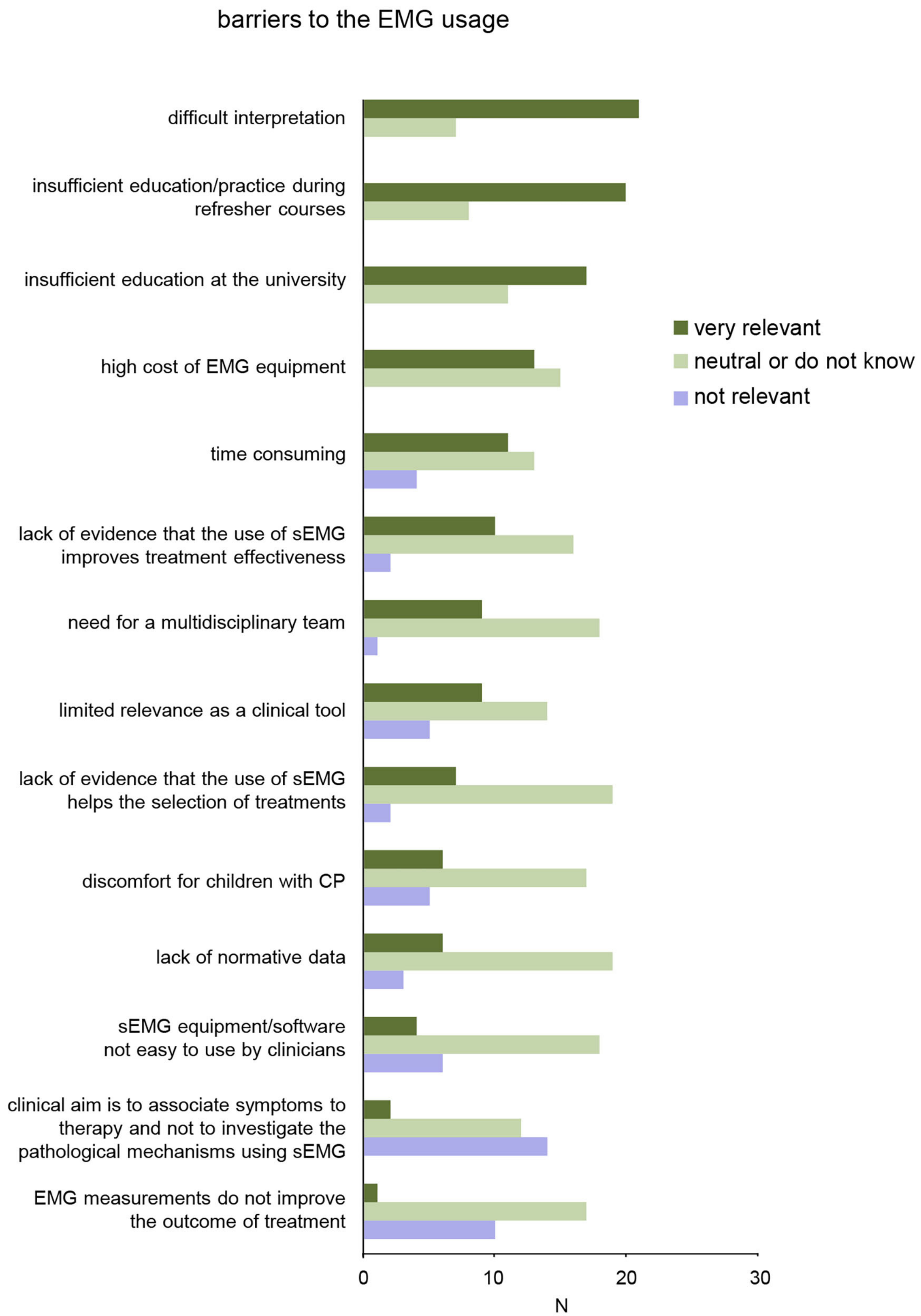

FIGURE 5 | Results of survey for barriers on sEMG use in clinical neurorehabilitation. The items are ordered according to relevance (from top to bottom).

operators potentially involved in sEMG application. Teachers of physiotherapy and neurology have in general, no or very limited research experience in this area. Insufficient continuing education and involvement of educators in research projects is a barrier to clinical use of all new technologies in general, and sEMG in particular. To overcome technical and education barriers, both better technical competence of clinicians and providing a medical technologist in major hospitals (like adopted in the Netherlands: https://www.tudelft.nl/en/2020/3me/june/clinical-technologists-officially-registered-healthcare-professionals/) may have an impact on increasing the use of sEMG in clinical practice. However, given the primary usage of this information by clinicians, we suggest specific theoretical-practical training to be carried out both during university courses for health rehabilitation professions and during medical specialization courses with outlets in neurorehabilitation. This implies recruitment of specialized professionals as teachers, availability of medical technology in university hospitals and therefore allocation of state or university funds.

CONCLUSIONS

Despite the uniqueness of the sEMG technology and the successes in clinical applications for planning and assessment of treatment of children with cerebral palsy, clinical application and practice in rehabilitation departments remain very limited because of many barriers. Various educational and technical barriers to a widespread use of sEMG were acknowledged by the end-users (therapists and medical doctors). Overcoming these barriers requires a highly interdisciplinary educational approach. Rehabilitators and engineers should have overlapping education and this would lead to overcoming the existing communication gap developing a common language and promoting the use of sEMG systems.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Surface Electromyography in Clinical Practice. A Perspective From a Developing Country

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Surface electromyography (sEMG) has long been used in research, health care, and other fields such as ergonomics and brain-machine interfaces. In health care, sEMG has been employed to diagnose as well as to treat musculoskeletal disorders, pelvic floor dysfunction, and post-stroke motor deficits, among others. Despite the extensive literature on sEMG, the clinical community has not widely adopted it. We believe that in developing countries, such as Chile, this phenomenon may be explained by several interacting barriers. First, the socioeconomics of the country creates an environment where only high cost-effective treatments are routinely applied. Second, the majority of the sEMG literature on clinical applications has not extensively translated into decisive outcomes, which interferes with its applicability in low-income contexts. Third, clinical training on rehabilitation provides inadequate instruction on sEMG. And fourth, accessibility to equipment (i.e., affordability, availability, portability) may constitute another barrier, especially among developing countries. Here, we analyze socio-economic indicators of health care in Chile and comment on current literature about the use of sEMG in rehabilitation. Then we analyze the curricula of several physical therapy schools in Chile and report some estimations of the training on sEMG. Finally, we analyze the accessibility of some available sEMG devices and show that several match predefined criteria. We conclude that in developing countries, the insufficient use of sEMG in health might be explained by a shortage of evidence showing a crucial role in specific outcomes and the lack of training in rehabilitation-related careers, which interact with local socioeconomic factors that limit the application of these techniques.

Keywords: surface electromyography, neurorehabilitation, physiotherapy education, low-income countries, Chile, clinical training, electromyographic biofeedback

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INTRODUCTION

Since the ′40s, surface electromyography (sEMG) has been used in a variety of settings, including motor-control research, education, health care, rehabilitation, ergonomics, and human-computer interfaces, among others (1). Unlike needle EMG, which has long been used in the assessment of neuromuscular disorders, sEMG is rarely employed in clinical and rehabilitation practice.

The literature on sEMG is extensive, and despite the total publications counting in the thousands, the number of papers devoted to clinical applications is considerably fewer.

For example, a search in PubMed with the terms "(surface EMG[Title/Abstract]) OR (sEMG[Title/Abstract]) OR (surface electromyography[Title/Abstract])" leads to 8,270 records. Adding terms such as "physiotherapy," "stroke," "gait," or "back pain" leads to 60, 376, 497, 124, and 521 records, respectively. This suggests an important gap between the total literature on sEMG and the part of it dedicated to clinical applications. This gap prevents the inclusion of sEMG applications into clinical practice guidelines (2–7).

In developing countries, such as Chile, high inequities in per-capita income determine the quality and opportunity of health care. Combined with a centralized distribution of high-complexity health centers and specialists, these factors create a scenario where only high-impact and cost-effective interventions are applied. Therefore, potentially useful but non-critical tools—such as sEMG—are usually left outside the clinical armamentarium.

The underrepresentation of sEMG in clinical guidelines determines that in rehabilitation careers, these topics are either not routinely taught, or maybe included in theoretical courses (i.e., movement control, muscle physiology) but not in clinical internships. These might be substantial reasons that explain why rehabilitation professionals do not routinely use sEMG in their practice (8).

Another barrier to the widespread use of sEMG in developing countries may simply be the accessibility (i.e., cost, availability, portability) of the current EMG devices. Thus, we explore and compare the characteristics of several devices to shed some light on this topic.

SOCIOECONOMIC ASPECTS

In developing countries, such as Chile, there are substantial barriers that impact health care access. The high inequity in income distribution determines the opportunity and quality of health care. For example, the Gini index, which measures income-distribution inequality (0: perfect equity, to 100: perfect inequity), shows that Chile scores 44.4 (9), placing it at the percentile 84 worldwide.

Public spending on health is also low. The Domestic General Government Health Expenditure index (10) shows that in 2017 Chile spent 4.5% of its GDP in health, placing it in the percentile 74 worldwide. Other countries in the region such as Argentina and Brazil spent 6.6 and 4%, respectively. Compared to Sweden (9.2%), Finland (7.1%), and Norway (8.9%), our expenditure places us far from developed countries.

Additionally, high-complexity health care centers and specialists are located mostly in the capital (11). According to the health department of the Chilean government (www.minsal.cl), there are currently 23 high-complexity (type 1), and 37 medium-high (type 2) hospitals in the country. According to our 2017 census, the current population is 17.5 million people. Considering that roughly 80% of this population is cared for by the public system, this implies that each of these centers has to take care of about 230,000 people.

These complex and intermingled factors create a scenario where health policies favor mostly high-impact and cost-effective interventions. For example, for 80 high-prevalence pathologies, the chilean government warrants access to diagnostic tools and treatments for which there is sufficient evidence of cost-effectiveness (12). As a particular case, for the treatment of acute ischemic stroke our public health system provides state of the art treatment (2) in many centers. Although expensive, there is enough evidence supporting the investment of our limited resources in such cost-effective interventions.

TRANSLATION OF sEMG LITERATURE INTO CLINICAL GUIDELINES

During the last three decades, evidence-based medicine (EBM) has encouraged the testing of many procedures and interventions that were routinely prescribed but not clinically proven (13). Based on the best available evidence, many clinical societies have produced guidelines that establish levels of recommendations for different interventions. Therefore those tests, protocols, or treatments that reliably lead to good outcomes are highly recommended over those whose applications do not provide a benefit or even harm (2, 14).

In the case of sEMG, a growing number of publications have explored its use in gait analysis (15, 16), muscle fatigue (17, 18), low-back pain (19, 20), muscle activity onset latency (21, 22), ankle instability (21), and techniques of analysis (23), just to name a few. Although sEMG is essential for the understanding of neuromuscular physiology and dysfunction, the scarcity of literature demonstrating that it is instrumental for reaching favorable clinical outcomes has prevented its general inclusion in EBM guidelines and might be one of the main barriers for its widespread use in clinical practice.

As we discussed earlier, developing countries, such as Chile, favor high cost-effective approaches, which poses considerable obstacles in applying potentially effective but unproven tools.

sEMG as a Tool for Therapy: Pearls and Pitfalls

As we previously discussed, sEMG has been an essential tool to understand the neuromuscular system; nevertheless, it has also been long employed as a tool for therapy in the form of biofeedback (24) to treat a number of conditions. In dysphagia, it has been used as an adjunctive treatment to standard therapy, where it increases the displacement of hyoid and the laryngeal elevation, increases myoelectrical activity, and improves swallowing (25, 26). In post-stroke motor deficits, it has been employed in the rehabilitation of upper and lower extremities. In the upper extremity, when compared to standard therapy, it improves motor scores, but not independence scores (FIM) (27). In the lower extremity, it improves the range of motion and clinical scores of impairment, although it is not clearly superior to standard therapy alone (28). In cervical and shoulder pain, the telerehabilitation treatment with EMG-BF has been shown to be at least as effective as conventional therapy in reducing pain scores (29). It also has been explored in the context

TABLE 1 | Summary results of a simple analysis of the presence of electromyography-related keywords ("Electromiografía," "Instrumentación," "bioinstrumentación," "EMG," and "sEMG") in the curricula of eight PT careers.

Number of PT curriculums analyzed	8
Number of PT students in the analyzed schools/Number of nationwide PT students	4,292/20,306 (21.1%)
Percentile of the national ranking of the PT schools' Universities included in this analysis	A: 1.4, B: 22.5, C: 7.0, D: 3.5, E: 29.6, F: 26.1, G: 33.1, and H: 31.7
Distribution of the percentiles of national rankings of the PT schools' Universities included in this analysis	Whitin percentile 10:3 Whitin percentile 25:4 Whitin percentile 50:8
Number of PT schools where any of the keywords are mentioned in the curriculum	5
Number of PT students from the sampled schools exposed to any EMG-related content/Number of PT students in the analyzed schools	3,780/4,292 (88.1%)
Number of courses where any of the keywords were mentioned/Total number of courses	A: 1/29, B: 1/60, C: 1/38, D: 2/51, and E: 3/69
Number of introductory or theoretical courses where any of the keywords are mentioned/Total number of courses in the first 3 years	A: 1/14, B: 1/39, C: 1/24, D: 2/36, and E: 3/39
Number of clinical oriented courses and internship where any of the keywords are mentioned/Total number of clinical or internship courses	A: 0/15, B: 0/21, C: 0/14, D: 0/15, and E: 0/30

PT, physical therapy. The letters in the third to fifth row refer to the curriculum of different schools. The number of students for the year 2019 was obtained from https://www.mifuturo.cl/bases-de-datos-de-matriculados/.

of sleep bruxism, where it showed that using EMG-BF during the day produced a decrease in the amplitude of myoelectrical activity of masticatory muscles during sleep, although the impact of this finding in clinical outcomes is not clear (30). In a pelvic floor musculature training and education program, the group receiving EMG-BF training was found to have a better quality of life. Nevertheless, the control group did not receive any therapy, which prevents obtaining stronger conclusions (31). In spinal cord injury, the use of EMG-BF as part of the rehabilitation protocol, leads to higher levels of muscle activation when requesting an elbow flexion. Also, patients reported higher levels of motivation during therapy and considered it as a useful and valuable tool (32).

One of the main difficulties with the application of sEMG in this context is that the pooled evidence does not offer reliable supporting results, which has been reflected in clinical guidelines and, therefore, in clinical practice.

For example, a 2007 meta-analysis of 13 studies on EMG-BF for post-stroke rehabilitation (33) showed that the analyzed evidence was not sufficient to conclude that it provided an extra benefit over standard therapy in the recovery of stroke patients. A 2014 meta-analysis examined the evidence of several physical-therapy interventions in the recovery of stroke (34). Among those interventions, it assessed EMG-BF in the context of upper and lower limb function and gait. Although there is a tendency for a positive effect, the pooled analysis revealed that it does not add to the standard therapy. These data have crystallized into clinical guidelines such as the Canadian "Evidence-Based Review of Stroke" (4) or the American Heart Association guidelines on stroke rehabilitation (2), which do not offer strong recommendations for the use of EMG-BF for stroke rehabilitation.

Reasons for the failure of these meta-analysis are explained by high study heterogeneity (33), small sample sizes (26–28), lack of electrode placement description, which may not correspond to current standards (35, 36); and finally, an inability to reach a certain level on therapy intensity, which is decisive for obtaining significant outcomes (37–40).

Despite being successfully used in several fields, there has been limited pooling of data or systematic reviews of EMG-BF for interventions. The lack of demonstrated effect size resulting from this is a barrier for the implementation of this tool in clinical use.

sEMG TRAINING IN CHILEAN PHYSICAL THERAPY SCHOOLS

Surface electromyography offers several benefits to rehabilitation professionals, nevertheless, its lack of widespread use may also be explained by insufficient training. To approach this question, we contacted 17 physical therapy (PT) schools, and eight sent us the curricula from their career. These account for 21.1% of the PT students of the country (4,292 of 20,306). As a means to approach the level of influence these schools exert in the local educational landscape, we report the national ranking of the schools' Universities (**Table 1**) (41). By using a python script, we searched for the keywords "electromiografía," "instrumentación," "EMG," and "sEMG." Candidate courses were manually checked by the authors and were only included if the keywords appeared in the contents but not under different headings, such as "bibliography" or "suggested readings." None of the collected course programs mentioned the number of hours or credits devoted to each of the contents, thus, approaching the time spent on electromyography-related content was not possible.

We first counted the number of curricula in which at least one course mentioned any of the keywords. This simple approach revealed that five out of eight curricula met these criteria (**Table 1**). These curricula account for 3,780 students in the country.

The total number of courses where EMG contents are present might be a loose proxy for the amount of training on this technique. Accordingly, for each curriculum with at least one

TABLE 2 | Description of solutions.

Company	Model	Cost	Link	Portability	Affordable	Ease of use
Advancer Technologies	Myoware	USD 37.99	http://www.advancertechnologies.com/p/myoware.html	Yes	Yes	No (requires additional hardware)
EMG One	EMG One	USD 410	http://waves-tech.cl	Yes	Yes	Yes
Athos	Athos	USD 348	https://shop.liveathos.com/	Yes	Yes	Yes
Shimmer technology	Shimmer3 Consensys EMG Development Kit	USD 534	http://www.shimmersensing.com/products/emg-develop-kit	Yes	Yes	Yes
OT-Bioelettronica	Forza, Duelite	∼USD 948–1,422	https://www.otbioelettronica.it/en/products/hardware/item/101-quattrocento-en	Yes	Yes ❖	Yes
mTrigger	mTrigger Biofeedback	USD 399–1.099	https://www.mtrigger.com/	Yes	Yes ❖	Yes
BTS Bioengineering	Freeemg	∼USD 20.000	https://www.btsbioengineering.com/products/freeemg-surface-emg-semg/	No	No	No (Tethered)
Noraxon	Ultium EMG	∼USD 20.000	https://www.noraxon.com/our-products/ultium-emg/#1541097720904-fe85b033-bd50	No	No	No
Delsys	Trigno	∼USD 20.000	www.delsys.com	No	No	Yes
MyMyo Science	MyMyo	NA	http://mymyo.science/	Yes	Yes?☩	Yes
Cometa	PicoEmg	NA	https://www.cometasystems.com/products/picoemg	Yes	No	Yes
Myon	Aktos	NA	https://www.myon.ch/aktos	No	No	Yes

NA, not available. ❖depends on the model. ☩ probably affordable, cost not available.

EMG course, we counted the number of courses in which any of the keywords above were present. This approach resulted in a mode of one course per career mentioning any of the keywords (**Table 1**).

Finally, during the internship, the PT student is placed in a real clinical environment that shapes the repertoire of techniques that he or she will use as a professional therapist. Hence, the presence of sEMG content on these clinical internships might be crucial for the use of this technique as a future PT. We found that none of the internships and clinical oriented courses mentioned any EMG-related content in their description (**Table 1**). Thus, sEMG training is not provided in all the PT schools, and is taught only in courses that take place during the first 3 years, but not during clinical internships (**Table 1**).

EMG DEVICES

Considering all the barriers to successfully applying sEMG to the clinical practice, a shortage of accessible EMG devices may add another barrier to its use. Here, we consider accessibility as the combination of portability, affordability, and ease of use of a particular EMG device. We define these criteria as follows:

- Portability: the device has a small size (pocket size, or hand-held device size), can be easily carried to different locations, has internal batteries, and does not require a computer for operation.
- Affordable: considering that one of the main end-users of these systems may be the physical therapist, we defined this term based on the average monthly income before taxes (AMI) of a Chilean PT. We chose this parameter because, in their clinical practice, many PTs have to purchase their own equipment. The official statistics indicate that the 1st year after school, the AMI is U$740, and during the 5th year after graduation, it rises to U$1,330 (42). Therefore USD 1,000 seemed like a reasonable threshold.
- Ease of use: all the necessary elements (hardware, software) are provided, and is compatible with smartphones or tablets (obtained from brochures or website descriptions).

The results are described in **Table 2**. Some of the devices found are expensive and more suited for research (BTS, Noraxon, Delsys, and Bioelettronica). On the other hand, the most inexpensive one, the Myowave, requires buying additional hardware (i.e., an Arduino board) and programming skills. Thus it is not suited for immediate clinical use.

We were pleased to find that at least four devices met all the predefined criteria, which provides the technical means to use sEMG directly in the office. This finding suggests that EMG device accessibility would not necessarily mean a barrier for the use of sEMG.

Finally, another issue could be related to the cost of electrodes, which may impose another barrier. Nevertheless, for most of the applications, either disposable (∼U$0.15/piece) or reusable (∼U$0.40/piece) electrodes do not constitute a substantial obstacle for using sEMG (reference prices obtained from amazon.com).

CONCLUSIONS

Based on available information and personal insights, we have discussed some of the barriers to the use of sEMG that might be relevant in a developing country such as Chile. Several socioeconomic, and political aspects of our country determine that health policies favor those interventions that are highly cost-effective. The failure of the literature to translate into decisive outcomes has kept sEMG restricted mostly to research. To open a path for the inclusion of sEMG into clinical guidelines that recommend it as a necessity and not only as a complementary tool, it will be necessary to produce well designed and outcome-guided studies that also attain clinical standards. This will lead to results suitable for pooling into a meta-analysis, which may influence contexts that favor cost-effectiveness.

Who should generate this research? We think that this type of literature can arise more easily from transdisciplinary teams of clinical professionals (physicians, physical therapists, speech therapists, etc.) and developers (engineers, designers, etc.), in which the patients are at the very center of their activity. Clinicians may perfectly understand patients' problems, but without help from engineers, they will not be able to solve them. On the other hand, engineers and designers that are not connected to a clinical setting may create solutions that are either too complex or too difficult to implement and do not necessarily solve practical problems. In either case, the patients' particular needs are left unmet. We think that these types of interactions are probably the best remedy to transform problems and needs into meaningful solutions and to advance the research on sEMG.

In a different vein, our analysis of the curricula from Chilean PT schools, confirmed our suspicion of a lack of training in this area. In the schools with EMG training, this is taught mainly in one or two courses during the entire career, and the training takes place at the beginning of the career but not in the clinical internships, which may explain why PTs do not regularly use sEMG in their practice.

Regarding the accessibility of sEMG devices, we found that at least four devices met predefined criteria of being portable, affordable, and easy to operate. This suggests that accessibility or price does not constitute in itself a barrier for the use of sEMG in the clinical practice and that the main limitations arise from political and economic characteristics of the country, from a paucity of compelling clinical indications, and from an insufficient amount of training.

Finally, some of the barriers for the use of sEMG in the clinical domain may interact with each other in a circular manner, for example, the paucity of clinical evidence and the view of sEMG only as biofeedback may create insufficient pressure for both the development of health policies and for the training of rehabilitation professionals in sEMG. This insufficient training leads to an insufficient mass of professionals using sEMG, which leads to fewer grant applications and less research in the area, which leads us to the starting point. Also, there could be insufficient teaching dedicated to instrumentation or on technologies for rehabilitation. These types of courses could broaden the view on interventions and techniques that could enrich the clinical practice of rehabilitation professionals.

Therefore, we think there is a need for more high-quality clinical evidence that presents an unavoidable pressure to employ this technique. There is a need for advancing the training not only in PT schools, but also in speech therapy and occupational therapy as well. A critical mass of professionals trained on these techniques backed up by sufficient clinical evidence may create the perfect scenario for the massive use of surface electromyography.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://data.worldbank.org/indicator/SI.POV.GINI, https://data.worldbank.org/indicator/SH.XPD.GHED.GD.ZS, https://www.mifuturo.cl/buscador-de-estadisticas-por-carrera.

AUTHOR CONTRIBUTIONS

JA-R and HM-V contributed equally to the manuscript and approved the submitted version. All authors contributed to the article and approved the submitted version.

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Use of Surface EMG in Clinical Rehabilitation of Individuals With SCI: Barriers and Future Considerations

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Surface electromyography (sEMG) is a widely used technology in rehabilitation research and provides quantifiable information on the myoelectric output of a muscle. In this perspective, we discuss the barriers which have restricted the wide-spread use of sEMG in clinical rehabilitation of individuals with spinal cord injury (SCI). One of the major obstacles is integrating the time-consuming aspects of sEMG in the already demanding schedule of physical therapists, occupational therapists, and other clinicians. From the clinicians' perspective, the lack of confidence to use sEMG technology is also apparent due to their limited exposure to the sEMG technology and possibly limited mathematical foundation through educational and professional curricula. Several technical challenges include the limited technology-transfer of ever-evolving knowledge from sEMG research into the off-the-shelf EMG systems, lack of demand from the clinicians for systems with advanced features, lack of user-friendly intuitive interfaces, and the need for a multidisciplinary approach for accurate handling and interpretation of data. We also discuss the challenges in the application and interpretation of sEMG that are specific to SCI, which are characterized by non-standardized approaches in recording and interpretation of EMGs due to the physiological and structural state of the spinal cord. Addressing the current barriers will require a collaborative, interdisciplinary, and unified approach. The most relevant steps could include enhancing user-experience for students pursuing clinical education through revised curricula through sEMG-based case studies/projects, hands-on involvement in the research, and formation of a common platform for clinicians and technicians for self-education and knowledge share.

Keywords: spinal cord injury (SCI), electromyography (EMG), EMG barriers, biomedical signal processing, clinical rehabilitation, high-density EMG

INTRODUCTION

The current state-of-the-art rehabilitation for individuals with spinal cord injuries (SCI) utilizes technologies such as neuromodulation using exoskeleton robotics, functional electrical stimulation (FES), treadmill training with and without body-weight support (BWS) in addition to the traditional exercise-based rehabilitation. The recent developments in neurorehabilitation research and technologies have resulted in a shift in focus toward the recovery of function through high intensity repetitive training after SCI (1). Some of the technologies such as epidural or transcutaneous spinal stimulation, robotic exoskeletons are currently under investigation while techniques such as FES (e.g., FES cycling, rowing) (2) and treadmill training using BWS (3) are commonly used in clinics to assist with the functional tasks such as respiration, mobility, hand function, metabolism, bladder, bowel or sexual function (2, 4, 5). Irrespective of the intervention approach used, the functional status as well as the evolutions of motor impairments and motor recovery are often tracked by visual and manual assessments in the clinic. To date, the primary method for evaluating the motor function for SCI is the American Spinal Injury Association Impairment Scale (AIS), which tests manual muscle strength in five key muscles in each limb and examines sensory function (6). Although easy to perform, such approaches are subjective and not sensitive to understanding the changes at the neuromuscular levels. Particularly for the interventions that target the neuromuscular mechanisms via application of electrical stimulation to the nerves, or peripheral musculature, the objective and quantifiable information on the myoelectric output of targeted muscles is highly relevant. For instance, when a clinician uses FES -the technique that involves the application of electrical current to the neuromuscular junction and cause contractions in paralyzed muscles (7)- it is clinically desirable to evaluate the resultant myoelectric output of the stimulated muscle. The questions such as "is the stimulation intensity sufficient to induce the desired contraction for the targeted movement?" "is the stimulation causing the targeted muscle to fatigue?" or "are the selected parameters appropriate for the patient to perform the desired task?" become highly relevant to the clinician to deliver patient-specific and effective interventions. Such questions are highly significant for any intervention that targets mobility and motor rehabilitation.

Surface electromyography (sEMG), a non-invasive technique for assessing the myoelectric output of a muscle, can provide objective answers to these significant questions. sEMG has shown great promise in neurorehabilitation research and has been a widely-utilized tool to assess neuromuscular outcomes in research (8). However, the application of sEMG in a clinical environment has been limited (9). The clinicians' perspectives on the use of sEMG have reported several barriers including limited time and resources, clinically inapplicable sEMG system features and the majority of clinicians' lack of training and/or confidence in utilization of sEMG technology (10, 11). In the domain of the SCI population, in addition to the aforementioned challenges of using sEMG in the clinic, severely impaired physiological and structural state of the spinal cord after SCI (compared to other pathologies such as stroke, traumatic brain injury, multiple sclerosis, etc.) further limits sEMG usage to provide time-efficient, meaningful interpretations. In this perspective report, we discuss these barriers and the directions toward overcoming these limitations that hinder the widespread use of sEMG technology in the clinical rehabilitation of individuals with SCI.

BARRIERS IN THE USE OF sEMG IN SCI NEUROREHABILITATION

General Barriers to Use sEMG in a Clinical Setting

Several barriers can be identified that restrict the adoption of sEMG technology in a clinical environment.

Lack of Information at Motor Unit (MU) Level

Needle EMG (nEMG) and fine wire EMG (fwEMG) are the invasive forms of EMG for accessing neurophysiological attributes of neuromuscular diseases. However, the invasiveness, discomfort, and limited applicability of these techniques on multiple muscles during dynamic tasks limit their use in the clinic. Nonetheless, nEMG still is gold standard for clinical diagnosis of nerve and muscle pathologies and preferred over non-invasive sEMG (12) for neurophysiological applications. This is because of the limited spatial resolution of sEMG that results in poor fidelity recordings of high-frequency signals (e.g., polyphasic potentials, fibrillation potentials, and positive sharp waves) (12). In addition, the electrical cross-talk between two or more neighboring muscles restricts the sEMG to identify the origin of the electrical signal when these muscles are active simultaneously (12). Further, the sEMG recorded from a muscle does not yield a non-ambiguous extraction of single MU information. As a result, the report of the therapeutics and technology assessment subcommittee of the American Academy of Neurology reported the sEMG technique unusable for clinical neurophysiological purposes (13). While the bipolar sEMG is used to measure muscle activations, the advent of high-density surface EMG (HDEMG) has made the extraction of MU features possible (14–16). Availability of such a sensitive tool is even more significant for individuals with clinically diagnosed motor and sensory complete SCI who do not have intact reflexes and who may still have intact neuronal axons across the injury lesion (17). However, in order to accomplish this, a careful application of sEMG decomposition and expertise in signal acquisition, interpretation of results, and manual assessment of decomposition quality is required (14–16). Further, the examination of the Motor Unit Number Index (MUNIX) in paralyzed muscles has been implemented to monitor MU loss after SCI (18). However, this approach requires intense experimental and computational setup, and specific selection criteria which may not be clinically feasible.

Lack of Available Time for a Clinician

A study collected perspectives of 22 clinicians [physical therapists (PT), occupational therapists (OT), and physiatrists] and reported limited clinician time as one of the barriers to the uptake of sEMG technology in clinics (11). The time-consuming aspect of sEMG technology presents a significant barrier to its translation into clinical practices. Electrodes and skin preparations, electrode placements, equipment setup, collecting maximal volitional contractions (MVC) for normalization prior to recording the data during activities of interest take significant time. **Figure 1** illustrates the sEMG placements for recording of lower extremity responses from an individual with an SCI.

FIGURE 1 | An EMG set up for assessing neuromuscular responses prior to a rehabilitation intervention for an individual with SCI.

Balancing a busy work schedule has been reported as one of the barriers to caring for patients, particularly for novice PTs (19). Therefore, the acceptance of sEMG technology that requires significant prep-time is low as the added time could adversely affect PT performance and care in the clinic.

Limited Background and Training Through Professional Curricula

Most of the PT and OT programs offer wide-ranging coursework in the rehabilitation domain including human anatomy, neuroscience, biomechanics, kinesiology, movement analysis, evidence-based practice, pharmacological interventions, etc. Irrespective of the breadth of topics covered, there is minimal focus on the technological aspects of rehabilitation. As a result, rehabilitation tools such as sEMG are theoretically taught, but practical knowledge imparted is limited. Further, the educational content may not cover ever-evolving aspects of sEMG technology and its applications. Feldner et al. reported that many clinicians felt less confident to use sEMG in clinics due to their limited experience (11). According to the study, newer clinicians pointed the "need for practice" and the seasoned clinicians weren't "tech savvy," making the clinical adoption of sEMG technology difficult (11). However, one limitation of this survey was the limited geographical spread of the clinicians who participated as they were recruited from rehabilitation settings within the Seattle metropolitan area (WA, USA). In a more recent survey by Manca et al., 35 EMG experts from different educational, professional and geographical backgrounds supported the clinical utility of sEMG for optimizing the quantification of muscle and physical function, to define the intervention plan, and optimize other methods used to quantify muscle and physical function (20). However, the collective opinion of these experts also confirmed the utilization of sEMG was more common in technical/methodological research than clinical research (20). The barriers that prevent prompt transfer of sEMG into practice were reported to be slow dissemination of research findings and the lack of education on sEMG (20). Further, successful adoption of any technology in the clinic not only involves collecting the information/data but also helps in making data-driven clinical decisions in functional diagnosis, recommending appropriate interventions, and optimizing the rehabilitation outcomes. In terms of sEMG, the processing and interpretation of the data require a multidisciplinary approach. This involves the working knowledge of several technical domains such as instrumentation, signal processing and analysis, algorithm development, and statistical analyses. The availability of such expertise can be challenging in a clinical setting. Identifying the experts with such a skillset and establishing collaborations could be time-consuming, and impractical for daily-workflow at the clinic. If a clinician wants to gain the necessary working knowledge on sEMG technology, there is no centralized knowledge-base where clinicians can, not only develop their understanding of sEMG procedures and data analyses but also interact with other clinicians and researchers in this specific domain to share ideas, discuss outcomes and even collaborate at the institutional levels. The training and education of teachers who are educating future clinicians is another important factor. In many countries where there are no doctoral-level programs in rehabilitation or physiotherapy, there is a scarcity of academic professors with doctorate-level credentials. Therefore, the educational experience of students in such countries may lack rigor, practical exposure to the technology, and the state-of-the-art information on sEMG practices and guidelines.

Lack of Technology Transfer From Research to Clinic

The field of sEMG is always evolving and new algorithms for sEMG processing, analysis, and classifications are continuously being developed. However, the rate at which these technological advances are frequently integrated into the existing sEMG systems is limited. For instance, many of the existing off-the-shelf sEMG systems have not gone beyond implementing the basic sEMG features such as mean and root-mean-square (RMS) amplitudes, moving average or RMS envelopes, basic filtering and rectifications, and basic Fourier-based analysis. Automatic burst or ON-OFF detections, activation timing analyses, signal decomposition, and time-frequency analyses are widely published (21–25) and accepted EMG analysis techniques that have not been integrated into most of the commercial systems; as a result, these techniques have not been transferred from research to clinic. This issue stems from lack of education or training on the application of such analysis methods in a clinical setting, resulting in virtually no demand for a commercial

EMG system with these capabilities, which in turn creates an insignificant market to manufacture such EMG devices. Therefore, the absence of commercial pressure further limits the development of said devices and education of operators to ultimately transfer research findings into the clinic.

Institutional Level Barriers

In addition to the sEMG setup time, other challenges hinder the adoption of sEMG technology in the clinic. Such barriers include the functionality in multiple environments, portability, the facility layout, purchasing cost and maintenance, providing evidence to support returns on such investments, and staff training.

Barriers Specific to the SCI Population

The need for assessing neuromuscular responses is highly significant for individuals with SCI, particularly motor complete SCI (cSCI). Studies have demonstrated the presence of intact neuronal axons across the lesion, even after cSCI (17). For instance, Calancie et al. (26) reported retained voluntary EMG control over one muscle in the foot in a small group of participants classified as motor complete. These findings highlight the significance of the ability to monitor neuromuscular responses during neuromuscular electrical stimulation (NMES) for cSCI for whom any functional and motor-related changes may not be apparent, while intrinsic electrophysiological changes and residual volitional neuromuscular drive may still be present. In evaluating the efficacy of any clinical therapy, the effects may not be visible at the functional or biomechanical levels but changes could be present at the neuromuscular level. Therefore, assessing neuromuscular output is critical to optimize the effects of any rehabilitation intervention for SCI. Currently, there are no standardized procedures for processing and interpreting sEMG data specific to the cSCI population; this may have vastly contributed to the diverse sEMG interpretations and/or continued reliance on outcome measures, such as force and torque. In addition, the lack of standards for sensors, configurations, electrode placement, and recording protocols has adversely affected the possibility of its integration into routine clinical use (9). Despite the 20-year presence of the EU project on "Surface EMG for Non-Invasive Assessment of Muscles (SENIAM)," real international standards are still missing (10). The diminished or weaker sEMG signals yield limited consensus on answers to the most basic questions such as, "*is the muscle active?*" "*what is the strength of the activation?*" or more complicated ones such as, "*what is the volitional contribution and how it relates to the applied stimuli during electrically induced activations?*" Answers to such questions remain unclear as there is no standardized approach to first process and then interpret such data. The existing off-the-shelf systems are not specifically tuned to address these SCI-specific challenges. For example, the most significant barrier in using sEMG during FES is interpreting the recorded sEMG signals due to the overpowering presence of stimulation artifact. The stimulation artifact is a broadband signal with widespread stimulation frequency harmonics at high amplitudes that engulf the myoelectric responses in sEMG. Particularly when a train of ES pulses is applied, the sEMG recordings are accompanied by ES artifact spikes with magnitudes that are manifold compared to the actual MU outputs. Moreover, the presence of stimulation artifact is not confined in the time-domain; it is also observed in the frequency domain. The harmonics of stimulation frequency overlap with the majority of the energy bands in a typical sEMG frequency spectrum (20–350 Hz). As a result, traditional selected-filtering of frequency bands, to remove ES artifacts, is ineffective and results in significant data loss (23). The ES artifact affects features derived from the sEMG signal; for instance, it biases conduction velocity estimations, spectral characteristic frequencies, and M-wave amplitudes (27). In the domain of SCI rehabilitation, where ES waveforms are often delivered as bursts (train of pulses) with high intensities and wide-ranging frequencies, the resultant contamination of sEMG recordings obstructs the understanding of the direct implication of FES on the neuromuscular output in terms of activation intensity (voluntary or ES induced), MU recruitment, and muscle fatigue. This is particularly impeding in studies where FES is combined with volitional efforts that need to be monitored or modulated in real-time to achieve optimal outcomes.

FUTURE DIRECTIONS

Rehabilitation professionals' acceptance and adoption of technologies rely on conditions that facilitate their use such as scheduling, support and a conductive environment (28). The following are the steps toward achieving these key aspects of sEMG utilization in the clinical neurorehabilitation.

Enhancing Knowledge and User-Experience

In order to ensure all rehabilitation professionals, especially clinicians, get an early exposure to the sEMG technology, the educational and professional training programs could integrate hands-on sEMG experience through case studies or small research projects. The clinicians could also enhance their involvement in ongoing sEMG-related research activities and get exposed to the several practical aspects of sEMG through interactions with their non-clinical counterparts (e.g., engineers, technicians, data scientists). The interfaces running the EMG data collection and processing algorithms with minimal user inputs could be beneficial for their widespread implementations. Another goal could be set to successfully transfer EMG-related research products (data collection, processing and analysis algorithms) into a clinical environment. Irrespective of the programming platforms (Matlab, Python, etc.) on which these algorithms are built upon, simple user-interfaces, application programming interfaces (APIs) and/or open-source executables can be created for their unobstructive and intuitive use by the clinicians with non-technical backgrounds. A centralized knowledge-base can be used to create and disseminate the sEMG tutorials on topics ranging from the basics of sEMG technology to step-by-step guidelines for data processing. Such a centralized open-source platform can also facilitate the collaborations among investigators and sEMG users with overlapping interests. With the help of well-established societies such as International Society of Electromyography and Kinesiology (ISEK), IEEE

Engineering in Medicine and Biology Society (EMBS), Society for Neuroscience (SFN), and several societies of clinical motion analysis [Gait Clinical Movement Analysis Society (GCMAS), the European Society for Movement Analysis in Adults and Children (ESMAC), Societa' Italiana di Analisi del Movimento in Clinica (SIAMOC) etc.], the long-term goal can be set to developing international scientific meetings or chapters specific to sEMG applications in specific rehabilitation domain (e.g., FES) where the specific pool of researchers can meet, share knowledge and collaborate. In recent years, efforts have been made to provide open-access tutorials and consensus articles on sEMG-related best practices, such as the consensus standards and guidelines on the sEMG detection (29), sEMG signal conditioning and preprocessing (30), and analysis of MU discharge characteristics using HDEMG (14). *The Consensus for Experimental Design in Electromyography (CEDE)* project, an international initiative which aims to guide decision-making in recording, analysis, and interpretation of sEMG have published the guidelines on the sEMG electrode selection and amplitude normalization (31, 32). Despite of these past and present efforts, these well-accepted guidelines, procedures and standards are not known to many clinicians. The paradigm shift in transferring such significant knowledge to clinic is only possible when the new generations of students pursuing education and professional training in clinical rehabilitation (e.g., PT, PTA, MPT, DPT, DScPT, PhD) are taught these "best practices in sEMG" by qualified teachers.

EMG for Real-Time Monitoring and Biofeedback During Rehabilitation

The instantaneous quantification of muscle response can serve as an important marker to track the impairment as well as recovery during rehabilitation. With access to the EMG in real-time, the clinicians or researchers can quantify, track, and manipulate levels of voluntary efforts by modulating intervention parameters. For example, if a clinician observes that the FES frequency of 100 Hz is causing a muscle to fatigue faster with less voluntary participation (shown by EMG features such as amplitude), s(he) could change to a lower stimulation frequency, which could potentially increase voluntary contribution and reduce fatigue due to stimulation, thus making the session still productive. Such modulations could happen simply by patient's own feedback on fatigue but the data-driven nature of this decision making could make the training more objective, patient-specific, safe and less *ad hoc*. This could result in more effective interventions for better long-term benefits.

A Ranking System for Standardization of EMG Interpretations for the SCI

Motivated by the ranking system provided by Heald et al. (17), a standardized sEMG ranking system can be developed to quantify the state of the residual neuromuscular output, especially during FES-based rehabilitation for SCI. For example, *Rank 1 – sEMG signal can be classified as no activity, baseline noise*; *Rank 2 – Sparse MU action potentials*; *Rank 3 – Burst of activity but no clear correlation to stimulation profile (e.g., FES, etc.)*; *Rank 4 – Burst of activity with partial correlation to stimulation*; *Rank 5 – Repeated burst of visible activity that is significantly correlated with applied stimulation*. Ranking procedures can be validated by visual inspection as well as automated, software-driven inspections. Such a standardized approach can track progress during or after different interventions. Once accepted and implemented, common standardized outcomes would enable comparing different interventions for efficacy.

The Potential Impact on the Rehabilitation Costs for SCI

For many of the SCI patients, functional or motor changes may not be present but electrophysiological changes or residual voluntary muscle activations may still be present (17, 26, 33, 34). If a clinician cannot directly track the volitional efforts or functional improvements, then medical reimbursement is suspended after only a few weeks with no ultimate benefit to the participant. If sEMGs show the neuromuscular changes during an intervention for individuals with SCI with no changes in functional status, researchers and clinicians can still continue with ongoing interventions and anticipate better outcomes. On the other hand, investing in expensive interventions for several months for non-responders is a financial liability. Thus, sensitive and reliable measures of neuromuscular recovery, designed specifically for the spectrum of SCI-induced deficits can lead to long-term functional improvement that would have a dramatic impact both on the quality of life and financial liability for those suffering from SCI.

In summary, addressing the current barriers in widespread use of sEMG in SCI rehabilitation will require a collaborative, interdisciplinary, and unified approach. Nonetheless, sEMG technology has the potential to present significant opportunities that can allow clinicians and researchers to transform future interventions into effective and impactful rehabilitation modalities for individuals with SCI.

DATA AVAILABILITY STATEMENT

The data sharing will be contingent upon the regulations applied by the funding agency. Requests to access the datasets should be directed to rpilkar@kesslerfoundation.org.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Kessler Foundation Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

RP and KM drafted the manuscript. All authors contributed to the revisions.

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Muscle Activity After Stroke: Perspectives on Deploying Surface Electromyography in Acute Care

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After a stroke, clinicians and patients struggle to determine if and when muscle activity and movement will return. Surface electromyography (EMG) provides a non-invasive window into the nervous system that can be used to monitor muscle activity, but is rarely used in acute care. In this perspective paper, we share our experiences deploying EMG in the clinic to monitor stroke survivors. Our experiences have demonstrated that deploying EMG in acute care is both feasible and useful. We found that current technology can be used to comfortably and non-obtrusively monitor muscle activity, even for patients with no detectable muscle activity by traditional clinical assessments. Monitoring with EMG may help clinicians quantify muscle activity, track recovery, and inform rehabilitation. With further research, we perceive opportunities in using EMG to inform prognosis, enable biofeedback training, and provide metrics necessary for supporting and justifying care. To leverage these opportunities, we have identified important technical challenges and clinical barriers that need to be addressed. Affordable wireless EMG system that can provide high-quality data with comfortable, secure interfaces that can be worn for extended periods are needed. Data from these systems need to be quickly and automatically processed to create round-ready results that can be easily interpreted and used by the clinical team. We believe these challenges can be addressed by integrating and improving current methods and technology. Deploying EMG in the clinic can open new pathways to understanding and improving muscle activity and recovery for individuals with neurologic injury in acute care and beyond.

Keywords: electromyography, translation, stroke, arm, paralysis, data visualization

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INTRODUCTION

Every brain injury is unique—making individualized evaluations especially important for diagnosis and prognosis. For individuals who have had a stroke, impaired movement is one of the most persistent and disabling sequela, severely limiting participation, and quality of life (1–3). Many individuals initially have limited or no ability to move their limbs after stroke. However, determining when and if an individual will regain movement is challenging (4–6). Surface electromyography (EMG) provides a non-invasive window to observe neuromotor activity. By monitoring activity and observing resulting movements, we can evaluate the integrity of neuromotor pathways (7). The initial weeks after stroke are viewed as a critical period of neural plasticity and recovery (8), yet EMG is rarely deployed during this time.

In acute care, function-based clinical exams remain the standard for evaluating and monitoring muscle activity and movement. The Manual Muscle Test (MMT) and NIH Stroke Scale (NIHSS) are among the most common evaluation measures used in the United States. These measures are often performed daily in the hospital to track recovery and document outcomes for insurance purposes. Clinicians conduct these measures by asking individuals to attempt to voluntarily move specific body parts, assigning an ordinal score based upon observed movement or muscle activity felt by palpation (9–12). Members of the care team can conduct these exams quickly, but they are coarse measures that provide limited insight into the extent of injury or prognosis, especially for individuals with language barriers, receptive aphasia, neglect, or other impairments that limit ability to follow instructions. The Fugl-Meyer Assessment (FMA) expands the repertoire of movements to evaluate synergistic or other inappropriate muscle activity (13, 14). While the FMA has shown promise for predicting recovery and future function (15), it is not often used in the clinic due to the time and training required. Like the MMT and NIH Stroke Scale, it also has limited utility for individuals with impaired voluntary movement or difficulty following instructions. An ideal assessment tool to monitor muscle activity and movement after stroke would provide deeper insight into the quantity and quality of movement, while requiring minimal time to execute.

In the 1950s, clinicians like Thomas Twitchell deployed EMG to monitor muscle activity (16–19), but today EMG is mainly confined to research settings. Twitchell's detailed observations of EMG recordings from stroke survivors in acute care remain some of our most detailed descriptions of early muscle activity after stroke. Twitchell would not recognize today's sophisticated EMG systems (20). Large sensors and tangles of wires have been replaced by sleek, small packages that wirelessly transmit data from dry electrodes that make it easier to target and isolate activity from individual muscles. Material selection and electrode design continue to improve, such that EMG sensors can even be worn for multiple days with minimal impact on signal quality or skin health (21–23). One of the largest changes has come in our processing and analytic ability. We have replaced the chart recorders that Twitchell used with systems that easily capture and analyze recordings (24, 25). EMG sensors can also be integrated with other sensors, such as inertial measurement units (IMUs) that provide concurrent measurements of movement.

Despite all of the opportunities provided by this advancement, the translation of EMG to clinical care has been a slow process. In this paper, we share our team's perspective translating EMG into the clinic through a multidisciplinary collaboration between engineers and clinicians. Over the past two years, we have monitored muscle activity with adult stroke survivors within the first 5 days after stroke. This experience has shown our team that there are great opportunities in expanding the use of EMG in clinical care, but significant barriers that need to be overcome to facilitate this translation. We hope our experiences and lessons learned can support other teams attempting this translation and accelerate the use of EMG technology to advance care.

SURFACE EMG IN ACUTE CARE

"I think my finger moved today" is a phrase that many clinicians in acute stroke care or rehabilitation have heard from a stroke survivor. During the early weeks, movement can return rapidly and seemingly unexpectedly, which makes every twitch or sensation a potential positive sign (19). Clinicians and their patients often cannot definitively determine whether an individual voluntarily moved their arm or finger, or if there were changes compared to yesterday (26, 27). While a clinician cannot wait by the bedside, an EMG system can unobtrusively monitor muscle activity while the patient and clinical team continue with standard care. Of course, the acute setting presents unique challenges in deploying any technology (28). Large care teams work around the clock to coordinate and conduct numerous tests and procedures to address the initial injury and prevent further damage.

In our work to deploy EMG in this challenging environment, our team prioritized selecting an EMG system that provided wireless sensing in a compact form. The BioStampRC sensors (BioStampRC, MC10, Lexington, MA) included integrated EMG and accelerometer sensors that could concurrently monitor muscle activity and movement. We targeted the muscles most commonly assessed by the clinical team, placing sensors on five muscle groups: the deltoid, biceps, triceps, wrist flexors, and wrist extensors of the affected upper extremity (**Figure 1**). We followed SENIAM guidelines for placing the sensors, but often had to adjust to accommodate IV's, bandages, or telemetry pads. Loose skin, adipose tissue, and sweat were also common issues that impacted signal quality and sensor adherence.

We deployed these sensors with stroke survivors who demonstrated impaired arm movement (NIHSS > 1) at a level-one trauma hospital. Patients were excluded if they were on comfort care, but otherwise we had broad inclusion as our main goal was evaluating deployment of the technology and observing muscle activity of all stroke survivors. We recruited patients from the acute stroke unit, where some patients may have received initial care in the intensive care unit. At this hospital, most stroke survivors stay in acute care for <2 weeks, receiving daily evaluations and therapy, before being discharged to inpatient rehabilitation, a skilled nursing facility, or their home. Our primary objective was to evaluate whether muscle activity could be detected during acute stroke care. We were especially interested in determining whether EMG sensors could detect muscle activity for those patients classified as having dense hemiplegia or flaccidity, who could not participate or be evaluated with other clinical measures. For each patient, we collected up to four hours of data. We manually identified contractions for each muscle, marking the start and stop time and coding each contraction as during periods of movement or rest based upon concurrent accelerometer data. Details on the data collection, EMG processing, and analyses can be found in (29, 30) and (REF), while here we aim to share key experiences in deploying this technology.

For the patients we monitored, muscle contractions were detected from all five muscles during a single four hour collection period during standard care (**Figure 1**). This was true even for the

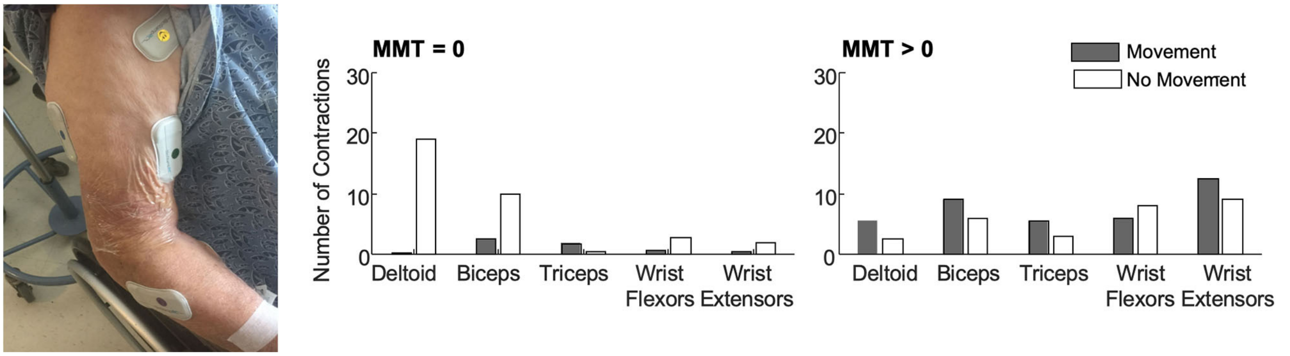

FIGURE 1 | (Left) BioStamp sensors provided a wireless and low-profile sensor to monitor muscle activity. We monitored muscle activity from five muscle groups on the paretic arm—the deltoid, biceps, triceps, wrist extensors, and wrist flexors. Tegaderm and Coband were placed over the electrodes to ensure they did not fall off or get stuck to bed sheets during 4 h of monitoring. The EMG data were used to evaluate outcome metrics like the median number of contractions (per 30-min of analyzed data) among patients with no observable muscle activity ($N = 11$, MMT = 0) and patients with some residual muscle activity ($N = 10$, MMT > 0). Accelerometer data were used to classify each contraction as occurring during periods with or without movement. **(Right)** Median number of contractions identified for each muscle with and without movement. Importantly, contractions were identified for all five muscles in all patients. For participants with MMT > 0, contractions were identified in all five muscles in a single 30-min monitoring session. Up to 3 h of monitoring was required to detect contractions in all five muscles for the participants with MMT = 0. As expected, participants with MMT > 0 had more contractions with movement. For participants with MMT = 0, contractions during movement likely reflect times when their arm was being moved during care. Participants with MMT = 0 also had more contractions in proximal muscle groups.

patients who had an MMT score of zero ($N = 11$), indicating no voluntary movement or muscle activity detected via palpation. For the participants with an MMT >0 ($N = 10$), only a single 30-min time window was required to identify contractions in all five muscles. For the patients who were initially flaccid, we did find moderate correlations between early contraction characteristics and scores on the MMT at follow-up. These findings indicate that muscle activity is present during the first week after stroke, even among participants characterized as flaccid, and EMG can provide quantitative metrics that may have prognostic value for predicting future function.

LESSONS LEARNED

Our experiences conducting this research presented several important lessons to inform translation of EMG into stroke rehabilitation. These lessons reflect the clinical realities of working in acute care, as well as opportunities to enhance care by using EMG for monitoring, diagnosis, or biofeedback. There are numerous technical and logistical hurdles that need to be overcome to take advantage of these opportunities—from sensor design to automated processing to clinician education. Deploying new technology in the clinic requires concerted and collaborative efforts, but can open new pathways for improving care and recovery.

Lesson 1: From Data to Unique Insights

While EMG provides compelling, quantitative metrics to monitor function and recovery, translating this technology into the clinic requires these data provide unique and compelling insights. There are numerous ways we believe EMG could enhance acute stroke care. Foremost, EMG may be useful for monitoring—allowing patients, families, and the care team to view daily updates on changes in muscle activity and movement. While the MMT can provide information about large-scale changes, the subtle changes we observed using EMG can be important for supporting patient motivation, providing evidence for discharge decisions (e.g., is progress being observed?), and determining eligibility for inpatient rehabilitation or other services.

Beyond monitoring, our clinical team and participants also suggested that real-time EMG data may be useful for biofeedback applications (31–33). Clinicians may use these data to enhance or supplement their clinical exams. Measures like the MMT rely on the clinician using palpation to try to detect muscle activity. If an EMG sensor was already on, the clinician could look at the live feed to quickly view and validate their observations. If a patient was struggling to understand the clinician's instructions, the EMG data could also be used to help them understand the desired action. These additions could improve the repeatability of these exams, which often have poor inter-rater and inter-session repeatability (9, 34). As one physical therapist imagined (35):

> "If I can't get them to do a certain movement, I'm like, 'Well, is there any activity in that muscle?' That would be helpful to get that information in terms of assessing, 'Oh, yeah, there's a little bit here', and then a couple of sessions later, 'Hey, there's a lot more activity."

Another observation from this work was that there is a lot of downtime for most patients in acute care (36, 37). EMG sensors that are being used for monitoring could serve double-duty by providing early opportunities to practice. A simple display, on the television or a mobile application, could let patients view their muscle activity, control devices (e.g., change the channel), or play simple games controlled by EMG signals.

EMG may also be useful for diagnosis or prognosis. Contraction characteristics from EMG could complement

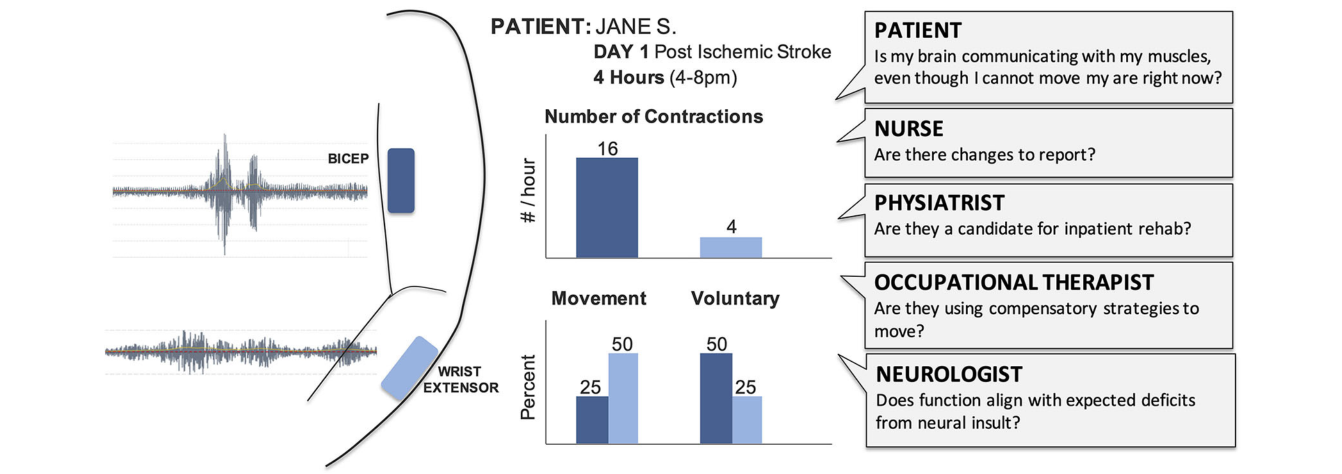

FIGURE 2 | Raw EMG signals provide limited value for the clinical team and need to be transformed into summary results that can support care and treatment decisions. Summary sheets with clear and concise graphs and metrics support clinical discussions and documentation. Different clinicians will require different outcome metrics from EMG to address their specific questions. We have highlighted potential outcomes of interest for acute care, such as number of contractions and whether those contractions were voluntary or occurred with movement. For example, a physical therapist could view these hypothetical results to help them understand which muscles are demonstrating volitional control, select activities for their next session with the patient, and provide specific feedback to the patient and their family.

imaging to help neurologists decipher the extent of neural damage (38–40). While two insults may appear similar, EMG recordings may reveal that one patient has greater residual muscle activity or reliance on synergistic patterns. There are numerous interventions available to stroke survivors, and EMG data may also inform treatment decisions. Certain interventions may be best suited for individuals with specific deficits detected from EMG (41). For all of these scenarios, extensive further research will be required to evaluate diagnostic and predictive value. These critical studies will determine whether the unique insights from EMG data justify the cost, training, and resources required to deploy these systems in acute care.

Lesson 2: Navigating Complex Care Teams

The large numbers of clinicians involved in acute care gives each patient a powerful team, but creates challenges for deploying new techniques, especially in time and resource-limited hospital settings (42). When introducing technology like EMG in acute care, we must ensure it will not interfere with existing tools and consider the potential insight offered for each team member (**Figure 2**). As EMG is typically not included in medical training (35), education would also be required. The frontline nurses would need to understand skin care and procedures (e.g., do these need to be removed before a shower?), while the physicians and therapists would need to understand how EMG data triangulates with other exams (e.g., does the presence of synergistic activity align with the injured brain regions?).

During our research, the physical and occupational therapists expressed the greatest interest in the EMG sensors and results. This likely reflects their prior exposure to muscle monitoring technologies (e.g., biofeedback and electrical stimulation), as well as the fact that much of their time is spent assessing movement. In the hospital where our data were collected, all patients participate in daily occupational and physical therapy sessions as soon as possible during acute care. The therapists were interested in which muscles were most active, and also if activity was present during therapy, particularly in patients with dense hemiplegia or emerging muscle strength. In considering who might deploy EMG in acute care, therapists may represent the best option although their current training involves very limited exposure to EMG. Preparing educational materials and ensuring EMG systems can be easily integrated into their care routines will be critical to support translation.

Lesson 3: Preparing Round-Ready Results

It is not enough to just collect EMG data. The data also needs to be summarized and presented in a compelling form. We call these "round-ready results" —results that can be interpreted quickly, compared to prior days, evaluated relative to expected norms, integrated into standardized reports, and discussed by the team during clinical rounds or care conferences (43).

Creating a curated collection of results will require careful evaluation of the most relevant outcome measures and robust processing pipelines. Many different quantitative metrics can be evaluated from EMG data—such as number of contractions, contraction magnitude, contraction duration, presence of synergistic activations, evaluations of spasticity, or measures of voluntary vs. involuntary contractions (24, 25). For most applications, all of these metrics will not be necessary or desirable for a clinical team. Processing pipelines will be needed that not only calculate specific outcome measures from the raw EMG data that can be integrated into standardized reports, but also assist with set-up (e.g., providing reminders and simple instructions), evaluate signal quality (e.g., monitor background noise), and alert users if there are errors (e.g., detecting cross-talk). While we manually identified contractions, high quality sensors and new processing techniques can help automate many of the processing methods (44–47). Finding the balance between systems that minimize training time, while still giving clinicians confidence and flexibility will require intentional collaboration between rehabilitation engineers and clinicians. Engineers need to clearly demonstrate the possibilities of EMG to clinicians, while clinicians need to provide detailed feedback to develop useful, round-ready results.

Lesson 4: Developing EMG Systems for Clinical Care

All of these applications require EMG systems that provide high quality data with easy-to-use, cost-effective, and comfortable interfaces. From our team's experience, there are currently no commercially-available EMG systems that are suitable for use in acute care settings. Research-grade systems provide high quality signals, but are often bulky and too costly for clinical use. Similarly, more-affordable systems often lack the specificity or signal quality to support clinical decision-making.

An ideal EMG system for use in acute care would be wireless and not require a base station, so that the patient can move freely within the clinic and minimize interference with other systems. The thin and flexible form factor of the BioStamp was excellent for use in acute care, but had significant technical limitations. The Bluetooth interface between the sensors and a tablet did not require additional equipment in the patient's room, but did increase the time for uploading and processing data. At only 0.3 cm thick, the sensors were comfortable to wear while lying in bed and had minimal interference with other activities. However, these sensors still required shaving and using adhesive and wrap to ensure the sensors did not fall off. The spacing between the electrode pairs was also too wide (48), which made it impossible to evaluate smaller muscles and increased the risk of crosstalk. We found that integration with an accelerometer or IMU was useful to evaluate whether contractions occurred with movement, although these additional sensors increase sensor size, decrease battery-life, and increase required memory storage.

An ideal sensor would use small, dry electrodes that eliminate the need to shave or use adhesives, yet can still target individual muscles and ensure high signal quality. Electrode arrays on cloth or other material that can flexibly fit around other equipment, intelligently identify active regions without precise alignment or consistent placement between sessions, may provide good options for clinical translation (49–53). Determining which muscles to monitor will also guide sensor development. Among stroke survivors, we found the wrist flexors and extensors provided some of the greatest differences between patients. Conversely, the triceps were consistently the most challenging to get high quality signals due to contact with the bed and skin and adipose tissues. Optimizing the EMG system, electrodes, and protocols to reduce burdens on clinicians and patients will be critical to create comfortable and flexible systems to support care and recovery.

CONCLUSION

Our experiences in acute stroke care have highlighted the promise and challenges for using EMG data to evaluate muscle activity and enhance recovery. We are optimistic about the use of this technology in the clinic for stroke survivors. Our perspectives are drawn from deploying this technology during the first week after stroke in a well-resourced clinic in a major metropolitan hospital in the United States. To deploy EMG in other clinics will require careful consideration of the resources and needs of the clinic and patients. The development of EMG systems for stroke can also help accelerate the use of this technology in other areas, as clinicians gain greater experience and confidence with these techniques. Continuing to embed research in clinical environments will be a necessary prerequisite to translating EMG into standard care. Key questions still need to be addressed regarding the prognostic and diagnostic value from EMG monitoring. Biofeedback may provide a more immediate application to assist clinicians and patients in visualizing early muscle activity. Our team is excited by these future opportunities and confident that the current barriers can be overcome through collaborative efforts at the interface of engineering, rehabilitation, and data science.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Washington Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CP and HF collected the EMG data in the clinic. KS and CP analyzed the EMG data and wrote the first draft of the manuscript. All authors contributed to the manuscript revision, approved the submitted version, and to the conception of this perspective paper.

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Barriers to sEMG Assessment During Overground Robot-Assisted Gait Training in Subacute Stroke Patients

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Background: The limitation to the use of ElectroMyoGraphy (sEMG) in rehabilitation services is in contrast with its potential diagnostic capacity for rational planning and monitoring of the rehabilitation treatments, especially the overground Robot-Assisted Gait Training (o-RAGT).

Objective: To assess the barriers to the implementation of a sEMG-based assessment protocol in a clinical context for evaluating the effects of o-RAGT in subacute stroke patients.

Methods: An observational study was conducted in a rehabilitation hospital. The primary outcome was the success rate of the implementation of the sEMG-based assessment. The number of dropouts and the motivations have been registered. A detailed report on difficulties in implementing the sEMG protocol has been edited for each patient. The educational level and the working status of the staff have been registered. Each member of staff completed a brief survey indicating their level of knowledge of sEMG, using a five-point Likert scale.

Results: The sEMG protocol was carried out by a multidisciplinary team composed of Physical Therapists (PTs) and Biomedical Engineers (BEs). Indeed, the educational level and the expertise of the members of staff influenced the fulfillment of the implementation of the study. The PTs involved in the study did not receive any formal education on sEMG during their course of study. The low success rate (22.7%) of the protocol was caused by several factors which could be grouped in: patient-related barriers; cultural barriers; technical barriers; and administrative barriers.

Conclusions: Since a series of barriers limited the use of sEMG in the clinical rehabilitative environment, concrete actions are needed for disseminating sEMG in rehabilitation services. The sEMG assessment should be included in health systems regulations and specific education should be part of the rehabilitation professionals' curriculum.

Clinical Trial Registration: www.ClinicalTrials.gov, identifier: NCT03395717.

Keywords: surface electromyography, overground robot-assisted gait rehabilitation, stroke, clinical applications, sEMG barriers

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INTRODUCTION

In neurorehabilitation services, new devices have been widely used for both assessment and rehabilitation. The technology-based assessment includes instrumentation for medical imaging, for measuring electrophysiological signals (Electroencephalography, EEG; surface ElectroMyoGraphy, sEMG) and biomechanics (motion capture, inertial sensors). The technology for rehabilitation includes a wide range of devices such as: electrical stimulators, mechanical vibrators, robotics, virtual reality-based systems, etc. While the diffusion of technology for rehabilitation has been simplified by the great clinical interest in maximizing the outcomes of the rehabilitative treatment, the technology for assessing electrophysiological signals (EEG and sEMG) has been usually confined to research studies. As a consequence, the clinical acceptance of measuring tools, like sEMG, is low and such devices are not included in the usual clinical practice (1). On the other hand, devices like robots for rehabilitation have been rapidly accepted and integrated into rehabilitation services since they have been considered by clinicians as devices which could help to maximize patient recovery (2). Recent cutting-edge robots include the Wearable Powered Exoskeletons (WPEs) which allow a person to walk on hard and flat surfaces by moving the lower limbs with a pre-programmed physiological gait pattern (3–6). The success of WPEs in neurorehabilitation services is mainly due to their capacity to allow overground ambulation even in subjects who are not able to maintain the upright position (7–10), inducing a coordinated, multisensory motor control stimulation. Since these mechanisms are crucial for the restoration of motor control, the o-RAGT could be considered as a rehabilitation treatment which generates a more complex, controlled multisensory stimulation of the patient and which may modify the plasticity of neural connections through the experience of movement (11). While the literature on overground Robot–Assisted Gait Training (o-RAGT) with a WPE is rapidly growing up (12–18), studies which included technology-based assessment, like the sEMG, are restricted (19–23).

The limitation to the use of sEMG in rehabilitation services is in contrast with its potential diagnostic capacity for rational planning and monitoring of the rehabilitation treatments (24–27). A number of barriers limiting the clinical diffusion of sEMG have been recently highlighted by Feldner et al. (28). Cultural, technical and administrative barriers seem to be the principal limitation to sEMG in the clinical practice. The cultural barriers impact on the clinical acceptance of sEMG among Physical Therapists (PTs) and clinicians. In fact, low acceptance is mainly due to the insufficient knowledge to interpret the sEMG outcomes and thus to recognize the clinical relevance of sEMG. Technical barriers are often caused by the limited user confidence of some equipment which may make the acquisition and processing phases problematic. Administrative barriers include device costs and the time required to perform acquisition and processing, which are characteristics common to most biomedical technologies. The cultural and technical barriers mainly depend on the educational background of the clinical staff. Indeed, wide differences between countries exist, since the training programs of PTs and clinicians are very different, especially in approaching new technologies (29, 30). Moreover, to our best knowledge, studies on the barriers to sEMG in clinical practice lack. For these reasons, this paper focuses on introducing the sEMG in a clinical context where technology-based rehabilitation is promoted.

The aim of this work is to assess the barriers faced during the implementation of a sEMG protocol in a clinical study on o-RAGT in subacute stroke patients. The analysis of difficulties encountered during the protocol will allow us to discuss strategies and options which could help to reduce them.

MATERIALS AND METHODS

An observational study was conducted in a rehabilitation hospital (IRCCS San Raffaele Pisana of Rome) in order to investigate the barriers in implementing a sEMG-based assessment protocol in subacute stroke patients who underwent o-RAGT.

Barriers Assessment

The primary outcome was the success rate of the implementation of the sEMG-based assessment, expressed as the percentage of successfully assessed patients relative to the total number of recruited ones. The number of dropouts and the motivations were registered. A detailed report on difficulties in implementing the sEMG protocol was edited for each patient.

The educational level and the working status of the staff involved in each phase of the study (patient recruitment; clinical assessment; sEMG acquisition; o-RAGT; sEMG analysis) were registered.

Each member of staff completed a brief survey indicating their level of knowledge of sEMG, using a five-point Likert scale: very poor (no knowledge about sEMG); poor (basic knowledge about muscle electrophysiology); fair (good knowledge of muscle electrophysiology and basic knowledge of detection/interpretation techniques); good (good knowledge of detection/interpretation techniques and ability to recognize artifacts, interference); excellent (good ability to detect, collect, process and interpret the signals).

The Clinical Study

A pilot clinical trial was carried out on a group of subacute stroke subjects who underwent o-RAGT with a WPE. This study was a subgroup analysis from a large multicenter clinical trial assessing the effects of o-RAGT (15, 16). The inclusion and exclusion criteria, the rehabilitation protocol, and the clinical assessment procedure were provided in the previous papers of the authors (15, 16). Ethical approval of the treatment and of the evaluation protocol was granted by the Ethics Committee of IRCCS San Raffaele Pisana of Rome (date: 18/11/2015; code number: 09/15). The study protocol was registered on ClinicalTrials.gov by the unique identifier number: NCT03395717, and all subjects gave informed written consent in accordance with the Declaration of Helsinki.

TABLE 1 | Characteristics of the staff who conducted the study.

ID		PT1	PT2	PT3	PT4	BE1	BE2
	Education level	PT M.Sc.	PT M.Sc.	PT M.Sc.	PT Ph.D.	BE Ph.D.	BE M.Sc.
	Staff	Clinical	Clinical	Research	Research	Research	Research
	sEMG knowledge*	Very poor	Very poor	Fair	Very poor	Excellent	Excellent
Phased of the study	Patient recruitment			X	X		
	Clinical assessment			X	X		
	sEMG acquisition			X	X	X	X
	o-RAGT	X	X				
	sEMG analysis					X	X

The "X" shows the phases that each member of staff was involved in.
PT, Physical Therapist; BE, Biomedical Engineer; M.Sc., Master of Science; Ph.D., Philosophiae Doctor.
**sEMG knowledge assessed by a five-points Likert scale: very poor (no knowledge about sEMG); poor (basic knowledge about muscle electrophysiology); fair (good knowledge of muscle electrophysiology and basic knowledge of detection/interpretation techniques); good (good knowledge of detection/interpretation techniques and ability to recognize artifacts, interference); excellent (good ability to detect, collect, process and interpret the signals).*

The sEMG Procedure

The subjects were screened at the beginning (T1) and at the end (T2: three weeks after T1) of the o-RAGT with both clinical measures and sEMG-based assessment. The sEMG-based assessment was carried out for assessing electromyographic activity during the following walking trials: at T1 and T2 during ecological overground gait at a self-selected speed along a 10-m walkway with assistance (e.g., crutches with or without antebrachial support, walker, tripod stick, ankle support orthoses, etc.); and during the first session of o-RAGT (o-RAGT$_1$). Two gait tasks for each walking trial were collected. The total duration of the experimental session was about 2 h. An eight-channel wireless sEMG device (FREEEMG 1000—BTS Bioengineering, Milan, Italy) was used to acquire (sampled at 1 kHz, filtered at 8–500 Hz) the activity of the agonist/antagonist muscles of the distal and proximal compartment of lower limbs. The skin was abraded and cleaned with alcohol, then electrodes were placed on Tibialis Anterior (TA), Gastrocnemius Medialis (GM), Rectus Femoris (RF), and Biceps Femoris caput longus (BF) muscles of each leg according to the SENIAM guidelines (31). In order to establish the gait phases, kinematics data were measured using two electrogoniometers for knee joint measurements (BTS Bioengineering, Milan, Italy) and an inertial measurement unit (G-Sensor—BTS Bioengineering, Milan, Italy), placed on the spinous process of the fifth lumbar vertebra. The SMART Analyzer software (BTS Bioengineering, Milan, Italy) was employed for the synchronization of kinematic and sEMG signals for data pre-processing and exporting. Specifically, data from the inertial sensor were analyzed in comparison with electrogoniometers with the SMART Analyzer software, and the heel strike and toe-off gait cycle events were identified for all walking trials. The gait cycle was considered as the interval of time between heel-strikes of the same foot (i.e., the right foot). These temporal events were used for all subsequent sEMG analyses. The sEMG and temporal events were exported for further custom analysis in MATLAB (MATLAB R2019a, The MathWorks Inc., Natick, MA, USA).

The sEMG data were high-pass filtered (20 Hz, 6th-order Butterworth filter, bidirectional) and full-wave rectified. For standardization, the sEMG data were normalized to 100% of a gait cycle based on the temporal events (heel strikes and toe-offs) extracted from the kinematic data. The sEMG signals of each gait cycle were processed as follows: (1) the sEMG envelope was obtained using a moving average filter (window duration equal to 120 ms) and normalized at the maximum sEMG amplitude level; (2) the activation threshold identifying onset and offset status of muscle activity was detected as the 20% of minimum-maximum amplitude level distance (32), when kept for at least 50 ms. Subsequently, the following sEMG outcomes were extracted, considering five gait cycles: (i) the Bilateral Symmetry (BS) coefficient (33); (ii) the Co-Contraction (CC) coefficient (34); (iii) and the Root Mean Square (RMS) value (35). Details on the calculation of BS and CC coefficients are described in the **Appendix**.

Descriptive statistics were computed in order to appropriately explain the clinical and demographic characteristics of the sample. Data were represented for each recruited stroke subject. The sEMG outcomes were averaged from the two gait tasks for each walking trial and were used for subsequent analyses. The one-way ANalysis Of VAriance (ANOVA) was applied between T1 and T2 in order to test the treatment effect of o-RAGT on sEMG outcomes.

RESULTS

The study was carried out by a multidisciplinary team composed of two Medical Doctors (MDs), four Physical Therapists (PTs), and two Biomedical Engineers (BEs). The MDs were Physical Medicine & Rehabilitation specialists. The sEMG acquisition and analysis were conducted by PTs and BEs. **Table 1** depicts the characteristics of the members of staff who were involved in the study. PT1 and PT2 are the PTs who worked in the clinical department and administered the o-RAGT: they hold an M.Sc. in physical therapy and the patent to use the WPE in rehabilitation. The patient recruitment and clinical assessment were conducted by PT3 and PT4, both working in the research department and having an M.Sc. and Ph.D. educational level, respectively. The sEMG acquisition phase was executed by members of the

TABLE 2 | Demographic and clinical characteristics of the sample.

ID	Age (years)	Gender	Affected side	Acute event onset time (days)	MAS-AL		MI-AL		FAC		TCT		10MWT (m/s)	
					T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
PAT02	64	M	R	11	3.0	3.5	60	76	2	4	87	100	0.44	0.62
PAT03	69	M	L	13	0.0	0.0	64	76	1	3	74	100	0.34	0.48
PAT06	54	F	L	29	1.0	0.0	48	65	1	3	61	100	0.16	0.32
PAT09	50	M	R	23	2.0	3.0	43	76	1	4	74	100	0.91	0.67
PAT11	76	F	R	30	1.0	1.0	64	76	2	4	87	100	0.45	0.56
PAT14	44	F	R	26	2.0	2.0	53	76	2	4	74	100	0.38	0.53
PAT18	66	M	R	12	0.0	0.0	76	82	4	5	100	100	0.44	1.41
PAT20	66	M	R	75	2.0	1.0	70	100	3	4	100	100	1.09	1.38

M, Male; F, Female; R, Right; L, Left; MAS-AL, Modified Ashworth Scale Affected lower Limb; MI-AL, Motricity Index Affected lower Limb; FAC, Functional Ambulation Classification; TCT, Trunk Control Test; 10MWT, 10-Meter Walking Test.

research department only (two PTs and two BEs). BE1 and BE2 were in charge of the sEMG analysis and have an M.Sc. and Ph.D. educational level, respectively. The self-administered evaluation of the sEMG knowledge shows that the PTs were unfamiliar with sEMG assessment, while BEs considered themselves as experts.

Indeed, the educational level and the expertise of the members of staff influenced the accomplishment of the implementation of the study. The PTs involved in the study did not receive any formal education on sEMG during their course of study. Two of them (PT3 and PT4) were part of the research staff and studied the sEMG recording procedures (electrodes' positioning, basic use of the device for the sEMG acquisition) as a self-taught. However, no PTs had enough knowledge to recognize artifacts and interferences or process the signals. The BEs, on the other hand, were responsible for the entire sEMG procedure from signal acquisition to processing. The limitation of sufficient knowledge in sEMG among PTs was one of the reasons for the limited diffusion of electromyography in the rehabilitation hospital, and specifically in the clinical study on o-RAGT.

A total of 22 subacute stroke patients were recruited in the clinical study. Two patients dropped out due to medical issues not related to the training or to the assessment. The remaining 20 participants completed the o-RAGT without reporting any adverse event. Fourteen patients agreed to participate in the sEMG-based assessment procedure. However, six of them could not complete the 10-m-long ecological overground gait at T1 and therefore were excluded from the study. Therefore, we recorded sEMG during ecological overground gait at T1 and T2, and at o-$RAGT_1$ of a sample composed of 8 patients (the demographic and clinical characteristics of each subject are depicted in **Table 2**). Data acquired during the o-$RAGT_1$ were partially altered and it was not possible to reliably study the muscle activity. Thus, the sEMG outcomes from 3 patients (PAT03, PAT11, PAT14) were not available. Specifically, the experimental setup for data acquisition during o-$RAGT_1$ was partially influenced by the presence of the WPE: the electrode application procedure did not always comply with the SENIAM guidelines (31), because of the cumbersome WPE braces and straps. Moreover, during movement, the placement of the electrodes was moderately affected by the relative movement between the subject and the WPE. In conclusion, the number of successfully assessed patients was 5 out of the 22 initially recruited ones, and the success rate of the implementation of the sEMG-based assessment was equal to 22.7%. **Figure 1** shows the flowchart of the experimental procedure.

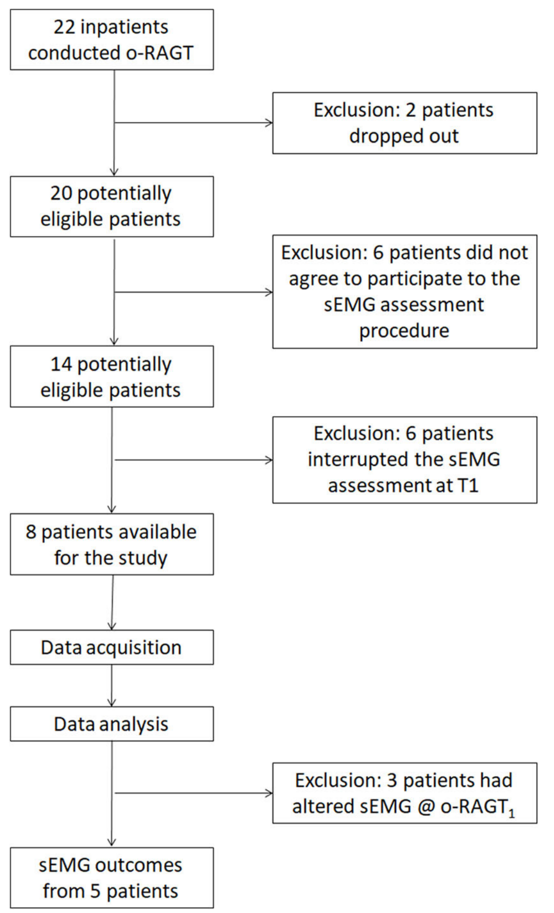

FIGURE 1 | Flowchart of the experimental procedure.

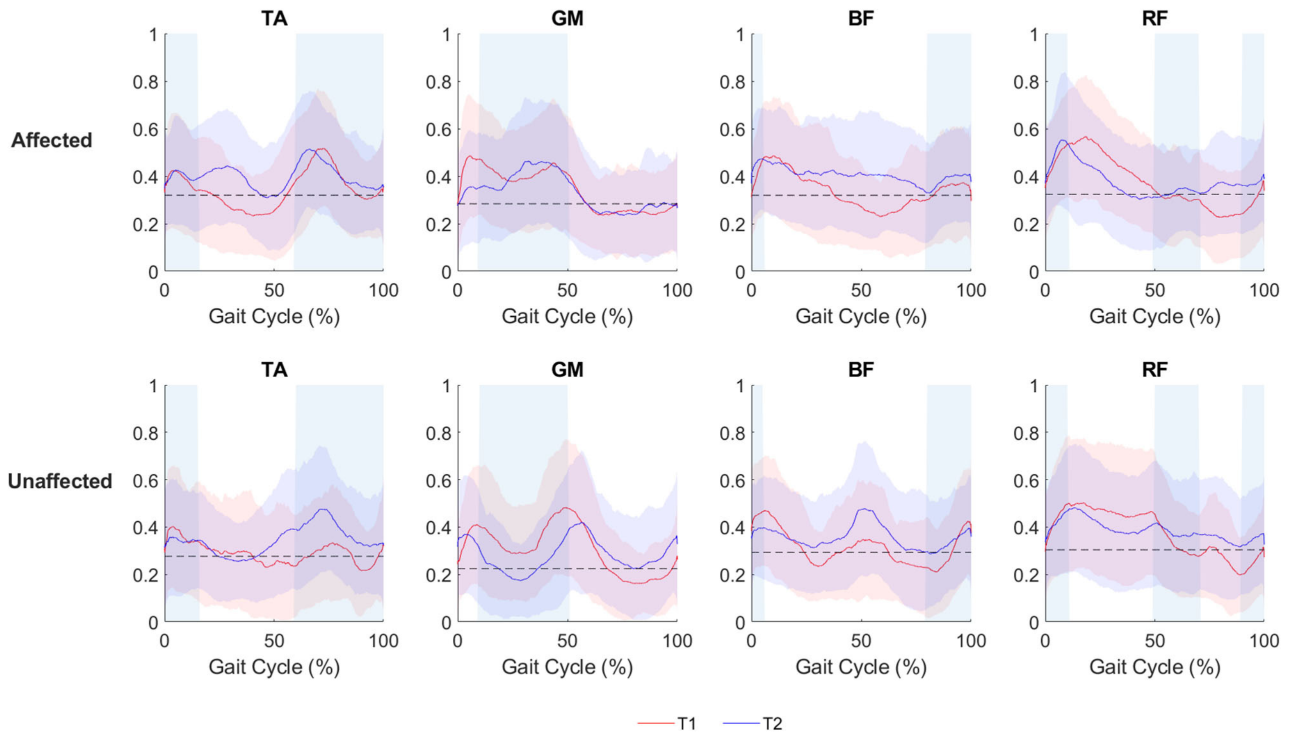

FIGURE 2 | sEMG activation of the affected and the unaffected limb for all patients (*N* = 8), depicted as mean and standard deviation plot, during ecological overground gait. The red line (mean) and the red band (standard deviation) represent the sEMG envelopes (normalized with respect to the maximum sEMG amplitude level of each side) before o-RAGT (T1). The blue line (mean) and the blue band (standard deviation) represent the sEMG envelopes at the end of o-RAGT (T2). For each subject, five gait cycles have been considered. Shaded rectangular areas indicate when a muscle is active based on normative healthy adult gait, Perry and Burnfield (36).

sEMG Outcomes

The visual assessment of sEMG patterns during walking reveals a vast heterogeneity of the data. The mean sEMG data (**Figure 2**) shows volitional muscle activations during gait at both T1 and T2 during ecological overground gait. Although such muscular activity is visible on both the affected and unaffected limbs, the level of activations are characterized by variations in amplitude and timing and do not consistently correlate with the activation timing of healthy gait (36).

A traditional amplitude analysis was conducted on the sEMG data, and the following sEMG outcomes were calculated: (i) the BS coefficient; (ii) the CC coefficient; (iii) and the RMS value (35). The results of the one-way ANOVA between T1 and T2 did not reveal any significant difference. The BS coefficient registered a relevant improvement between T1 and o-RAGT$_1$ in a subset of patients (PAT02 at TA and GM; PAT06 at TA, GM, BF, RF; PAT09 at TA, GM, BF; PAT11 at TA; and PAT18 at TA and BF). The effects of the 15 sessions of o-RAGT improved the BS in TA (PAT02, PAT06, PAT09, PAT11, PAT20) and moderately in RF (PAT06, PAT20). The proximal muscles registered a decrease in CC between T1 and o-RAGT$_1$ (PAT02, PAT06, PAT18, PAT20) and between T1 and T2 (PAT02, PAT11, PAT14, PAT18), while the distal muscles did not. In the future, an advanced analysis of sEMG (by means of a time-varying multi-muscle coactivation function) could help to investigate the o-RAGT effects, in terms of simultaneous coactivation of a group of muscles during gait (37–39). The RMS revealed differences between the same muscles of different limbs, although the one-way ANOVA did not reveal statistical significance. Data showed a mean increase of muscle activity at T2 of TA (affected and unaffected sides), GM (affected side), BF (affected and unaffected sides), and RF (unaffected sides), although the standard deviations were high. The o-RAGT$_1$ registered an increase in the RMS of TA, GM, BF, and RF of the affected side.

DISCUSSION

This paper focuses primarily on the difficulties encountered in the investigation of the o-RAGT technique by mean of sEMG, and secondarily on the results obtained in the o-RAGT study. This experience evidences a number of barriers limiting the implementation of the study on the effects of o-RAGT in terms of muscle activation. The low success rate (22.7%) of the protocol has been caused by several factors which can be grouped in: patient-related barriers; cultural barriers; technical barriers; and administrative barriers.

Patient-related barriers are mainly caused by low patient compliance. Except for two drop-outs caused by medical issues [no adverse events were evidenced during the o-RAGT as in (15, 16, 22)], from the 22 recruited subjects, 12 patients were excluded from the study for these reasons: (1) six patients did not agree to participate in the sEMG assessment due to tiredness; (2) six patients found the gait motor task at baseline too challenging and could not complete the sEMG assessment at T1. Both motivations depended on the subacute and complex phase of the disease. The acceptance of the sEMG assessment from patients could be improved introducing new strategies for increasing the perceived usefulness of sEMG (e.g., dedicating time to give the patient accurate and detailed information about the benefits of sEMG). Indeed, the typical impairment of stroke patients in the subacute phase should be considered in the definition of future sEMG-based protocols, and thus the analysis of basic motor tasks should be preferred.

Cultural barriers depend on the insufficient knowledge of sEMG among PTs. The role of PTs in the study was mainly as assistants of BEs during the sEMG acquisition phase. Specifically, PT3 and PT4 placed the electrodes and helped the patients to conduct the requested motor tasks. This situation is representative of the condition of PTs with respect to sEMG in Italy. In fact, the Italian academic curriculum in Physical Therapy does not include any courses on electromyography, and thus the professional figure of PT is usually focused on conventional therapy. Indeed, considering the dramatic introduction of new technologies in rehabilitation services, the role of PT should be drastically changed, and this change should start from the university curricula (40). While the bachelor's degree in PT could remain more oriented to the classical clinical role of PT, the master's degree in PT should include more technical courses. Specifically, academic courses on sEMG, EEG, gait analysis, and statistics should be added to the Italian Universities. Considering the sEMG, the PTs should be able to carry out the sEMG recording procedure (electrodes' positioning, sEMG acquisition) autonomously, using a commercial device. Moreover, the PTs should have enough knowledge to distinguish the "quality" of the acquired signals and to use commercial and user-friendly software for the basic sEMG analysis. Of course, it does not mean that the figure of BEs is not necessary for the rehabilitation hospital, but their role should be more oriented to the use of innovative prototypal sEMG devices and to the development of novel advanced signal processing techniques.

Technical barriers have been encountered during o-RAGT$_1$. The sEMG signal was affected by the change of electrode location (41, 42), due to the presence of the WPE: the space between the limbs and the WPE did not allow to place the electrodes appropriately and the electrodes were partially moved by the exoskeleton during the movement of the patient. Thus, the quality of the sEMG signals of 4 patients during the o-RAGT$_1$ was altered and the sEMG outcomes were unreliable. This barrier could be overcome in future studies by using high-density sEMG (43, 44) or making structural changes to the WPE.

Administrative barriers related to management and time-related issues had a negative impact on the dissemination of sEMG assessment in our clinical environment: a limited amount of time was available for the sEMG acquisition, because of the intensive schedule of rehabilitative treatments. These time-related barriers have been highlighted also by Feldner et al. (28) and by Swank et al. (21). A solution for increasing the diffusion of electromyography could be the inclusion of sEMG acquisition in the routine clinical practice for patient assessment (recognized by regional regulations for public health), thus dedicating a timeslot of the planned schedule to this procedure. Indeed, in this case, the clinical PTs should have an appropriate educational background on sEMG. Our results evidence that a multidisciplinary team is required to conduct the study because of the heterogeneity in technical skills: while the BEs, which were involved in both the sEMG acquisition and analysis, had a solid knowledge of sEMG, mainly learned during their course of study in higher education (M.Sc. and Ph.D.), the PTs did not receive any specific training on the topic during their course of study. In this context, a higher diffusion of a sEMG in an intensive rehabilitation hospital could be facilitated by the introduction of a specific education of PTs on sEMG. In our experience, while the background of clinical PTs on WPE is influenced by the need to have a patent to use the device in rehabilitation, the knowledge of sEMG is rarely supported by the Italian PT university curricula and by the need to use this technology in daily clinical practice. A solution to overcome the educational barriers could be the constitution of appropriate training of PTs on both the theory and the technical aspects of sEMG. An alternative solution could be the introduction of a new figure (i.e., the Clinical Technologist) as a healthcare professional who has the expertise to translate medical technology use into improved patient-specific procedures (45). However, in our opinion, the competence of rehabilitation professionals in the use of new technologies (i.e., sEMG) should be increased with the diffusion of specific training courses [like the one described by De la Fuente et al. (46)].

CONCLUSION

In conclusion, this paper offers an insight into the barriers limiting the use of sEMG during o-RAGT in subacute stroke patients. Certainly, since a series of barriers limited the application of sEMG in the clinical rehabilitative environment, concrete actions are needed for disseminating sEMG in rehabilitation services. The sEMG assessment should be included in health systems regulations and specific education should be part of the rehabilitation professionals' curriculum.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by IRCCS San Raffaele Pisana, Via della Pisana, 235, 00163 Rome, Italy. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MG, FI, and MF have made substantial contributions to conception and design. SP, DGal, and DGab participated in the enrollment phase and carried out the o-RAGT treatment. SP, MG, and PR carried out the clinical and sEMG assessments. MO and PR designed the algorithm for sEMG data analysis. LP, PR, MO, and AG participated in the study design and coordination, and statistical analysis. SP and FI participated in the manuscript revisions. MF and FI gave the final approval of the version. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fneur.2020.564067/full#supplementary-material

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Surface Electromyography Applied to Gait Analysis: How to Improve Its Impact in Clinics?

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Surface electromyography (sEMG) is the main non-invasive tool used to record the electrical activity of muscles during dynamic tasks. In clinical gait analysis, a number of techniques have been developed to obtain and interpret the muscle activation patterns of patients showing altered locomotion. However, the body of knowledge described in these studies is very seldom translated into routine clinical practice. The aim of this work is to analyze critically the key factors limiting the extensive use of these powerful techniques among clinicians. A thorough understanding of these limiting factors will provide an important opportunity to overcome limitations through specific actions, and advance toward an evidence-based approach to rehabilitation based on objective findings and measurements.

Keywords: electromyography, EMG, locomotion, machine learning, clinical practice, rehabilitation, physical therapy, outcome measurements

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INTRODUCTION

Walking is one of the most essential activities of daily living (ADL) (1). The study of muscle activity during locomotion is of the uttermost importance in clinics, in the management of patients suffering from a wide variety of different neurological (2), orthopedic (3, 4), and peripheral vascular diseases altering gait patterns (5). Examples of neurological patients that might benefit from a thorough examination of the dynamic muscle activity are those affected by Parkinson disease (PD) (6, 7), post-stroke (8), multiple sclerosis (MS) (9), and hemiplegic children after cerebral palsy (10–13). Examples of orthopedic patients that might benefit from having the same examination are patients after anterior cruciate ligament (ACL) surgery (14), total knee arthroplasty (TKA) (3), knee megaprosthesis after tumor bone resection (15), total hip arthroplasty (THA) (16), and patients chronically affected by low back pain (17). Peripheral neuropathy (PN) and peripheral artery disease (PAD) are two distinct but related conditions that affect diabetic patients, altering their gait patterns up to the point of causing them foot ulcers often difficult to treat ("diabetic foot") (5, 18). In the more severe cases, this can even lead to leg amputation.

Instrumented gait analysis provides comprehensive data on normal and pathological gait, which are useful in clinical practice producing objective information about time-distance variables (spatio-temporal data), joint motions (kinematics), and joint moments and powers (kinetics) (19). In the last decade, simplified, "user-friendly" techniques for gait analysis such as those based on accelerometric sensors are demonstrating their usefulness in the clinical setting and have had a significant impact in the literature (20–22). In addition, dynamic electromyography (EMG) allows for obtaining the timing and action of muscles, contributing to outline the patient's walking pattern and an empirical basis for identifying the functional cause of a gait abnormality (19).

Indeed, the knowledge about the dynamic contractile activity of the muscles during pathological gait may provide unique information to help clinicians in the following activities:

- to support diagnosis (2, 23)
- to design complex surgical interventions [e.g., multilevel surgery of hemiplegic children (24, 25)]
- to design personalized rehabilitation protocols and objectively prove their effectiveness (e.g., outcome evaluation of a proprioceptive training in MS patients), including new rehabilitation trends exploiting exoskeletons, e.g., in acute stroke patients (26), neurorehabilitation with Functional Electrical Stimulation (FES) (27), and any other system providing biofeedback based on myoelectric control (28–31)
- to support clinical decision (e.g., appropriate candidate selection for botulin toxin injection and choice of the target muscles (32), evidence-based choice of the type of joint prosthesis to implant (15)
- for therapy evaluation (e.g., to assess the effects of levodopa, or Deep Brain Stimulation on the muscle activation and muscle synergies of PD patients) (33–35)
- for the production of quantitative reports to optimize patient's follow-up or to conduct longitudinal studies (16)
- to evaluate muscle fatigue (e.g., in ergonomics and sports) (36–39)
- to support forensic medicine with objective outcomes (e.g., to help medical insurance companies estimating a patient's risk, establishing adequate insurance compensations, unmasking simulators and avoiding frauds) (40, 41).

Despite the wide variety of possible clinical applications described above and their unquestionable relevance, clinicians underutilize instrumented gait analysis (GA) (42), especially associated to surface myoelectric signal detection (43–45). Surface electromyography (sEMG) is a well-established technique to investigate muscle activity non-invasively (46–48). In spite of that, clinicians rarely exploit the benefits of performing a "richer" and more complete gait analysis that includes, in addition to the analysis of the traditional spatio-temporal gait parameters and joint kinematics, the study of the muscle activation patterns during gait. Although underappreciated, the electrical activity of the muscles can be observed and recorded easily and non-invasively during locomotion (2, 49).

In the following, we will indicate with the acronym sEMG-GA gait analysis when it includes the recording of sEMG signals for sensing muscle activity during locomotion. SEMG-GA requires the acquisition of sEMG signals from the main lower limb muscles and, in some cases, from the trunk (50). The arm swing activity is more rarely reported, although it may be of clinical interest [e.g., PD patients may show a reduced arm swing activity during gait, in one or both sides (51)].

In a standard sEMG-GA session (52–54), sEMG probes are placed, at least, over Tibialis Anterior (TA), Lateral Gastrocnemius (LGS), Rectus Femoris (RF), and Lateral Hamstrings (LH), bilaterally, as reported by **Figure 1**. This allows for analyzing at least a pair of agonist-antagonist muscles acting at each joint of both lower limbs (ankle: TA/LGS; knee: LH-LGS/RF; hip: RF/LH). Indeed, since both LGS and RF are bi-articular muscles, this configuration makes it possible obtaining relevant biomechanical information using a minimum set of sEMG probes. SEMG signals can be acquired synchronously with foot-switch signals, joint kinematic signals, and a video recording (55). **Figure 2** provides an example of signals acquired during a typical recording session performed using the multichannel recording system STEP32 (Medical Technology, Italy) (53). In this example, 16 channels with gait signals are synchronized with a video recording: 8 for the left side (channels from 1 to 8) and 8 for the right side (channels from 9 to 16). For each lower limb, the user-interface shows, in the same screenshot: the foot-switch signal, the knee joint-angle kinematic signal in the sagittal plane, and the sEMG signals over TA, LGS, RF, LH, and Vastus Lateralis (VL) muscles, respectively. For each muscle, the activation patterns are automatically recognized by the system, and re-visualized in red (distinguished from background noise, which remains yellow-colored).

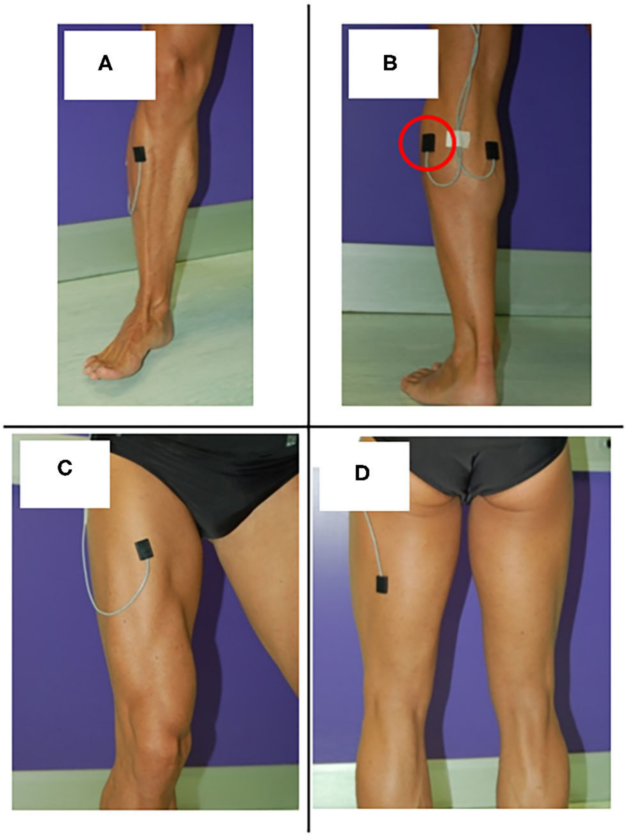

FIGURE 1 | Surface EMG probes positioned over **(A)** Tibials Anterior (TA), **(B)** Lateral Gastrocnemius (LGS), **(C)** Rectus Femoris (RF), and **(D)** Lateral hamstrings (LH).

A sEMG-GA test requires, overall, from 15 to 30 min (including sensor positioning). It is well-tolerated by children, adults, and the elderly, and by patients affected by a wide variety of pathologies altering locomotion patterns (2, 16, 18, 52, 56–63). The only requirement is the ability to walk

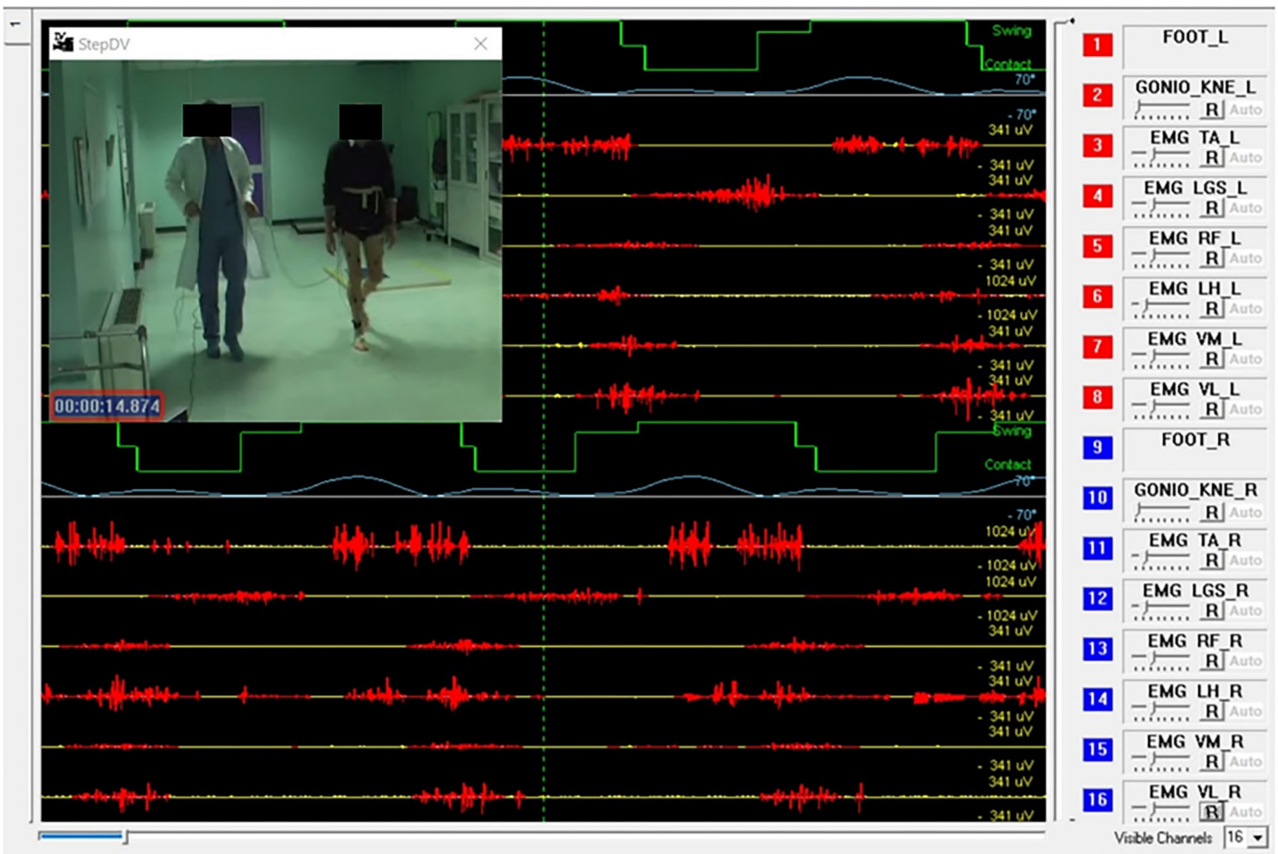

FIGURE 2 | Example of signals acquired during a gait analysis session (multichannel recording system: STEP32, Medical Technology, Italy). Sixteen channels are synchronized with a video recording of gait: 8 for the left side (channels from 1 to 8) and 8 for the right side (channels from 9 to 16). For each lower limb the screenshot shows: 1 foot-switch-signal (green), 1 knee joint-angle kinematic signal in the sagittal plane (light blue), 5 sEMG signals over Tibialis Anterior (TA), Lateral Gastrocnemius (LGS), Rectus Femoris (RF), Lateral Hamstrings (LH), and Vastus Lateralis (VL). For each muscle, the activation patterns are automatically recognized by the system, and displayed in red, while the background noise is yellow-colored.

independently for a few minutes. The exam can be carried-out also if the patient needs some walking aid or support (64), but, in this case, results must be carefully interpreted considering the specific situation. SEMG-GA is able to evidence even subtle gait abnormalities or gait pattern changes that are not perceivable at the naked eye by the clinician, in addition to "macroscopic" alteration or modifications of gait patterns. A possible application of sEMG-GA is the early evaluation of the effectiveness of a rehabilitation program (65, 66). Using sEMG-GA, clinicians will be able to obtain measurable outcomes after a few weeks of rehabilitation, even if only sub-clinical changes are present. In this manner, both the clinician and the patient will have a documented evidence that the rehabilitation program is working as expected or that it needs to be re-designed, if it did not lead to any measurable improvement. Therefore, performing sEMG-GA test during the patient's follow-up may also improve patient motivation and compliance to the rehabilitation program.

Yet, although there is a relevant number of studies supporting the use of sEMG in clinical gait analysis (2, 3, 16–18, 54, 60, 67), they seldom translate into routine clinical practice. The aim of this contribution is to critically analyze the key factors limiting the widespread use, among clinicians, of powerful techniques of clinical gait analysis based on sEMG signals. Possible solutions will also be outlined and discussed.

ANALYSIS OF THE MAIN FACTORS LIMITING THE USE OF sEMG-GA IN THE CLINICAL PRACTICE

In this section, we discuss the following key factors limiting the widespread use of the sEMG signals in clinical gait analysis:

- lack of normative (reference) data of sEMG patterns [section Lack of Normative (Reference) Data Regarding sEMG Patterns]
- low intra-operator repeatability and inter-operator reproducibility in the collection of high-quality sEMG signals (section Low Intra-operator Repeatability and Inter-operator Reproducibility in the Collection of High-Quality sEMG Signals)

- inappropriate use of treadmill (instead of overground natural walking) (section Inappropriate Use of Treadmill (Instead of Overground Natural Walking)]
- difficulties in the sEMG-GA interpretability due to the large intra-subject variability of myoelectric patterns (section Difficulties in the sEMG-GA Interpretability Due to the Large Intra-subject Variability of Myoelectric Patterns)
- lack of reliable/compact/unique clinical scores obtainable from sEMG-GA (section Lack of Simple/Compact/Unique Clinical Scores Obtainable From sEMG-GA)

and discuss their characteristics and criticalities. The pinpointing of these limiting factors are the result of a 15-year experience of cooperative work and tight collaboration with clinicians of different specialties (neurologists, orthopedic surgeons, neurosurgeons, physiatrists, rehabilitation therapists, diabetologists...), in different gait analysis laboratories (hosted by hospitals, medical ambulatories, clinics, rehabilitation centers, gyms), with the aim of solving the research and clinical questions they had through sEMG-GA systems.

For each of these limiting factors, we also present, when available, possible solutions to overcome the described criticalities. When solutions are not currently available, we suggest future developments that might help bridging the gap between academic knowledge and clinical practice.

Lack of Normative (Reference) Data Regarding sEMG Patterns

When a physician has available a sEMG-GA report, the first question that comes to his/her mind is: "How do I interpret this exam?" To provide a satisfying answer to this fundamental question, normative (reference) data on healthy populations are necessary. These normative data should be available, for each age class (children, adolescents, adults, elderly), differentiated by gender and body mass index (BMI). However, there is a lack of open databases of "physiological" sEMG activations patterns. One study analyzed 100 typically developing children aged 6–11 (52). Another study analyzed 40 healthy subjects, 20 aged 6–17 and 20 aged 22–72 (59). Most frequently, in the literature, only small datasets of 15–20 healthy subjects can be found, typically involving individuals recruited to build a control population (e.g., patient caregivers) related to a specific pathological target population (PD patients, diabetic patients...), and selected for a specific study aim. Only a few studies focus on making available large datasets (larger than 100 subjects) of physiological muscle activation patterns during locomotion. Furthermore, different sEMG acquisition systems and acquisition protocols are used, and there are different ways of processing and reporting data. Therefore, a standard is unavailable at the moment.

The authors suggest that the sEMG-GA systems to be used in clinics should be designed to automatically support clinicians with reliable reference data. Just as reference ranges (and eventually asterisks) appear on a blood test report, reference ranges should appear on a sEMG-GA report. Consequently, it is strongly advisable to integrate sEMG reference datasets into newly designed systems for clinical gait analysis. It would be ideal to produce these embedded reference datasets following the recommendation guidelines established through worldwide accepted standards, specifically developed for clinical gait analysis (67).

Low Intra-operator Repeatability and Inter-operator Reproducibility in the Collection of High-Quality sEMG Signals

In a gait analysis laboratory, different professional figures may perform the acquisitions, such as biomedical engineers, gait analysis experts, physiatrists, physical therapists, and students. They have different expertise and some of them may lack experience in sEMG probe positioning, in recognizing the presence of detrimental artifacts in the signals, or in being aware of signal saturation or very low signal-to-noise ratio (SNR). This can lead to low inter-operator reproducibility. However, in clinical gait analysis, it is fundamental to guarantee that the different operators alternating in the various shifts do not affect the outcome measures derived from sEMG-GA. It follows that user-independent systems are required. Furthermore, it is also fundamental that the same operator is able to provide repeatable outcome measures, at different time-points, for a specific patient (e.g., to evaluate possible improvements after a therapeutic intervention).

A key factor to promote intra-operator repeatability and inter-operator reproducibility is the automatic assessment of the quality of the sEMG signals acquired, performed during the acquisition itself. However, there is a lack of systems designed to provide this essential feature (68). We suggest designing innovative systems that provide real-time information on the quality of each sEMG channel being acquired. These devices should help the training of less expert operators, independently from their background. As an example, to display the sEMG quality in real-time, a very intuitive semaphore's color coding might be used:

- GREEN: ok, good signal quality;
- YELLOW: sufficient, signal quality should be improved if possible;
- RED: completely inadequate, please stop the acquisition and check the electrodes.

Inappropriate Use of Treadmill (Instead of Overground Natural Walking)

Frequently, sEMG signals are collected while the patient walks on the treadmill (12, 69, 70). This is often chosen merely for "tradition" (71), because it is "easier" for the experimenter (although not for the patient). Indeed, using treadmill allows confining the subject's cyclic motion to a small space-volume. This simplifies the acquisition protocol if there is the need to use a synchronized stereophotogrammetric system to detect gait events and jointly analyze 3D kinematics. Indeed, optical motion-capture systems were considered as the gold standard in the past, but they require to be calibrated over small sample volumes, in a confined lab space (72). Another "historical" reason why researchers frequently use the treadmill to study human gait is the possibility to obtain more controlled conditions, e.g., the possibility to set the velocity or the inclination to a predefined value.

However, the use of treadmill to study gait in pathological subjects may be rather inappropriate. Indeed, patients affected by neurological or musculoskeletal pathologies are not always able to walk on a treadmill, or it could be unsafe testing them on a treadmill, since additional balance skills are required to walk on a treadmill with respect to walk overground, naturally, at self-selected speed. Furthermore, when on the treadmill, the use of harnesses, or the fact that the patient, to maintain balance, leans on the treadmill horizontal bars or grasps vertical bars alters patient's perception, proprioception and muscle activation patterns. In addition, also if dynamic balance can be properly maintained without any external help, the muscle activations patterns during natural and treadmill gait are not the same (73). It was also demonstrated that the coordination between upper- and lower-limb movements is different during overground and treadmill walking (74). Hence, the possibility to perform sEMG analysis during "physiological" overground walking, instead of using a treadmill, can be important from a clinical point of view. This is something that should be carefully considered in the design of systems for clinical gait analysis.

Already 15 years ago, our research team designed a multichannel recording system for clinical gait analysis that integrated this design concept. The system was technologically transferred to an Italian company to reach the market (STEP32, Medical Technology) and it is being sold mainly in Italy and Spain. Thanks to this device, the possibility to perform sEMG-GA in the clinical setting, during overground walking, was fully demonstrated by several works (11, 16, 52, 63, 75, 76).

In recent years, the market revolution around wearable sensors based on Inertial Measurements Units (IMUs) has taken hold and is trying to substitute traditional motion capture systems with new devices, allowing for out-of-the-lab and low-cost motion analysis (77–79). We expect that this will reduce the use of treadmill in favor of the overground study of locomotion. Therefore, it seems promising to integrate wireless sEMG probes with IMUs to probe the dynamic muscle activity during overground locomotion, while reconstructing gait events and 3D joint kinematics. We think that such integrated wearable systems might greatly increase the use of sEMG-GA analysis in hospitals, rehabilitations centers and assisted-living facilities.

Difficulties in the sEMG-GA Interpretability Due to the Large Intra-subject Variability of Myoelectric Patterns

It is well-known that human locomotion is characterized by a high intra-subject variability (80). Each gait cycle is different from the other, when muscle activation patterns are analyzed. Even in individuals with physiological walking patterns, sEMG activations noticeably vary from stride to stride (81). The sEMG variability can further increase in pathological subjects (11). This is the main reason why previous literature in clinical gait analysis discouraged analyzing a few gait cycles, and, it rather suggested analyzing "long" natural walks, lasting at least 3–5 min (16, 60, 82). Indeed, analyzing prolonged overground walks, carried out at natural pace, has been a successful strategy to obtain repeatable and reliable outcome measures, both in normal and pathological gait. However, this requires the use of advanced techniques of sEMG processing to automatically analyze hundreds of strides. Furthermore, if appropriate post-processing algorithms are not applied, the results obtained are cumbersome and the interpretation of muscle activation patterns becomes difficult or even impossible.

In the following, we will analyze various issues related to the sEMG gait variability and how it can make it difficult to interpret sEMG-GA, if not properly handled. In particular, we will distinguish between *extrinsic* and *intrinsic* sources of sEMG variability.

Extrinsic Sources of sEMG Variability: The Walking Track and the Need to Time Gait Events

Among the problems to tackle for analyzing a natural walk lasting several minutes, there is the fact that the acquisition should be performed, at least in theory, along a straight walking track between 200 and 500 m of length. However, this is unfeasible in many practical situations, for both technical and logistic issues, and it would require outdoor pathways. A reasonable solution is to have available, indoor, a large room or a long corridor (of length 10–15 m), which is not difficult to obtain in a hospital setting. Therefore, the patient can walk continuously, without interruptions, back and forth along the corridor. When arrived at the end of the walking track, the patient simply turns, reverses his/her direction, and keeps on walking, for many rounds. At each round, the patient travels for 10–12 gait cycles along the straight path, at an approximately steady velocity. Walking uninterruptedly for several minutes allows the patient to walk naturally, as in everyday life. Indeed, after a few rounds, the patient feels at ease and walks at his/her natural pace. Then, the signal acquisition can start.

To process gait signals during overground walking, the first step is to segment gait cycles occurred during straight steady-state locomotion, separating them from the cycles relative to the direction changes, including decelerations before, and accelerations after the U-turns. **Figure 3** shows this concept. In this way, gait parameters can be calculated in a repeatable manner, ruling out a first source of sEMG variability. However, it should be noticed that not only the U-turns, and their surroundings, must be discarded from the analysis, but also any other possible signal-epoch outliers, such as those corresponding to the abrupt distraction or sudden stop of the patient for any reason, or the unexpected change in his/her walking style that may happen along the walk. This issue can be properly handled if additional signals for timing gait events are collected, synchronous to the sEMG signals. These signals can be acquired through: (1) *indirect* measurements, by using stereophotogrammetric systems or wearable IMU sensors; (2) *direct* measurements, by using sensorized mats, foot-switches or foot-pressure insoles.

Indirect measurements to time gait events

As mentioned above, sterephotogrammetric systems have been historically considered the gold standard in gait analysis, both with and without an associated sEMG investigation. However, they never truly succeeded to help medical practitioners in clinical gait analysis, and most of the research-work done remained confined to academic studies. Indeed, stereophotogrammetric systems are expensive, they require a dedicated gait analysis laboratory and technical personnel, their sample volume is intrinsically limited to a few cube-meters, and they are complex to use, necessitating highly trained experts (typically biomedical engineers) to manage the system calibration and acquisition procedures. On the other hand, IMU systems are experiencing a "market boom" in many different applications, since they are lightweight, low-cost, and wearable, allowing for out-of-the-lab applications. Researchers, as well as medical-device producers, are actually trying to improve the performances of IMU systems on the reconstruction of joint angle measurements and 3D

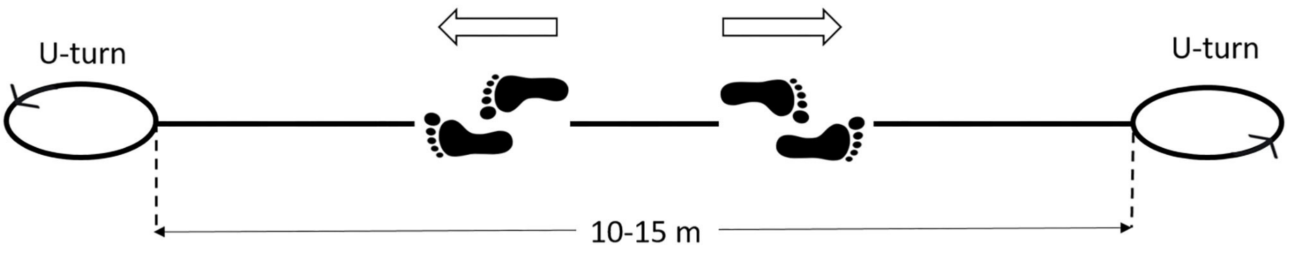

FIGURE 3 | Scheme of the walking protocol for gait analysis. The patient walks back and forth, without interruptions, along a straight path of 10–15 m, for 3–5 min. The U-turns must be automatically removed from the analysis.

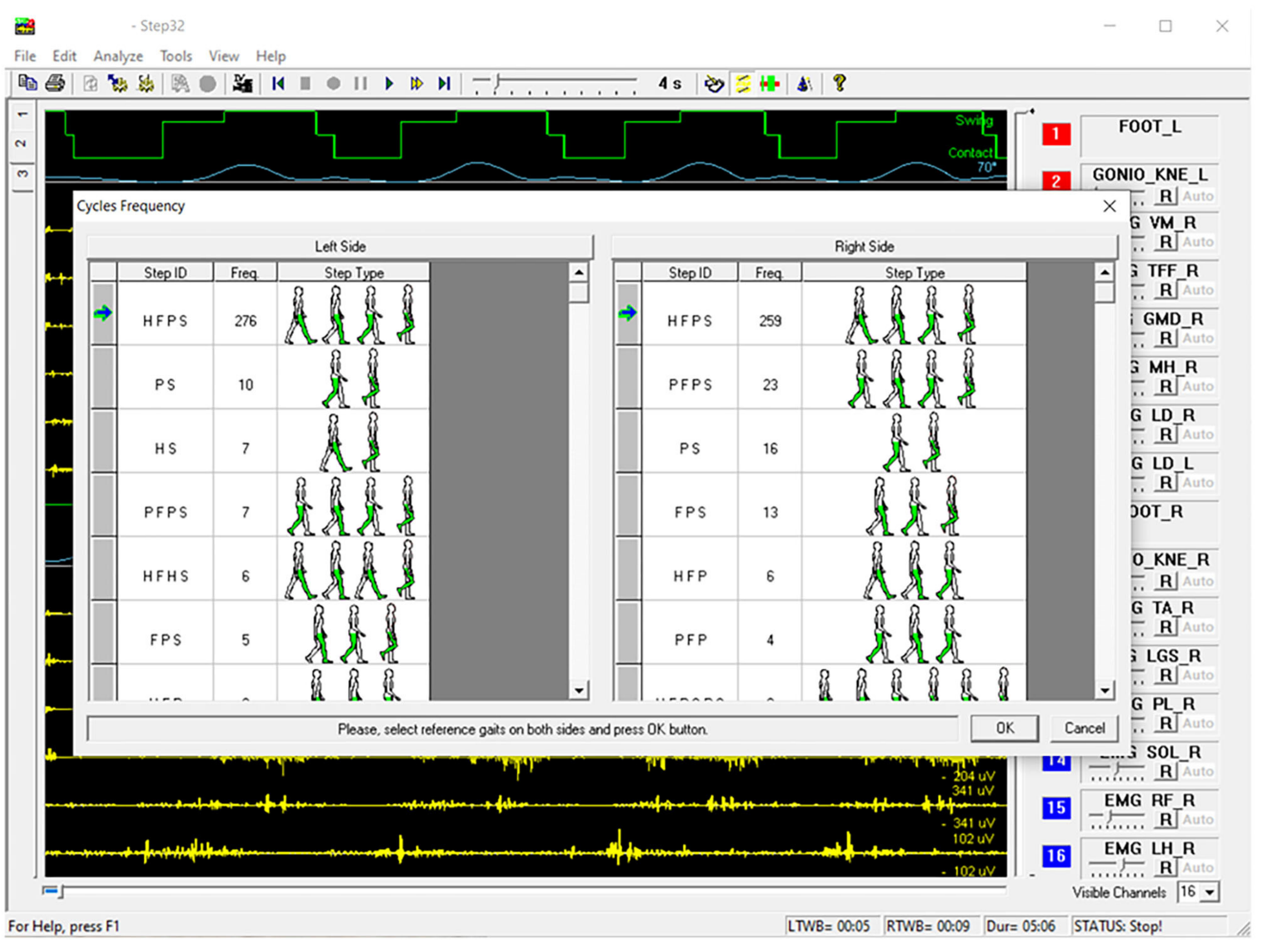

FIGURE 4 | Example of STEP32 interface showing the automatic segmentation and classification of gait cycles for a walk lasting 5:06 min (Parkinson disease subject).

biomechanical models, and to mitigate drift errors observed during gait analysis (55, 79, 83, 84).

Direct measurements to time gait events

For what concerns direct measurements systems for timing gait events synchronous to sEMG signals, foot-switches already demonstrated their high potentialities in terms of accuracy, versatility, and ease of use in the past decades (85). Like IMUs, foot-switches are low-cost, lightweight, and allow for unconstrained acquisitions. At this time, they are the most valid alternative for timing gait events in clinical sEMG-GA. Timing gait events directly through foot-switches, the gait signals acquired from the whole walk of 3–5 min can be divided into strides, identifying the start and end of each gait cycle. Furthermore, within each gait cycle, the sequence of gait phases and their duration can be obtained. Then, sEMG signals corresponding to straight steady-state gait cycles, can be extracted and further analyzed, while disregarding outliers cycles. This can be performed by applying appropriate classification algorithms to recognize each gait cycle sequence ("cycle typology") (85), and multivariate statistical filters based on gait phase duration (Hotelling *T*-square test) (86, 87). It should be noticed that this can be performed both in physiological and pathological gait, without the need for pre-defined stride templates, or complex algorithm customization targeting specific pathologies.

More specifically, placing 3 foot-switches under the heel, the first, and the fifth metatarsal heads (the main contact points of the foot with the ground in a normal subject) it is possible to obtain a 4-level basography, as shown by the green lines in **Figure 1**. This allows establishing the sequence of foot-floor contact gait phases and their duration. In normal gait, the standard sequence of gait phases of a stride is Heel contact (H), Flat foot contact (F), Push-off (P), Swing (S). Therefore, HFPS is the name assigned to the "normal" gait cycle. The average duration of gait phases in young adults (53), expressed as percentage of gait cycle (% GC), is:

- H = 6.6 ± 2% GC
- F = 26.4 ± 4% GC
- P = 22.6 ± 4% GC
- S = 44.4 ± 4% GC

However, other gait cycle typologies are also observed, especially (but not exclusively) during U-turns. A markedly different sEMG activity is expected in these cases. Furthermore, the specific duration of gait phases, within a specific cycle typology, depends on the individual subject and gait speed, and it slightly changes

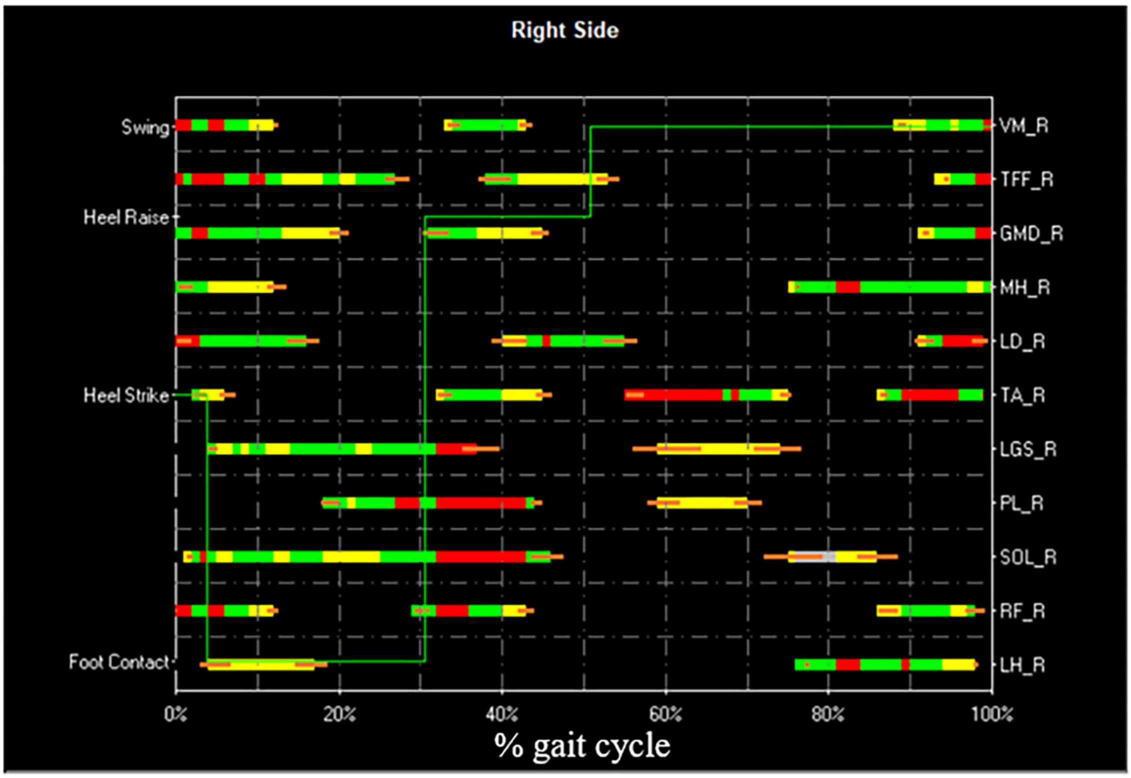

FIGURE 5 | Example of STEP32 interface showing the results of the sEMG analysis. After the selection of the HFPS cycles reported in **Figure 4**, the most frequent activation patterns are shown for Vastus Medialis (VM), Tensor Fasciae Latae (TFF), Gluteus Medius (GMD), Medial Hamstring (MH), Longissimus Dorsii (LD), Tibialis Anterior (TA), Lateral Gastrocnemius (LGS), Peroneus Longus (PL), Soleus (SOL), Rectus Femoris (RF), Lateral Hamstring (LH) of the right side (most affected side of the PD subject). For each muscle, the orizontal bars represent the average activation intervals of the most frequent activation modality. The normalized amplitude is color-coded in three levels: high amplitude in red, medium amplitude in green, and small amplitude in yellow. Orange bars represent the standard error on the onset/offset detection of the activation intervals. The basographic signal is also shown superimposed (green line).

from cycle to cycle. For each subject, and for each gait cycle type (e.g., HFPS), the mean, or the median value (more robust against outliers), of each gait phase duration can be calculated. In correspondence of the U-turns/outlier epochs, a relevant change in the sequence or in the duration of the gait phases appears in the basography and can be automatically detected. In pathological gait, the number of gait phases, their sequence, and duration can change with respect to normal gait, as well as the overall intra-subject variability. As an example, hemiplegic children after cerebral palsy, with a foot drop on the affected lower limb, typically strike the floor with the forefoot instead of the heel. They mainly show PFPS and/or PS sequence of gait phases instead of HFPS (82). Nevertheless, in the same manner as for healthy subjects, proper algorithms can handle gait cycle segmentation and classification, discarding outlier cycles, based on a statistical analysis (85). This approach is known as Statistical Gait Analysis (SGA) and it was developed and validated by our research group, specifically to deal with the challenges of clinical gait analysis mentioned above, to analyze hundreds of gait cycles in a user-independent way. The software of the STEP32 system integrates this "SGA philosophy". **Figure 4** shows the user interface where the gait cycles are classified and sorted by their frequency of occurrence (for a PD subject). Then, only sEMG signals corresponding to the gait cycles sharing the same foot-floor contact sequence are considered (HFPS was selected in this case). **Figure 5** shows the results of the sEMG analysis.

We would like to stress that, if the subject contacts the floor differently in different gait cycles (e.g., with the forefoot instead of with the heel), it is evident that different sEMG patterns are produced. These differences are more pronounced in the distal part of the lower limb, e.g., for the ankle flexo-extensor muscles (TA and LGS). If this source of extrinsic sEMG variability is not properly handled, the results of the analysis cannot be accurate. Hence, a fundamental step before analyzing sEMG patterns is to group together only those patterns belonging the same typology of gait cycle.

While a gait analysis expert can select the subject's most representative gait cycles, choosing them one-by-one "manually," this is unfeasible in clinical applications, requiring a reliable and repeatable analysis of hundreds of gait cycles, in a user-independent manner. Therefore, in summary, it is advisable

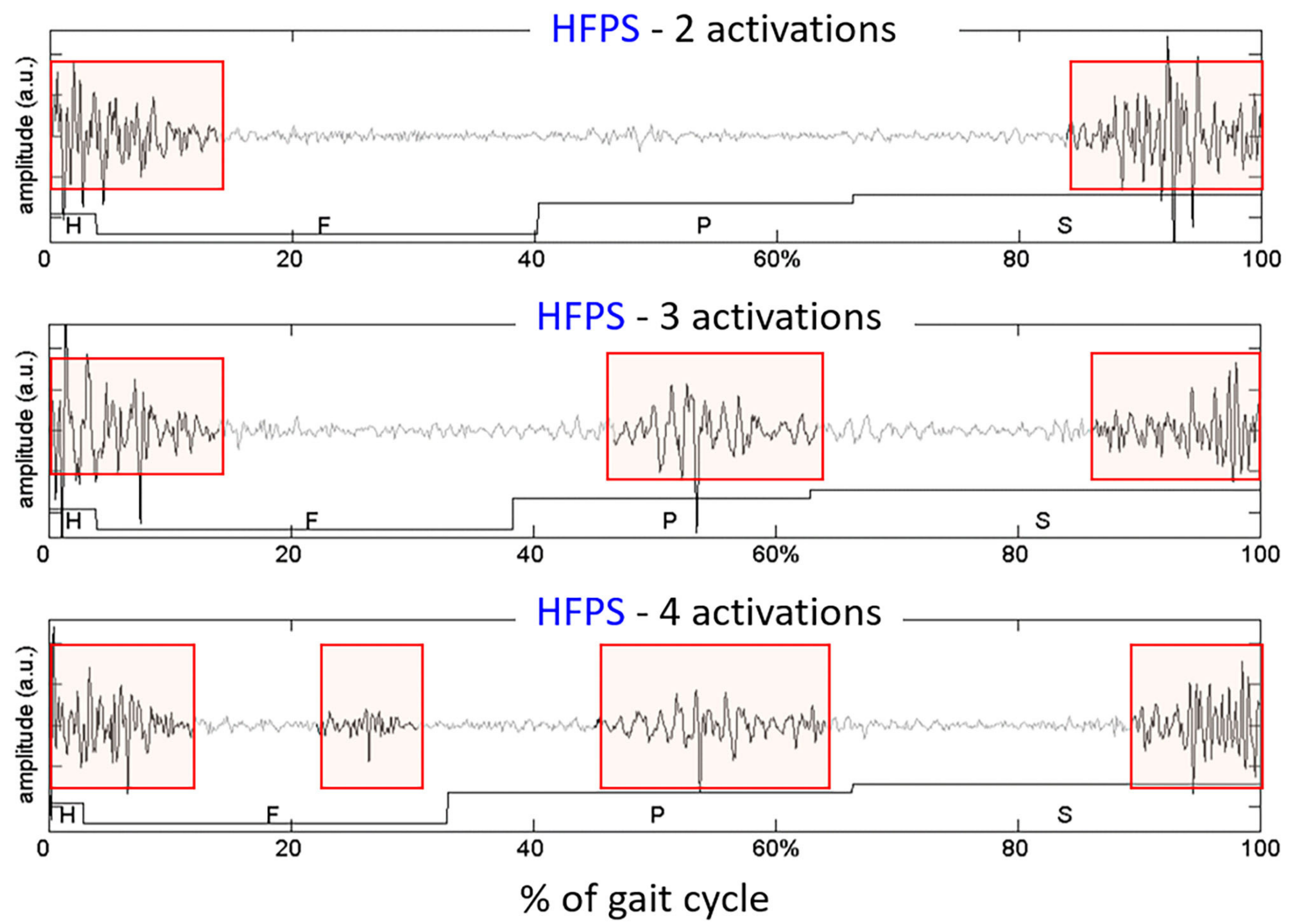

FIGURE 6 | Example of different activation modalities of the Rectus Femoris, observed in sEMG signals collected from an healthy subject, on 3 gait cycles of the same type (HFPS) collected during the same walk. The colored boxes highlight the intervals in which the muscle activity is present.

that systems designed for clinical sEMG-GA incorporate algorithms to:

- remove U-turns and outlier epochs
- segment and classify gait cycles and their frequency of occurrence
- focus sEMG analysis on representative gait cycles of the same type.

Intrinsic Sources of sEMG Variability

Even if sEMG signals are processed separately for each class of representative gait cycles, there are other sources of intra-subject variability that must be accounted for. More specifically, literature reports that, even in normal HFPS gait cycles of healthy subjects, a specific subject's muscle does not show a single "preferred" pattern of activation. Instead, from 3 to 5 distinct sEMG patterns are usually observed, each characterized by a different number of activation intervals occurring within the gait cycle. These are called "activation modalities" (52). **Figure 6** shows sEMG variability on a representative subject (young healthy individual). However, especially when analyzing pathological subjects, inspecting separately each modality of activation and its frequency of occurrence (88) may be rather cumbersome. Consequently, clinicians may lose interest, since results are difficult to interpret.

In recent years, a clustering algorithm was proposed and validated, both on healthy and pathological subjects, to manage intrinsic sources of within-subject sEMG variability in overground locomotion. This algorithm, named CIMAP (Clustering for Identification of Muscle Activation Patterns) allows grouping together sEMG patterns sharing similar timing patterns (58, 81, 89). Then, it is possible to define, in a unique manner, the sEMG principal activations (PA) of a subject during gait (63, 90–93). A single binary string, representing PA intervals, is associated to the overall dynamic activity of the muscles during a subject's locomotion (1: the muscle is active; 0: the muscle is non-active). **Figure 7** shows the effects of intra-subject variability on the interpretation of sEMG activation patterns, graphically illustrating the importance of using clustering algorithms. **Figure 8** schematically depicts the extraction of PA in a representative subject.

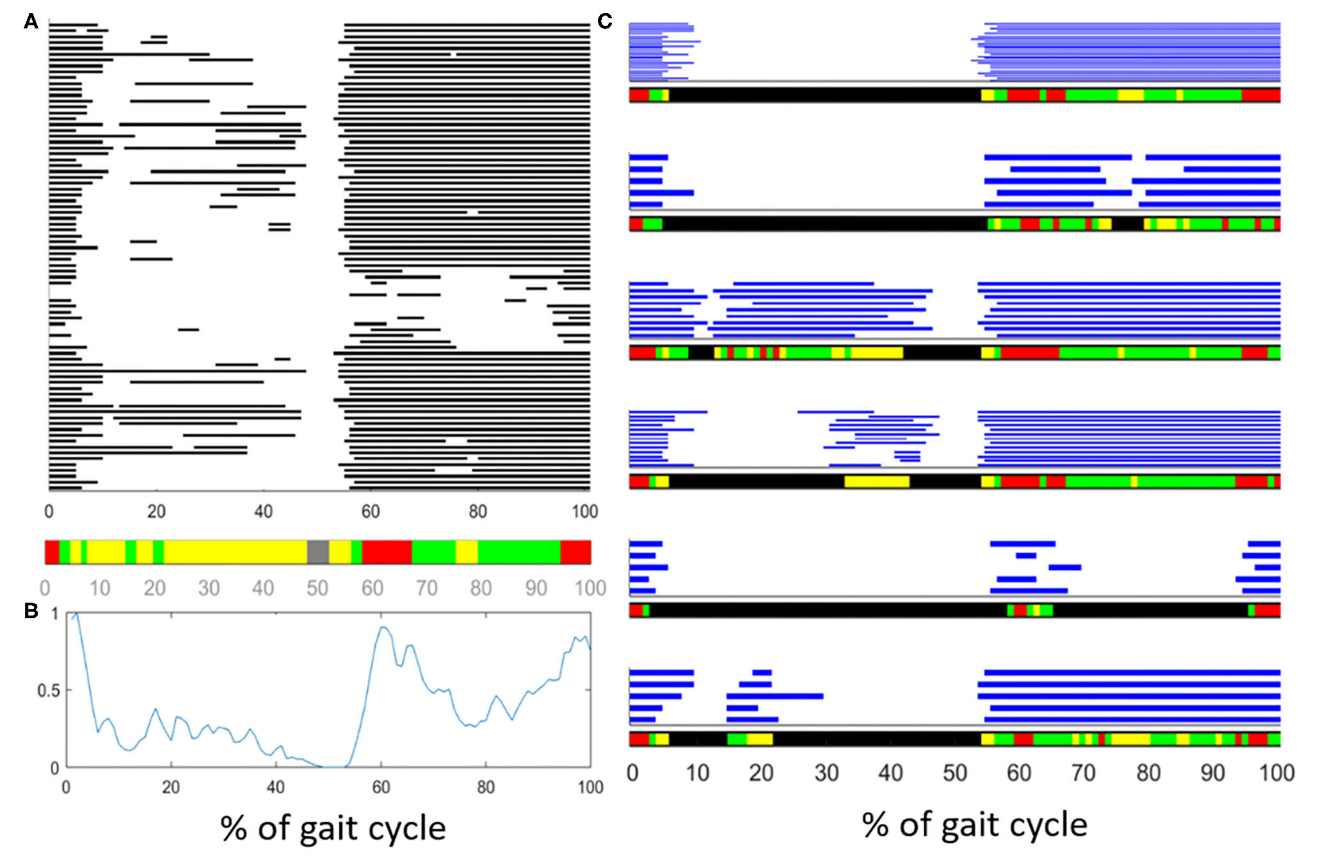

FIGURE 7 | Description of the effects of intrasubject variability on the interpretation of muscle activation patterns during gait. **(A)** Example of variability in the activationd of the Tibialis Anterior (TA) muscle of an healthy subject. Gray bars represent the activation intervals in different gait cycle of the same walk. Observing the average activity, represented in the color bar below **(A)** or represented as a "linear envelope" in **(B)**, one would conclude that TA muscle is almost always active. **(C)** After grouping together the gait cycles sharing the same activation-timing patterns, the average activation intervals (within each group) really represent the muscular activation patterns. In the latest case, the biomechanical task of each activation interval becomes clear.

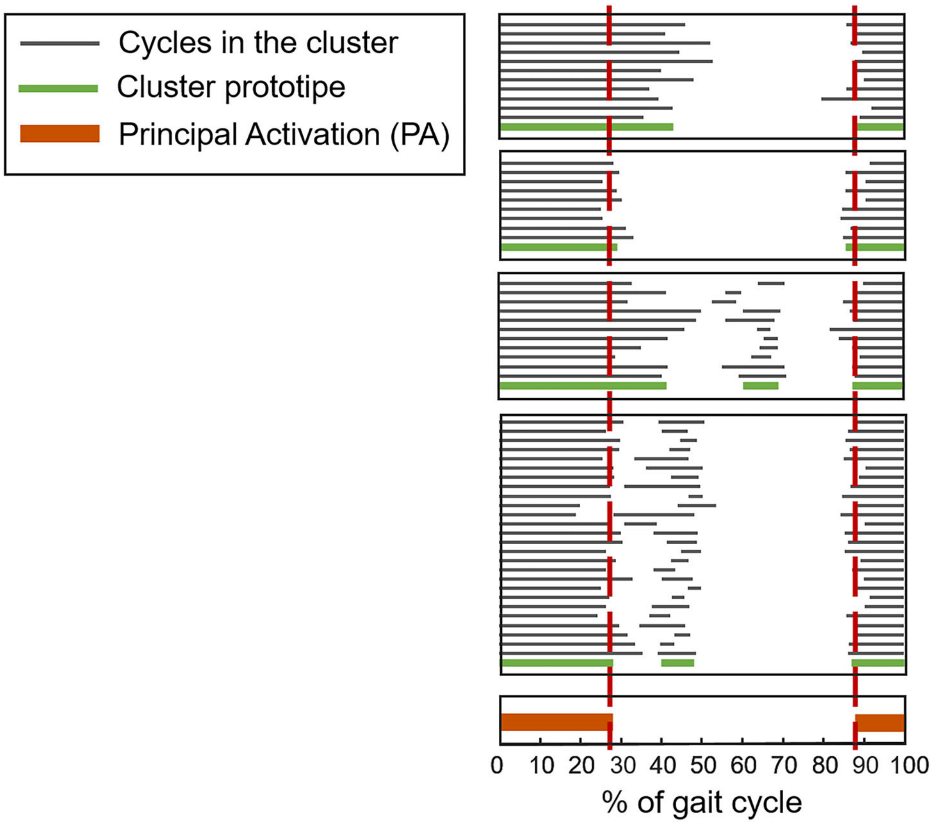

FIGURE 8 | Example of application of CIMAP (Clustering algorithm for Identification of Muscle Activation Patterns) for the Rectus Femoris muscle. Gray bars represent the activation intervals in different gait cycles of the same walk. The Principal Activation (PA) is univoquely determined as the intersection of cluster's prototypes.

The use of this kind of algorithms would enormously simplify the interpretation of sEMG signals during locomotion. Indeed, a single (but representative) PA-string might be compared before and after a rehabilitation program, or a therapeutic intervention, helping clinicians in their work. Notice that this process is scalable, and can be repeated to obtain unique PA from a cohort population (instead of a single patient) to ease the interpretation of randomized clinical trials using sEMG measurements (91).

However, the described advanced sEMG processing tools, aimed at managing the intrinsic sources of sEMG variability, are currently not available to clinicians. Presently, there are no medical system integrating these important features. Future systems designed for clinical sEMG-GA should incorporate, cascaded to the algorithms mentioned in the previous section, CIMAP-like algorithms.

Lack of Simple/Compact/Unique Clinical Scores Obtainable From sEMG-GA

After many years of tight collaborative work with clinicians, and fervent requests of help in the interpretation of sEMG signals during gait, we understood that an essential point is providing simple/compact/unique clinical scores for easily comparing the patient outcome at different time points (and with reference data).

The great majority of research papers typically presents results from dozens of different parameters, typically estimated from signals of each specific muscle under study. This makes the application to patient management difficult. A few attempts can be found in literature to summarize the information obtained from sEMG-GA test in a unique and representative value of the patient's locomotion performance. One successful recent example is the introduction of a sEMG-based "asymmetry index" (54). This index defines the patient's global asymmetry during gait, and it was validated on different orthopedic populations (total hip arthroplasty, total knee arthroplasty) and neurological populations (hemiplegic children, normal pressure hydrocephalus). Furthermore, reference values for different age populations (children, adults, elderly) were also provided.

However, none of the available systems for sEMG-GA integrates this index or similar ones.

DISCUSSION AND CONCLUSIONS

One of the fathers of modern sEMG analysis, Prof. C.J. De Luca, already 30 years ago warned that the sEMG signal, if not properly analyzed, could become "a seductive muse." In the last decade, there have been intense efforts to find reliable methods to process and correctly interpret muscle activation patterns in locomotion. Nevertheless, there is still an evident gap between literature findings and clinical practice. In this contribution, we critically analyzed the main key factors limiting the widespread use of sEMG signals in clinical gait analysis.

In synthesis:

- There is a lack of open databases related to reference populations (of healthy children, adults, and elderly) containing normative activation patterns as well as raw sEMG signals, collected during gait. Furthermore, there are no accepted standards on how to report muscle activation patterns.
- There is a lack of systems for clinical gait analysis that integrate quality information about the collected sEMG signals, in real-time, to improve intra-operator repeatability and inter-operator reproducibility.
- There is a lack of (wearable and wireless) systems for sEMG detection that integrate algorithms for the study of gait in natural conditions.
- There is a lack of systems that integrate algorithms aimed at managing the high intra-subject variability of sEMG patterns in human gait (both of extrinsic and intrinsic nature).
- There is a lack of systems that integrate simple scores or indexes, calculated from sEMG-GA data, to help clinical interpretation.

Therefore, the authors believe that it is fundamental to rethink this research field, organizing debates, consensus meetings, interdisciplinary projects and other initiatives to provide a critical view of the topic and, last but not least, redesign user-friendly systems for sEMG-GA, usable in clinics. In addition, it would be important to offer training on sEMG-GA techniques to clinicians and health practitioners, including open education and open data resources. If the proposed "positive actions" will be successful, good clinical practices will benefit from new evidence-based approach to rehabilitation.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

VA and MK designed the article structure and topics covered. VA drafted the article, with the contribution of MG for the production of some of the figures. MG, SR, GB, and MK critically revised the article. All authors contributed to the article and approved the submitted version.

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A Survey on the Use and Barriers of Surface Electromyography in Neurorehabilitation

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Historical, educational, and technical barriers have been reported to limit the use of surface electromyography (sEMG) in clinical neurorehabilitation settings. In an attempt to identify, review, rank, and interpret potential factors that may play a role in this scenario, we gathered information on (1) current use of sEMG and its clinical potential; (2) professional figures primarily dealing with sEMG; (3) educational aspects, and (4) possible barriers and reasons for its apparently limited use in neurorehabilitation. To this aim, an online 30-question survey was sent to 52 experts on sEMG from diverse standpoints, backgrounds, and countries. Participants were asked to respond to each question on a 5-point Likert scale or by ranking items. A cut-off of 75% agreement was chosen as the consensus threshold. Thirty-five invitees (67%) completed the electronic survey. Consensus was reached for 77% of the proposed questions encompassing current trends in sEMG use in neurorehabilitation, educational, technical, and methodological features as well as its translational utility for clinicians and patients. Data evidenced the clinical utility of sEMG for patient assessment, to define the intervention plan, and to complement/optimize other methods used to quantify muscle and physical function. The aggregate opinion of the interviewed experts confirmed that sEMG is more frequently employed in technical/methodological than clinical research. Moreover, the slow dissemination of research findings and the lack of education on sEMG seem to prevent prompt transfer into practice. The findings of the present survey may contribute to the ongoing debate on the appropriateness and value of sEMG for neurorehabilitation professionals and its potential translation into clinical settings.

Keywords: surface electromyography, sEMG, neurorehabilitation, survey, expert opinion, muscle activation, clinical research

INTRODUCTION

Surface electromyography (sEMG) is a technique for non-invasive measurement of the electrical activity of a muscle through adequately positioned surface electrodes on the skin (1). sEMG has been suggested as a tool to enhance neuromuscular assessment and rehabilitation of individuals with neurologic conditions. Although sEMG has been used extensively for research and its potential value in neurorehabilitation has been proposed (2–4), the true benefits that this technology may bring to clinicians and patients are unclear, possibly limiting its translational use in clinical practice. Based on a recent qualitative study conducted among neurorehabilitative experienced personnel (5), sEMG was deemed by clinicians as hardly compatible with practical aspects of rehabilitation, with limited time and resources perceived as the most relevant barriers to its employment. Transferring medical innovations into clinical practice is quite difficult in rehabilitation (6, 7). Two main reasons have been identified for this challenging translation: (1) limited knowledge of the relevant physical laws and conditions that apply to problems or circumstances, in contrast to evidence-based practice (EBP) guidelines and recommendations; (2) failure of an individual or group to apply established knowledge correctly in a specific circumstance (7, 8). According to Jette (7), these limitations may very well apply to the rehabilitation domain. Indeed, while EBP provides clinicians with a systematic approach to appraise, select, apply, and integrate research findings with patient preferences and clinicians' expertise as part of their clinical decision-making process, inappropriate, or insufficient adherence to indications results in a limited impact on patients (9). We believe that such line of thought may be stretched to the paradigmatic case of sEMG usage in clinical practice, as the benefits of this technology may not be perceived as compelling enough to support its incorporation into clinical practice, given the current lack of translational evidence.

Due to its non-invasive nature, sEMG has been used as a clinical tool in several neurological conditions such as Parkinson's disease (10, 11), stroke, and cerebral palsy (12), but also in orthopedic and gynecological rehabilitation, in sport, aging, and space medicine, as well as in gnathology (13). Specific examples of routine clinical use include measuring muscle fiber conduction velocity after electrical stimulation of peripheral nerves (14, 15) and as a standard for recording compound muscle action potentials after transcranial or peripheral magnetic stimulation (16). Moreover, integration of sEMG into gait analysis has greatly advanced our understanding of muscle function during typical and pathological gait (17). Other clinical applications in human movement analysis include recording a muscles' reaction time or the synergistic properties of multiple muscles. Recent findings have also shown that sEMG can be useful for neurorehabilitation (3–5) in the context of physician-supervised programs designed to rehabilitate people with diseases, traumas, or disorders of the nervous system. Ample evidence exists for its use in predicting long-term recovery from neurologic injury such as stroke and spinal cord injury, understanding healthy and pathological muscle activity profiles and interlimb coordination, quantifying dynamic motor control parameters in gait, supporting the design of neuro-orthopedic surgery, providing biofeedback, and tracking the effects of conservative rehabilitation and surgery (18–22). Moreover, methodological recommendations are nowadays available thanks to *ad-hoc* European actions and to the efforts made by national scientific societies (17, 23).

However, since its very first applications to assess human gait in the 1950s and the massive developments of this technology in the 1970s (24), its value as a clinical tool is still controversial (3, 5, 11). In fact, even when integrated into clinical movement analysis, the lack of an accepted gold standard prevents it from being widely considered as an essential component. Indeed, sEMG was generally regarded as an auxiliary tool rather than the main investigation method in the functional evaluation of a patient (16).

In a recent qualitative study, Feldner et al. (5) set out to examine the clinicians' perceived value, benefits, drawbacks, and ideas for technology development and implementation of sEMG recordings in neurologic rehabilitation practice. Semi-structured interviews and focus groups were organized among 22 clinicians in the United States with a rehabilitative background (59% occupational therapists, 32% physiotherapists, 9% physiatrists) from inpatient, outpatient, and research settings. The main conclusion of this study was that, despite the acknowledged clinical benefits for neurorehabilitation, sEMG is not routinely employed for assessment or intervention following neurologic injury. Furthermore, limited time and resources were identified as the key barriers to sEMG usage by clinicians. This indicates the need to streamline intuitive and clinically impactful sEMG applications and systems, and to conduct further research to determine the clinical relevance of sEMG in neurorehabilitation, its clinical feasibility and current barriers preventing widespread usage.

In this study, we further expanded the work of Feldner et al. (5) by gathering information from a multidisciplinary panel of experts with different backgrounds to originate experts' opinion on the current use of sEMG and its clinical potential in neurorehabilitation. To achieve this, we departed from Feldner's choice to enroll only clinicians and opted for conducting survey research [which is defined as "the collection of information from a sample of individuals through their responses to questions" (25)] among leading experts who published on sEMG and neurorehabilitation from both a methodological and clinical point of view. Indeed, the present work was conceived and planned as a first step in the establishment of an international, clinical research initiative aimed at appraising the translational value of sEMG in the clinical setting.

Within this framework, we developed questions to gather experts' opinion on: (1) current use of sEMG and its clinical potential in neurorehabilitation; (2) professional figures primarily dealing with sEMG; (3) educational aspects, and (4) possible barriers and reasons for the apparently limited employment of sEMG.

As such, we aimed to outline a common framework and a stimulus for future research on specific sEMG-related issues.

METHODS

An online survey involving experts on sEMG from diverse standpoints, backgrounds (i.e., biomedical engineers, neurophysiologists, kinesiologists, neurologists, physiotherapists) and geographical origins was conducted.

Participants

Through a literature scan of three biomedical databases (PubMed/Medline, Scopus, Web of Science, as of August 31, 2019) using common keywords (surface electromyography AND neurorehabilitation) and limiting to medical subject headings (MeSH) and MeSH Major Topic, we retrieved an initial set of 821 articles (396 with PubMed/Medline, 247 with Scopus, 178 with Web of Science) to be then manually screened. Based on the title, abstract and keywords, pertinent articles were selected by two of the authors (AM, FD) (87 with PubMed/Medline, 72 with Scopus, 54 with Web of Science). After removing duplicates across the databases, manual screening of the full-texts led to retain 32 articles specifically dealing with the topic under study. From these, a set of unique authors' names was extracted, leaving 82 authors who had published at least two articles which major topic was the application of sEMG to neurorehabilitation from a methodological/technical or clinical perspective, or both. Of these 82 individuals, 52 had authored at least two articles in a prominent role (first or second or last or corresponding author). After extracting contact information, electronic invitations were sent to these 52 authors. The participants were requested to respond anonymously to a questionnaire, which had been developed iteratively by a primary research team (AM, AC, FD) and then reviewed and pilot-tested by an external board of eight "core experts" (LB, AB, UDC, MK, NM, DM, AM, SR, AT). Feedback received during review and piloting was incorporated into the survey.

Survey Questions

The survey (**Supplementary File 1**) comprised 30 questions. The last 8 questions (questions 23–30) concerned demographic, background, and professional information, while the 22 remaining questions covered four main themes that had been conceived, shared, and developed into their final form through an iterative process between the primary research team and the external board of core experts. Based on extensive discussion and on experts' suggestions and feedback, the thematic framework was approved as follows: (1) current EMG employment in clinical settings and potential utility (questions 1–10); (2) professional figures using EMG and potential advantages of better qualified professionals (questions 11–15); (3) education, training, and teaching (questions 16–20); (4) potential barriers to sEMG usage (questions 21 and 22).

The Survey Process

An online software [SurveyMonkey http://survey-monkey.com] was used to deliver the questionnaire electronically. Identified experts were invited to participate via an e-mail that included key information about the study, its purpose, how it would inform consensus on sEMG employment, potential utility, professional figures involved in its usage, education, training and teaching, and potential barriers.

Participants were asked to respond to each question on a 5-point Likert scale (e.g., 1, strongly disagree; 2, disagree; 3, neutral; 4, agree; 5, strongly agree), and in two questions (11 and 21), by ranking items. They were also instructed to leave unanswered those questions that were perceived as outside their expertise/knowledge. We asked them for any additional comments/insights they wished to provide using free-text boxes. These comments were recorded and, based on an eventual trend (i.e., two or more participants raising the same issue), taken into consideration and commented upon when interpreting the survey results. The survey was available for 6 weeks. Four reminders were sent by e-mail to participants on days 14, 28, 35, and 42.

Data Analysis

A cut-off of 75% agreement was chosen as the consensus threshold based on the findings of a systematic review of surveys and consensus studies (26). Accordingly, we considered consensus to be reached if at least 75% of respondents scored the question 4 or 5 (positive consensus toward agreement) or 1 or 2 (negative consensus toward disagreement) on the 5-point Likert scale. For ranking questions, we analyzed the distribution of the response frequencies and considered only the first three in rank, based on the number of preferences received. Descriptive statistics are reported in the form of counts/proportions/percentages. Subgroup analyses were also carried out to compare the response rates of non-clinical vs. clinical professional figures. The frequency rates were compared using two-tailed Chi-square tests with the significance level set at $p < 0.05$.

RESULTS

Participation by Round

Of the 52 invitation e-mails sent (February 24 to April 7, 2020), 35 invitees (67%) completed the 30-question survey. Responses were received from a minimum of 26 to a maximum of 35 participants (74–100%). Data were analyzed from the 35 respondents and the consensus threshold (75%) was calculated for each question relative to the number of respondents.

Table 1 details the respondents' characteristics. Professional background was varied, with 13 (37%) physiotherapists, 12 (34%) biomedical engineers with a focus on instrumentation, e-health, and rehabilitation (hereafter referred to as biomedical engineers), 5 (14%) Physical Medicine and Rehabilitation (PM&R) specialists, also known as physiatrists, 3 (9%) kinesiologists/human movement scientists, and 2 (6%) clinical neurophysiologists. Clinicians accounted for 57% (20/35) of the cohort, of which 17 (85%) were active in the neurorehabilitation field. The other professionals were either engaged purely in research or as lab technicians/engineers in clinical settings.

The specific clinical subfields of the interviewed cohort were also checked (question 30). The majority of the respondents declared to engage in "Activities to improve

TABLE 1 | Respondents' characteristics ($n = 35$).

Background	*n*	(%)
Biomedical engineers*	12	34
Clinical neurophysiologists	2	6
Kinesiologists/human motion scientists	3	9
PM&R specialists	5	14
Physiotherapists	13	37
Neurorehabilitation subfield#		
Activities to improve mobility, muscle control, gait, and balance	23	66
Exercise programs to prevent or decrease weakness, manage spasticity and pain, and maintain range of motion	20	57
Help with obtaining assistive devices that promote independence'	12	34
Help with activities of daily living	9	26
Patient's education and counseling	6	17
Not working in a clinical setting	8	23
Geographical location		
Australia	1	3
Austria	1	3
Belgium	2	6
Canada	1	3
France	3	9
Germany	1	3
Ireland	1	3
Italy	19	54
Netherlands	2	6
Switzerland	2	6
United Kingdom	1	3
United States	1	3

**With a focus on instrumentation, e-health, and rehabilitation; PM&R, Physical Medicine and Rehabilitation; #Percent values do not add up to 100 since some respondents identified themselves as part of more than one category.*

mobility (movement), muscle control, gait, and balance" (23/35, 66%) and in "Exercise programs to improve movement, prevent, or decrease weakness caused by lack of use, manage spasticity and pain, and maintain range of motion" (20/35, 57%). Twelve (34%) specifically engaged in "Help with obtaining assistive devices that promote independence," 9 (26%) in "Help with activities of daily living (ADLs)," and 6 (17%) in "Patient's education and counseling." Two respondents declared in the comment areas to specifically engage in "Measuring human motion in clinics." Eight out of 35 (23%) declared not to work in a clinical setting, but rather in clinical research.

Table 2 summarizes all items which exceeded the predefined 75% threshold for consensus. The items for which no consensus was reached are detailed in **Table 3**.

1. Current sEMG employment in clinical settings and potential utility (questions 1–10) – Consensus was reached on that sEMG is more frequently employed in technical/methodological research than clinical research (29/35, 83%), and that it should be used in neurorehabilitation to obtain information on neuromuscular function that is not provided by other assessment techniques/tools (32/35, 91%). With regard to its clinical utility, the respondents agreed by consensus that sEMG can enhance the assessment and characterization of neuromuscular impairments in patients (34/35, 97%), positively influences the intervention plan design (28/35, 80%), allows better tracking of changes in muscle activity from baseline when neurorehabilitation interventions are administered (32/35, 91%), allows evaluating the effects of non-invasive interventions designed to impact muscle activity (such as therapeutic exercise, orthotics, medication, physical agents, manual therapy techniques) (32/35, 91%), and allows evaluating the effects of invasive interventions designed to impact muscle activity (such as surgery and neuromuscular blocks) (30/35, 86%). Moreover, its employment for biofeedback training in case of abnormal patterns of muscle activity that may be modified through motor learning was agreed upon by 30/35 (86%) of the respondents.

When enquired specifically on the role of sEMG in patient's assessment, sEMG was deemed by consensus very likely to be useful to outline the sequential timing of muscular actions during given movements (i.e., gait, motor tasks) (35/35, 100%), evaluate the appropriateness of the muscle activity during a specific movement (muscle balance/imbalance/synergy/function) (34/35, 97.1%), and characterize the stretch reflex (28/35, 80%).

Regarding the utility of sEMG in the definition of an intervention plan, sEMG was indicated as potentially useful when there is need to investigate or quantify abnormalities in the sequential timing of muscular actions during given movements (32/35, 91%), muscle imbalance/dyssynergia (26/33, 79%), and involuntary muscle activity (e.g., dystonia, ataxia) (25/32, 78%). No consensus was reached for 6 of the 8 items questioning whether sEMG information may prove useful to track changes induced by a therapeutic intervention. The cohort agreed that sEMG can, instead, track rehabilitation-induced changes in the sequential timing of muscular actions during given movements (i.e., gait, motor tasks) (31/33, 94%) and for involuntary muscle activation (e.g., dystonia, ataxia) (24/32, 75%).

Regarding the employment of sEMG as a stand-alone technique or in combination with other methods used by neurorehabilitation professionals to assess muscle and physical function, only 18 out of 32 respondents (56%) suggested the stand-alone use of sEMG, whereas they agreed by consensus on the combination of sEMG with gait/motion analysis (with or without motion capture) (35/35, 100%), muscular hyperactivity/muscle tone assessment (29/34, 85%), accelerometry (25/31, 80%), and stretch-reflex assessment (26/34, 77%).

When questioning about the employment of sEMG for biofeedback training in case of abnormal patterns of muscle activity, consensus was reached for its utility in allowing the patient to learn how to "change the coordination pattern of an agonist with respect to antagonists and synergists (muscle

TABLE 2 | Survey items that reached consensus.

Survey items	Agreed	(%)
1. sEMG is more frequently employed in technical/methodological research than clinical research.	29/35	(83)
2. sEMG provides information on neuromuscular function that is not provided by other assessment techniques/tools in neurorehabilitation.	32/35	(91)
3. Practical utility of sEMG in clinical neurorehabilitation. sEMG information on neuromuscular activation may:		
Enhance the assessment and characterization of neuromuscular impairments in patients	32/34	(94)
Influence the intervention plan design	28/33	(85)
Allow to better track the changes in muscle activity from baseline when neurorehabilitation interventions are administered	32/34	(94)
Allow to evaluate the effects of non-invasive interventions designed to impact muscle activity (such as therapeutic exercise, orthotics, medication, physical agents, manual therapy techniques)	32/25	(91)
Allow to evaluate the effects of invasive interventions designed to impact muscle activity (such as surgery and neuromuscular blocks)	30/34	(88)
Be employed as biofeedback training if the clinician identifies abnormal patterns of muscle activity that may be modified through motor learning	30/34	(88)
4. Role of sEMG in patient's assessment—sEMG may be useful to:		
Outline the sequential timing of muscular actions during given movements (i.e., gait, motor tasks)	35/35	(100)
Evaluate the appropriateness of the activation among muscles participating to a specific movement (muscle/balance/imbalance/synergy/function)	34/35	(97)
Characterize the stretch reflex	28/35	(80)
Characterize muscular hyperactivity (e.g., spasticity, spastic co-contraction, spastic dystonia)	26/33	(79)
5. Utility of sEMG in the definition of an intervention plan - sEMG may be useful when there is need to investigate or quantify: *Abnormalities in the sequential timing of muscular actions during given movements (i.e., gait, motor tasks)*		
Muscle imbalance/dyssynergia	26/33	(79)
Muscular hyperactivity (e.g., spasticity, spastic co-contraction, spastic dystonia)	25/32	(78)
6. If a therapeutic intervention is administered, sEMG information may prove useful to track changes from baseline in:		
Sequential timing of muscular actions during given movements (i.e., gait, motor tasks)	31/35	(89)
Involuntary muscle activation (e.g., dystonia, ataxia)	24/32	(75)
7. sEMG assessment can be performed as a stand-alone technique or to complement/optimize other methods used by neurorehabilitation professionals to quantify muscle and physical function. It seems useful adding sEMG to:		
Gait/motion analysis (with or without motion capture)	35/35	(100)
Hyperactivity/Spasticity/muscle tone assessment	29/34	(85)
Accelerometry	25/31	(81)
Stretch reflex	26/34	(76)
8. sEMG, when used as biofeedback, may help to:		
Learn how to change the coordination pattern of an agonist with respect to antagonists and synergists (muscle selectivity)	30/33	(91)
Learn how to decrease the activity of overly tense and/or involuntarily hyperactive muscles	29/33	(88)
Learn how to increase the activity of weak and/or hypoactive muscles	29/32	(91)
9.* Professional figure who is most frequently involved in sEMG recordings:		
Biomedical engineer with a focus on instrumentation, e-health, and rehabilitation	Ranked 1st	
Physiotherapist	Ranked 2nd	
Kinesiologist/human motion scientist	Ranked 3rd	
10. Professional figures involved in sEMG signal acquisition, processing, and quality control:		
Biomedical engineer with a focus on instrumentation, E-health, and Rehabilitation	31/34	(91)
Kinesiologist/human motion scientist	27/34	(79)
11. Professional figures involved in sEMG interpretation:		
Kinesiologist/human motion scientist	27/33	(82)
Clinical neurophysiologist	26/32	(81)
Physical Medicine and Rehabilitation physician, also known as physiatrist	25/32	(78)
Biomedical engineer with a focus on instrumentation, e-health, and rehabilitation	25/33	(76)
Physiotherapist	24/32	(75)
12. Greater qualification of neurorehabilitation professionals on sEMG would contribute to improve the quality of neurorehabilitation care delivery	28/35	(80)

(Continued)

TABLE 2 | Continued

Survey items	Agreed	(%)
13. Years of practice/experience with sEMG techniques needed to qualify for providing education and training on the use of sEMG to clinical neurorehabilitation professionals:		
<1 year: very inadequate	29/32	(91)
>5 years: very adequate	25/29	(86)
14. In addition to basic know-how on sEMG recording (i.e., correct placement of electrodes, adequate skin preparation, etc.), further technical skills are needed:		
Ability to recognize and filter out artifacts at the skin-electrode interface	32/35	(91)
Ability to choose the processing technique that is most appropriate for a given application	30/35	(86)
15. EMG-derived variables considered of utmost importance for clinical applications in neurorehabilitation:		
Timing of muscle activations and their variability	34/34	(100)
Amplitude estimators (i.e., average rectified value, root mean square)	28/35	(80)
Signal quality/reliability indicators (e.g., artifact reporting)	26/34	(77)
Envelope time course	25/33	(76)
16. In addition to knowledge on physiological and non-physiological factors that influence sEMG, neurorehabilitation professionals need further competencies to interpret sEMG:		
Knowledge about sEMG patterns of recruitment in the main central and peripheral neuromuscular disorders	33/34	(97)
Knowledge about the use of sEMG to assess muscular hyperactivity	31/33	(94)
Knowledge about sEMG patterns of recruitment of healthy individuals	31/34	(91)
Knowledge about the pathologies that affect muscle fiber conduction velocity	23/30	(77)
17.* Work environment most likely to favor the usage of sEMG:		
Privately operated clinic (with public or insurance-based reimbursement)	Ranked 1st	
Publicly operated clinic (with either public or insurance-based reimbursement)	Ranked 2nd	
Privately operated clinic (out-of-pocket)	Ranked 3rd	
18. Potential barriers to the employment of sEMG in clinical neurorehabilitation:		
sEMG data analysis/interpretation difficult to perform without specific education/training	32/33	(97)
Inadequate education for professionals in neurorehabilitation	30/34	(88)
Lack of widely accepted evidence that the use of sEMG improves treatment effectiveness	26/34	(77)
Inadequate education and training on sEMG in graduation courses	27/34	(79)
Time-consuming	26/34	(77)

**Questions were presented as ranking items, with ranking reported in the table only for the first three items.*

selectivity)" (30/33, 91%), "decrease the activity of overly tense and/or involuntarily hyperactive muscles" (29/33, 88%), and "increase the activity of weak and/or hypoactive muscles" (29/32, 91%).

sEMG was expected to have practical utility in clinical neurorehabilitation for five neurological disorders: "Neuromuscular disorders" (31/32, 97%), "Stroke/cerebrovascular diseases" (28/31, 90%), "Spinal cord disorders" (24/29, 83%), "Peripheral nerve disorders" (24/30, 80%), and "Multiple sclerosis/demyelinating diseases" (24/31, 77%).

2. Professional figures using sEMG and potential advantages of better qualified professionals (questions 11–15) – Interviewees were asked to rank the professional figures who are most frequently involved in sEMG recordings in neurorehabilitation settings. Respondents listed "Biomedical engineer" in first place (13, 3, and 4 respondents for 1st, 2nd, and 3rd place, respectively) followed by "Physiotherapist" (6, 5, and 4 respondents for 1st, 2nd, and 3rd place, respectively) and "Kinesiologist/Human movement scientist" (3, 5, and 6 respondents for 1st, 2nd, and 3rd place, respectively).

When judging the level of involvement of each of the professionals for sEMG signal acquisition, processing and quality control, consensus was reached only for "Biomedical engineer" (32/34, 94%) and "Kinesiologist/Human movement scientist" (27/34, 79%) but not for other professions. When asked about the involvement for sEMG interpretation, respondents agreed by consensus on five professional figures: "Kinesiologist/Human movement scientist" (27/33, 82%), "Clinical neurophysiologist" (26/32, 81%), "PM&R" (25/32, 78%), "Biomedical engineer" (25/33, 76%), and "Physiotherapist" (24/32, 75%). Both PM&R doctors and physiotherapists were professionals with the highest number of "very high" agreement (23/32, 41%).

Participants were also asked whether greater qualification of neurorehabilitation professionals on sEMG would contribute to improve the quality of neurorehabilitation care and

TABLE 3 | Survey items that did not reach consensus.

Survey items	*n*	(%)
1. Overall, sEMG is rarely used in clinical neurorehabilitation	19/34	(56)
2. sEMG is currently more relevant for researchers than clinicians	24/34	(71)
3. Regarding the role of sEMG in patient's assessment, sEMG may be useful to:		
Identify pathological patterns of motor unit behavior	24/35	(69)
Evaluate the percent of maximal voluntary activation	19/35	(54)
Characterize motor fiber conduction velocity	22/33	(67)
4. Regarding the utility of sEMG in the definition of an intervention plan, sEMG may be useful when there is need to investigate or quantify:		
Muscular fatigue	19/33	(58)
Abnormalities in the motor unit behavior(muscle/balance/imbalance/synergy/function)	22/33	(67)
Abnormalities in the percent of maximal voluntary activation	16/34	(47)
Abnormalities in motor fiber conduction velocity	20/31	(65)
5. If a therapeutic intervention is administered, sEMG information may prove useful to track changes from baseline in:		
Muscular fatigue	20/33	(61)
Muscle imbalance/dyssynergia	25/34	(74)
The pattern of motor unit behavior	20/33	(61)
The percent of maximal voluntary activation	16/34	(47)
Stretch reflex	22/33	(67)
Motor fiber conduction velocity	21/32	(66)
6. sEMG assessment can be performed as a stand-alone technique or to complement/optimize other methods used by neurorehabilitation professionals to quantify muscle and physical function. It seems useful adding sEMG to:		
Mobility assessment (i.e., Timed Up and Go test; 10-Meter Timed Walk, etc.)	21/34	(62)
Muscle strength assessment	20/35	(57)
Posture analysis	19/33	(58)
Assessment of swallowing	12/27	(44)
Tremor analysis	20/30	(67)
Goniometric assessments of the joint's passive range of motion	16/34	(47)
Goniometric assessment of the joint's active range of motion	18/34	(53)
Stand-alone	18/32	(56)
7. sEMG, when used as biofeedback, may help to:		
Learn how to associate intrinsic kinesthesia with the desired movement	16/26	(62)
8. Professional figures involved in sEMG signal acquisition, processing, and quality control:		
Clinical neurophysiologist	15/34	(44)
Kinesiologist/Human motion scientist	27/34	(79)
9. Professional figures involved in sEMG interpretation:		
Clinical neurophysiologist	26/32	(81)
Neurologist	11/33	(33)
Neurophysiopathology/Biomedical laboratory technician	19/33	(58)
Occupational therapist	7/33	(21)
Speech therapist	3/32	(9)
10. Greater qualification of clinical neurorehabilitation professionals on sEMG would contribute to reduce the cost of neurorehabilitation care delivery	22/35	(63)
11. Assuming proficiency with sEMG techniques, which of the following professions should provide education and training on the use of sEMG to neurorehabilitation professionals? Please judge the adequacy of the following professional figures:		
Neurologist	15/32	(47)
Neurophysiopathology/Biomedical laboratory technician	13/32	(41)
Occupational therapist	5/32	(16)
Physical Medicine and Rehabilitation physician, also known as physiatrist	20/33	(61)
Speech therapist	5/29	(17)

(Continued)

TABLE 3 | Continued

Survey items	*n*	(%)
12. In addition to basic know-how on sEMG recording (i.e., correct placement of electrodes, adequate skin preparation, etc.), further technical skills are needed:		
Neurorehabilitation professionals should be able to import EMG data into environments for advanced numerical computing (i.e., MatLab)	13/35	(37)
13. EMG-derived variables considered of utmost importance for clinical applications in neurorehabilitation:		
Mean/median envelope	19/32	(59)
Normalized envelope (i.e., to maximal voluntary contraction)	25/34	(74)
Myoelectric fatigue estimators (i.e., average rectified value and root mean square increase, mean and median frequency reduction)	20/33	(61)
Time-frequency / time-scale analysis (wavelet analysis)	15/33	(45)
Intensity plot with reference histograms (e.g., control activation timing key)	15/30	(50)
14. In addition to knowledge on physiological and non-physiological factors that influence sEMG, neurorehabilitation professionals need further competencies to interpret sEMG:		
Knowledge about myoelectric manifestations of muscle fatigue	23/32	(72)
Knowledge about the use of sEMG to assess spasticity	21/33	(64)
15. Potential barriers to the employment of sEMG in clinical neurorehabilitation:		
Lack of widely accepted evidence that the use of sEMG in neurorehabilitation impacts the selection of treatments	24/34	(71)
Lack of normative ranges to characterize the patient based on sEMG data	21/34	(62)
Purchase and maintenance costs of sEMG equipment	15/34	(44)
sEMG device/software not clinician-friendly enough	19/34	(56)
Uncomfortable for the patient	2/34	(6)
No multidisciplinary team available	23/34	(68)

reduce the cost of its delivery. Consensus was reached for quality improvement (28/35, 80%) but not for cost reduction (22/35, 63%).

3. Education, training, and teaching (questions 16–20) – Regarding the adequacy of the professional figures in the education, training, and teaching of neurorehabilitation professionals on sEMG, consensus (i.e., adequate to very adequate) was reached for four figures: "Biomedical engineer" (29/32, 91%), "Kinesiologist/Human movement scientist" (25/32, 78%), "Physiotherapist" (25/33, 76%), and "Clinical neurophysiologist" (24/32, 75%). A combination of professional figures was also indicated as adequate (27/32, 84%). Interestingly, this option received the largest number of "very adequate" preferences (21/32, 66%), followed by "Biomedical engineer" (14/32, 44%), and "Physiotherapist" (12/33, 36%).

Participants were asked to indicate how many years of practice/experience with sEMG techniques are necessary to qualify for providing education and training on the use of sEMG for clinical neurorehabilitation. They agreed by consensus that practice/experience <1 year is inadequate to very inadequate (29/32, 91%). At least 5 years were indicated as an adequate to very adequate period (25/29, 86%).

When analyzing the technical skills for sEMG recording and interpretation that neurorehabilitation professionals should own (in addition to basic know-how on sEMG recording, such as correct placement of electrodes, adequate skin preparation, etc.), respondents agreed they should be able to recognize and filter out artifacts at the skin-electrode interface (i.e., baseline noise contamination, movement artifacts, cross-talk, etc.) (32/35, 91%), and choose the processing technique that is most appropriate for a given application (30/35, 86%).

With regard to the importance of sEMG-derived variables for clinical applications, consensus was reached for the "Timing of muscle activation and their variability" (34/34, 100%), amplitude estimators (i.e., average rectified value, root mean square) (28/35, 80%), "Signal quality/reliability indicators (e.g., artifact reporting)" (26/34, 77%), and envelope time course (25/33, 76%).

When asked to indicate further competencies to complement basic knowledge on physiological and non-physiological factors that influence sEMG, respondents agreed by consensus that neurorehabilitation professionals should own knowledge about sEMG patterns of recruitment in the main central and peripheral neuromuscular disorders (33/34, 97%), about the use of sEMG to assess muscular hyperactivity (31/33, 94%), about sEMG patterns of recruitment of healthy individuals (31/34, 91%), and about the pathologies affecting muscle fiber conduction velocity (23/30, 77%).

4. Potential barriers to sEMG usage (questions 21 and 22) – Respondents agreed by consensus on 5 of the 12 suggested potential barriers limiting the widespread use of sEMG in clinical neurorehabilitation: "sEMG data analysis/interpretation is difficult to perform without specific education/training" (32/33, 97%), "Inadequate education for professionals in neurorehabilitation" (30/34, 88%), "Lack of widely accepted evidence that the use of sEMG improves treatment effectiveness" (26/34, 77%), "Inadequate education and training on sEMG in graduation courses" (27/34, 79%), and "Time-consuming" (26/34, 76%).

We asked participants to rank which clinical environment is most likely to favor the usage of sEMG. Respondents listed "Privately operated clinic (with public or insurance-based reimbursement)" in first place (ranked 1st by 7 respondents; 2nd by 11 respondents; 3rd by 8 respondents) followed by "Publicly operated clinic (with either public or insurance-based reimbursement)" (ranked 1st by 10 respondents; 2nd by 5 respondents; 3rd by 4 respondents) and "Privately operated clinic (out-of-pocket)" (ranked 1st by 1 respondent; 2nd by 8 respondents; 3rd by 14 respondents).

Table 4 reports the results of the subgroup analyses carried out to verify whether responses were influenced by the professional figure of the interviewees. Significant differences were detected in the response rates of non-clinicians and clinicians regarding a number of items. Among these, clear discrepancies emerged in the way sEMG is viewed ("more relevant for researchers than clinicians" for 93 and 53% of non-clinicians and clinicians, respectively, $p = 0.01$), and in a potential barrier perceived to limit its clinical translation ("Purchase and maintenance costs of sEMG equipment"), which was deemed relevant by 71% of the clinicians and by 19% of the non-clinicians ($p < 0.0001$).

DISCUSSION

We conducted survey research to elucidate key aspects on four main themes including trends in the current employment of sEMG in clinical settings and its potential utility, professional figures involved in sEMG assessment and interpretation, educational aspects, and potential barriers to the incorporation of this technique in daily neurorehabilitation practice. By building consensus, we intended to gather information from experts in the field who published prominently on the topic for establishing a common platform to streamline future clinically-applied research on the topic. Importantly, the majority of the interviewed cohort were clinicians (57%). Consensus was reached

TABLE 4 | Subgroup analysis comparing response rates of clinicians vs. non-clinicians.

Survey items with significant differences in response rates	Percentage of agreement		Statistics	
	Non-clinicians $N = 16$	Clinicians $N = 19$	Chi-square	*p*-value
- sEMG is currently more relevant for researchers than clinicians	93	53	6.42	0.01
- Regarding the role of sEMG in patient's assessment. sEMG may be useful to evaluate the percent of maximal voluntary activation	44	75	5.11	0.02
- If a therapeutic intervention is administered. sEMG information may prove useful to track changes from baseline in muscular fatigue	47	75	4.02	0.04
- Score the utility of adding sEMG to the following techniques:				
Accelerometry	57	90	4.31	0.04
Goniometric assessment of the joint's active range of motion	20	71	20.27	<0.0001
Stand-alone	27	76	15.80	<0.0001
- To motivate and help patients learning motor strategies that satisfy a particular muscle activity goal, sEMG biofeedback may help them learning how to associate intrinsic kinesthesia with the desired movement.	42	75	5.94	0.01
- Judge the level of involvement of each of the following professionals for sEMG signal acquisition, processing and quality control:				
Clinical neurophysiologist	31	53	4.08	0.04
Physical Medicine and Rehabilitation physician, also known as physiatrist	20	69	19.22	<0.0001
- Score the level of involvement of each of the following professionals for sEMG interpretation:				
Occupational therapist	27	13	4.10	0.04
- Assuming proficiency with sEMG techniques, which of the following professions should provide education and training on the use of sEMG to neurorehabilitation professionals? Please judge the adequacy of the following professional figures:				
Clinical neurophysiologist	96	56	6.06	0.01
Physical Medicine and Rehabilitation physician, also known as physiatrist	40	81	8.80	0.003
- Based on your experience and knowledge. please score the relevance of the following elements as potential barriers to the clinical use of sEMG:				
Inadequate education for professionals in neurorehabilitation	61	94	3.99	0.05
Purchase and maintenance costs of sEMG equipment	19	71	21.41	<0.0001

Non- clinicians: biomedical engineers, kinesiologists/human movement scientists. Clinicians: clinical neurophysiologists; neurophysiopathology/biomedical laboratory technicians; neurologists; Physical Medicine and Rehabilitation physicians, also known as physiatrists; occupational therapists; physiotherapists; speech therapists.

on 17 of the 22 proposed questions encompassing the four main themes of the survey focused.

Current Usage and Perceived Clinical Utility of sEMG

Contrary to our first assumption, no consensus was reached on the statement that sEMG is rarely used in clinical neurorehabilitation (56%). This finding is in disagreement with previous reports (2–5), which, overall, outlined a negative scenario where methodological and clinical knowledge is widely available but clinicians fail to access and use sEMG in daily practice. A possible reason for such discrepancy may reside in the different professional backgrounds and countries of the interviewees [only clinicians from USA in Feldner's study (5) vs. professionals with wide-ranging background mostly from Europe in our survey]. The item on how frequently sEMG is employed in neurorehabilitation was extensively commented upon. Experts highlighted that employing sEMG is not a matter of frequency but utility and appropriateness, i.e., using a device/technique/therapeutic approach only when it should be used and vice versa. In this regard, the invitees agreed by consensus on the appropriateness and utility of sEMG for neurorehabilitation purposes.

sEMG was deemed by consensus to provide unique information on neuromuscular function that is not offered by other assessment techniques/tools. Among the advantages for which consensus was established (ranging from 80 to 97% of the respondents, see questions 5–10), its use was considered to substantially enhance the quality of patient's assessment. This result supports the use of sEMG as a tool for motion analysis as it can record and quantify clinically important muscle-related activity. Given that sEMG is deemed to cause minimal burden to the subject or the patient (1), this result highlights the importance of collecting such muscle-level information from patients in neurorehabilitation settings.

Participants also agreed that sEMG has a role in the assessment of psychophysical indicators of reaction and movement time in clinical settings as well as to evaluate gait and posture. Consensus was not reached (67%) on whether it could be used to differentiate the many types of tone-regulations impairments such as myoclonus, dystonia, and tremors. It may be that these latter applications require more clinical validation before being employed in neurorehabilitation settings.

As strongly agreed by the respondents, the potential of sEMG for accurate analysis of movement disorders is maximized by its combination with other quantitative and qualitative methods, such as gait/motion analysis, muscular hyperactivity/reflex/tone assessments, and accelerometry. Interestingly, the item on muscular hyperactivity was widely commented on. Two invitees for example, remarked that sEMG could differentiate between spasticity and rigidity, as suggested by Levin et al. (27), Mullick et al. (28), and more recently by Baude et al. (29). Moreover, regardless of whether sEMG is applied stand-alone or combined with other techniques/tools, according to the cohort's aggregate view (86–91%), it can specifically track objective changes from baseline following therapeutic interventions in the sequential timing of muscular actions during given movements (i.e., gait, motor tasks) and for involuntary muscle activation (e.g., dystonia, ataxia).

The cohort was also very clear in highlighting by consensus that sEMG is more frequently employed in technical/methodological reports than in clinical research, possibly suggesting that a substantial distance still exists between researchers and clinicians, in agreement with previous reports (2, 3, 5, 18, 19, 22). A possible explanation for such a gap might be a limited ability to transfer research knowledge to practice, requiring clinical translational research, which is still limited. Moreover, it is also likely that clinicians do not keep updated with research findings, which corroborates historical claims that clinicians fail to access and thus employ EBP information into daily practice despite the vast availability of excellent resources (30). According to Berwick (31), "Health care is rich in evidence-based innovations, yet even when such innovations are implemented successfully in one location, they often disseminate slowly, if at all." Also, rehabilitation professionals now have easy access to evidence syntheses, systematic reviews, and meta-analyses that condense research articles, still EBP-derived knowledge hardly and slowly transfers to patient's bedside (7, 32). Even if not tested by the present study, we speculate that slow dissemination of EBP-derived knowledge may also apply to the persisting resistance to sEMG employment despite decades of development of this technology (33, 34), and a massive body of knowledge accumulated so far in support of its translational utility. Enhancing education and training (i.e., by including technology teaching into undergraduate and postgraduate physiotherapy/health professional courses and in medical courses) as well as increasing clinicians' awareness of the potential advantages offered by this technology may help accelerate the transfer from proven health care discoveries to patient care needs. Moreover, in the attempt to fill the gap, we believe that professional and clinicians' associations (e.g., the American Physical Therapy Association) could serve as cultural bonds between researchers and practitioners and ensure the dissemination of novel knowledge.

Potential Barriers and Educational Aspects

Specific education and training of professionals were considered to play a decisive role, particularly to improve the quality of neurorehabilitation care. Accordingly, inadequate education and training on sEMG in graduate courses, lack of continuing education for professionals in neurorehabilitation and time-consuming set up were listed as the main barriers to the clinical employment of this technique.

Acquiring and consolidating knowledge on physiological and non-physiological factors that influence sEMG was also put forward as a key point for the interpretation of sEMG findings by neurorehabilitation professionals. In particular, strong consensus (>90%) was achieved for three elements to be part of their educational background: (1) knowledge on the sEMG patterns of recruitment of healthy individuals, (2) knowledge on the main central and peripheral neuromuscular disorders, and (3) salient sEMG features of muscles affected by spasticity/hyperactivity. Relatedly, the respondents agreed that sEMG data analysis and interpretation may be difficult to perform without such knowledge and specific training, thus confirming the key role of education in the gap between EBP and daily practice. The cohort of experts agreed that professions teaching sEMG must have a minimum of 5 years of experience with sEMG, which may be due to the lack of teaching in academic courses and the need for learning by experience or by trial and error. While this period could undeniably appear very long, it may be necessary for those professional engaged in sEMG teaching.

Interestingly, even though the cohort was mainly composed of clinicians, the professional figures who were deemed best qualified for teaching sEMG to neurorehabilitation professionals were not medical doctors nor physiotherapists. Indeed, biomedical engineers and kinesiologists/movement scientists were ranked, respectively, in first and second place, provided that they hold superior expertise and skills which, regardless of the professional figure, was indicated as the key factor.

The item on potential barriers was extensively commented upon, with invitees converging on four additional factors: (1) poor reliability/validity if the subcutaneous tissue layer is too thick, which may often be the case in the adult and aged (sedentary) population, and particularly in women, even though the role of fat interference has also been downplayed (2, 35) general distrust in technology; (3) lack of self-confidence due to poor education; (4) need of a dedicated team.

Taking together the interviewees' responses and comments on factors potentially limiting the usage of sEMG in neurorehabilitation, it appears that the integration of sEMG into an agreed framework for diagnosis and treatment is still challenging for clinicians. Furthermore, there is currently poor translational evidence to make sEMG part of a coherent diagnostic or measurement context and to use it to track the right clinical outcomes. For all these reasons, it is likely that sEMG is not used extensively in neurorehabilitation.

Professional Figures Involved in sEMG

As for teaching, biomedical engineers were deemed the professional figure most frequently involved in sEMG signal acquisition, processing, and quality control. Kinesiologists/human movement scientists, clinicians (clinical neurophysiologists, PM&R physicians, physiotherapists) and biomedical engineers were, instead, indicated as those most likely in charge of data analysis, post-processing, features extraction etc. Among the comments accompanying this specific item, the relatively new professional figure of "human motion analyst" was put forward by some respondents as a possible reference to manage sEMG assessments in the clinical setting.

Technical and Methodological Aspects

Data indicate that neurorehabilitation professionals should hold basic know-how (i.e., correct placement of electrodes, adequate skin preparation, etc.) but also additional abilities to recognize and filter out artifacts, distinguish between cross-talk and co-activation, and also choose the most appropriate processing technique. More advanced expertise, such as importing data into external environments and further computing were regarded as "not required for all clinical neurorehabilitation professionals." Overall, the item about the ideal technical skills was also widely commented. What clearly emerged from additional reasoning and elaborations from the experts was that a basic knowledge about the identification of "bad" signals (e.g., power line interference, artifacts, poor contacts) may be sufficient for clinicians, whereas familiarity with signal acquisition issues management (data clipping, low-pass and high-pass filtering, down-over sampling, algorithms for the estimation of signal-to-noise ratio, etc.) along with relatively more advanced analyses (e.g., power spectral density, developing custom software scripts, etc.) are skills that are necessary for professionals working in the laboratory and dealing with human motion analysis.

A question specifically surveyed which sEMG variables should be considered. This is a relevant point considering the "*too many data–no data*" paradox (36), which refers to the difficulties that clinicians experience in extracting clinically meaningful parameters from newly introduced biomedical technologies (e.g., sEMG, gait analysis, back shape measurement), for which a general sentiment of distrust is often shown by clinical practitioners. Four sEMG-based parameters were indicated as important to report: (1) timing of muscle activations, (2) amplitude estimators, (3) envelope time course, and (4) indicators of signal quality/reliability. From experts' free commenting, power spectrum density, and muscle fiber conduction velocity also emerged as likely important to control for data quality and reliability.

Differences in Responses Between Clinicians and Non-clinicians

Data revealed significantly different views between clinicians (54% of the cohort) and non-clinicians (46%) for several issues. For instance, unlike clinicians, the majority of the non-clinicians considered sEMG more relevant for research than clinical purposes. As for those factors potentially limiting the usage of sEMG in clinical practice, different beliefs emerged between the two categories being "inadequate education" and "purchase and maintenance costs of sEMG equipment" perceived as more relevant barriers by clinicians. These findings reveal that for selected items the professional figure background influence the questionnaire responses.

LIMITATIONS

The findings of the present survey research may be limited by the characteristics and geographical location of the selected contributors who participated in the survey, possibly subjecting the survey findings to selection bias as the usage of sEMG may vary by country. In particular, 86% of the interviewees were from Europe and 54% from Italy, possibly reflecting a greater sensitivity and interest to the problem in this country. Although we collected responses from the majority (67%) of the sEMG experts invited, it cannot be excluded that responses from a larger number of individuals with different backgrounds may have led to different results, possibly leading to reduced likelihood of consensus. Another element that needs to be considered in the interpretation of the findings is the choice to interview only scientists, researchers, and clinicians who had authored indexed articles on the topic rather than clinicians who did not. Therefore, the results of the survey and their external validity and generalizability may be limited and biased by this choice and will need to be compared to a larger sample of clinicians who specifically engage in neurorehabilitation on a daily basis, but not necessarily on research. Moreover, while being iterative in the conception and planning of the survey, we acknowledge that the methodological robustness of this study could have been enhanced by adding one or more rounds to the present one-round survey.

Finally, while we attempted to be comprehensive in the development of the survey questions and sub-items, other questions could have been asked to address specific issues that were here possibly overlooked.

CONCLUDING REMARKS

This survey research clarified several aspects of sEMG in neurorehabilitation ranging from current trends in its use, educational, technical, and methodological features as well as the translational outreach and potential utility of this technique for clinicians and patients.

In particular, sEMG was indicated as practically useful in clinical neurorehabilitation for patient assessment, to define the intervention plan and complement/optimize other methods used to quantify muscle and physical function. Nevertheless, the aggregate opinion of the interviewed experts clearly revealed that sEMG is more frequently employed in technical/methodological than clinical research. Moreover, the slow dissemination of research findings, lack of education on sEMG and lack of incorporation of the patients' goals when applying the technology seem to prevent prompt translation into practice. Additionally, multidisciplinary competences are necessary to face the challenges of the complexity of the matter, beside the identification of more specific procedures, for increasing clinical use and benefits for the patients.

Future translational studies aimed at testing whether the addition of sEMG brings clinically important benefits are required to fill the gap between research and clinical practice, which may itself limit the employment of sEMG in neurorehabilitation. With the present survey findings obtained by bringing together the expertise, guidance, and insights of leading experts in the field, we are now better positioned to open a debate on the appropriateness and value of sEMG for neurorehabilitation professionals and its potential translation into clinical practice.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Review Board Department of Biomedical Sciences University of Sassari, Italy. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AMa, AC, and FD conceived the idea and managed all aspects of the work. LB-O, AB, UD, MK, NM, DM, AMe, SR, and AT developed the survey questions, developed and piloted the survey. All authors provided critical feedback and helped shape the research, analysis, and manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fneur.2020.573616/full#supplementary-material

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"It's All Sort of Cool and Interesting...but What Do I Do With It?" A Qualitative Study of Stroke Survivors' Perceptions of Surface Electromyography

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Background: Stroke is one of the most common neurologic injuries worldwide. Over decades, evidence-based neurorehabilitation research and advancements in wireless, wearable sensor design have supported the deployment of technologies to facilitate recovery after stroke. Surface electromyography (sEMG) is one such technology, however, clinical application remains limited. To understand this translational practice gap and improve clinical uptake, it is essential to include stakeholder voices in an analysis of neurorehabilitation practice, the acceptability of current sEMG technologies, and facilitators and barriers to sEMG use in the clinic and the community. The purpose of this study was to foreground the perspectives of stroke survivors to gain a better understanding of their experiences in neurorehabilitation, the technologies they have used during their recovery, and their opinions of lab-designed and commercially-available sEMG systems.

Methods: A qualitative, phenomenological study was completed. In-depth, semi-structured interviews were conducted with eight stroke survivors (age range 49–78 years, 6 months to 12 years post-stroke) and two caregivers from a large metropolitan region. A demonstration of four sEMG systems was provided to gather perceptions of sensor design, features and function, and user interface. Interviews were audio-recorded, transcribed verbatim, and coded for analysis using constant comparison until data saturation was reached.

Results: Three themes emerged from the data: (1) "*Surface EMG has potential….but…*" highlights the recognition of sEMG as a valuable tool but reveals a lack of understanding and need for clear meaning from the data; (2) "*Tracking incremental progress over days or years is important*" highlights the persistence of hope and potential benefit of sEMG in detecting small changes that may inform neurorehabilitation practice and policy; and (3) "*Neurorehabilitation technology is cumbersome*" highlights the tension between optimizing therapy time and trying new technologies, managing cost, logistics and set-up, and desired technology features.

Conclusion: Further translation of sEMG technology for neurorehabilitation holds promise for stroke survivors, but sEMG system design and user interface needs refinement. The process of using sEMG technology and products must be simple and provide meaningful insight to recovery. Including stroke survivors directly in translational efforts is essential to improve uptake in clinical environments.

Keywords: surface electromyography, stroke, qualitative research, perceptions of technology, rehabilitation

INTRODUCTION

Over the past decades, there has been a prolific amount of research and development of technology to enhance both the understanding of neurologic injuries and the application of evidence-based neurorehabilitation interventions. Surface electromyography (sEMG) is one such technology that has undergone rapid advancement in development, but has yet to reach its full translational potential to help drive neurorehabilitation and maximize recovery. Understanding this translational gap must consider multiple factors across a complex landscape of healthcare provision, especially given the public/private healthcare model in the United States. Successful deployment of sEMG in clinical environments relies on an interaction of system design, funding, translational research findings, clinician training, and user acceptance, among many other factors. While user acceptance of neurorehabilitation technology is just a small piece of a much larger puzzle, it is an essential one, and a more explicit understanding of the perceptions and experiences of individuals with neurologic injury, such as stroke, is warranted to better understand the barriers, facilitators, and untapped potential of sEMG technology in clinical neurorehabilitation,

Stroke is one of the most common neurologic injuries worldwide (1, 2). Recent global statistics estimate nearly 14 million new instances of stroke annually; stroke related healthcare costs in the US alone have topped $750 billion annually and are projected to increase as a result of the aging population (3, 4). Further, the psychosocial and functional impacts of stroke are also significant, leading to stress, isolation, and potential comorbid health conditions (5, 6). While neurorehabilitation is a central feature of recovery for individuals with stroke, outcomes can be disparate and long-term impairment is common, further influenced by the extent to which stroke survivors have the geographic, financial, healthcare, and socio-emotional resources to maximize recovery following their injury (1). It is because of this significant impact of stroke at both individual and institutional levels that the field of neurorehabilitation must engage in a deeper exploration of the translation of advanced healthcare technologies into clinical settings to enhance our knowledge and provision of care during recovery from neurologic injuries.

Surface EMG today is used in research and clinical environments across a wide variety of physiological and engineering applications relating to rehabilitation, sport performance, occupational performance, and beyond (7). More specific to neurorehabilitation, foundational literature in the mid-twentieth century described sEMG as a useful tool to characterize neuromuscular patterns, demonstrated the relative contribution of different muscles in functional movement, and in some cases, assisted in prognosis of recovery following neurologic injury (8, 9). Across many subsequent decades, researchers have used sEMG to examine factors in participants with and without neurologic impairments such as interlimb coordination, muscle activation and co-activation patterns, response to biofeedback, and most recently, as a tool to determine treatment appropriateness and costs in stroke survivors with gait impairments (7, 10–14). Despite these advances, a significant body of literature supporting the use of sEMG, and the establishment of expert guidelines for sEMG implementation through SENIAM (Surface EMG Non-Invasive Assessment of Muscles), a lack of clinical translation of sEMG technology has also been recognized by researchers (7, 15–18).

One potential reason for the slow clinical uptake of sEMG and related neurorehabilitation technologies may be the paucity of perspectives in research from clinicians as providers of sEMG assessment or intervention, and individuals with neurologic conditions and their caregivers as recipients of sEMG assessment or intervention. Considering sEMG alongside other neurorehabilitation technologies more broadly, the literature is lacking a clear picture of how and how often these technologies are used in clinics across the US, and how technology users and their caregivers respond to the design, logistics of use, and output of the devices. However, user and caregiver perspectives are a key untapped resource in the design and implementation of rehabilitation technologies such as sEMG, and have the potential to richly contextualize the barriers and facilitators that affect technology acceptance and use. For example, within the broader realm of neurorehabilitation technology, Alt Murphy et al. (19) recently published a qualitative analysis of participant responses to a novel wearable sensor garment to monitor physiologic and movement parameters for individuals with stroke, Parkinson's Disease, or Epilepsy. The authors reported that responses to the upper body garment was acceptable, but participants noted challenges with fit and comfort and felt uncertain about consistent monitoring and privacy (19). Another study noted similar comfort issues with wearable sensors, but highlighted that despite the discomfort, participants preferred the automated data tracking features of the sensors compared to more time-intensive activities such as completing activity or symptom diaries (20).

Additional qualitative work with stroke survivors and clinicians has also explored perspectives and experiences of the rehabilitation process itself, as well as technologies such as virtual reality, gaming, robotic exoskeletons, or other wearable devices, but little work has focused specifically on sEMG (21–29). One study included gaming as part of a structured, enriched rehabilitation environment, which garnered positive responses from participants who noted increased motivation to move as well as friendly competition between other participants on the unit (29). Perceptions of virtual reality systems varied, with one study reporting low rates of side effects but high rates of perceived exertion by stroke survivors (21), and another describing how users felt enjoyment and motivation using a novel technology they would not otherwise have had access to, but felt that the experiences with virtual reality did not translate into improved functional carryover (23). Many studies have examined robotic applications for stroke rehabilitation, but very few have included survivor perspectives. Those that have describe user priorities of cost, better movement quality, endurance, practicality, and appropriate training and support, but also highlight technology acceptance issues as a potential barrier for clinical or home use (30–33). One set of studies investigated the preliminary use of sEMG as a control mechanism for a gaming system in chronic stroke survivors, finding significant pre and post intervention sEMG changes, and qualitative outcomes which indicated most participants would recommend neurogaming to others for enjoyment, despite a lack of reported functional carryover (26, 34). Our recent work has explored rehabilitation clinicians' perspectives of the use of sEMG in practice with individuals with neurologic conditions, who noted the potential benefits of objective recovery tracking, muscle training, and patient motivation, but also acknowledged barriers to sEMG use such as time, training, and access to funds and technical support for sEMG equipment (35).

The literature notes that the introduction of novel healthcare technologies into existing clinical practices can be challenging, as the process often disrupts engrained care routines (36). Resistance to new technology integration, as well as distinct ways of evaluating the utility of technology from professional and lay perspectives are common (37). This has consequences for both healthcare providers as well as patients. For example, healthcare providers have noted translational difficulties, including challenges with clearly communicating results to patients and using technology outputs to meaningfully guide treatment decisions. Patients have expressed uncertainty about the purpose of technology as a part of their care, and a failure to receive meaningful results from their providers (37). Applied to rehabilitation, it is reasonable to expect that there may be similar challenges when considering the implementation of sEMG technology, especially considering the introduction of a high-tech, objective, instrumented assessment tool juxtaposed with clinical standards that typically involve low-tech, subjective, scaled tools such as manual muscle testing or dynamometry. Experiences such as these underscore that clinician training, communication about technology intent, impact, and translational capacity to assist in healthcare decision-making are important factors to consider in improving uptake of technology in clinical settings.

The purpose of this early-stage study was to foreground the perspectives of stroke survivors and gain a better understanding of their experiences in neurorehabilitation, the technologies they have used during their recovery, and their introductory perceptions of one lab-designed prototype and three commercially available sEMG systems. Centering these perspectives is critical to understanding the barriers and untapped potential of sEMG and other neurorehabilitation technologies that may support the recovery of individuals with neurologic injuries. This qualitative work complements and builds upon past milestones in sEMG research across rehabilitation and engineering fields. It offers a preliminary look at baseline user perspectives to inform more robust research in the future, and provides a unique opportunity to leverage user-centered perspectives to support potential innovations in sEMG design, implementation, and outcomes.

METHODS

All procedures in this study were approved by the authors' institutional review board, and written consent was obtained by all participants prior to initiation of study procedures. Participant names are pseudonyms to protect privacy and confidentiality. This qualitative study was conducted using a phenomenological approach, which is ideal for understanding the lived experiences of a group of participants with similar characteristics (38). Ultimately, the goal of phenomenological research is to describe and interpret a given phenomenon through the lens of individuals with first-hand knowledge of the event or experience, in this case, the experience of having and living with stroke and experiencing neurorehabilitation (39, 40). While this lived experience may or may not have included technology use during recovery, it provided a shared foundation from which to obtain informed perceptions of sEMG as a potential part of this experience.

Research Team Background

This study was conducted by a multidisciplinary research team, including a physical therapist with qualitative research expertise, mechanical engineer with wearable sensor expertise, and two research scientists. All members of the team had extensive training and experience in the clinical application of sEMG systems to track muscle activity changes in stroke survivors. In addition to this qualitative work, the research team was concurrently collecting sEMG data from stroke survivors in acute care and community-based settings. Therefore, the researchers were well-positioned to engage with and provide baseline information to the participants about sEMG technology.

Study Procedures

Semi-structured interviews were conducted to obtain primary source thoughts, opinions, and interpretations from the participants, using an interview guide that was developed by the authors, edited for content until consensus was reached, and piloted with a volunteer to ensure clarity of question content and order. **Figure 1** contains a list of sample questions from the interview guide.

During each interview, a brief demonstration of four, research lab-owned sEMG systems was conducted. This included one lab-designed sEMG sensor prototype as well as three

1) *What things are most important/fun for you to be able to do? Do you do those activities now? Why or why not?*

2) *What are/were your top priorities for recovery from your stroke?*

3) *There are a lot of different kinds of technology out there, like cell phones, TV, video games, tablets, sensors to turn lights on, etc. What kinds of technology do you use on a regular basis?*

4) *What types of technology do/did you use during your stroke rehabilitation?*

5) *What do you think are the potential benefits of using sEMG with individuals who have had a stroke?*

6) *What do you think are the potential challenges of using sEMG with individuals who have had a stroke?*

7) *Do you think sEMG might have the potential to allow healthcare professionals to do their jobs better? Why or why not?*

8) *If you were to use sEMG in your rehabilitation in the clinic or at home, what features would be essential?*

FIGURE 1 | Sample Semi-Structured Interview Questions: These questions were among those asked of each participant during the semi-structured interview. Responses were audio-recorded and transcribed verbatim.

commercially available sEMG systems, chosen to represent a broad range of system design, aesthetic, and capabilities: (A) MC10 BiostampRC® (Lexington, MA, USA); (B) Thalamic Labs Myo™ Armband (Kitchener, Ontario, CAN); (C) Delsys Trigno™ (Natick, MA, USA); and (D) Epidermal Sensor System (Austin, TX, USA, patent pending), a lab-designed prototype with sensor filament embedded in medical tape. See **Figure 2** for images of each sEMG system. Participants were able to examine each system and were briefed on features including functionality and purpose, battery life, skin preparation needs, anatomical placement, user interface, and cost. Participants were also oriented to print versions of sample signal outputs from each system, since time constraints prohibited real-time system use. To minimize the potential for biased responses, the research team refrained from endorsing any given system and only provided pre-scripted, general purpose information about each system and the clinical applications of sEMG to assist the participants in offering informed perceptions. Participants were able to ask clarifying questions about the purpose and features of the systems, and self-assessed their understanding of the information presented prior to continuing the interview. Feedback about the features and perceived utility of each sEMG system was then solicited from each participant.

Interviews were conducted at a location of the participant's choosing, with half the interviews taking place at the participant's home, and half taking place in university settings such as an office or research lab. All interviews were audio-recorded, transcribed verbatim, and de-identified.

Participants

Participants were recruited via convenience sampling through stroke clinics and rehabilitation professional contacts across a large metropolitan area. To be included in the study, participants must have been over the age of 18 years, have the cognitive capability to consent for themselves, have had any type of stroke in the past or be the spouse or caregiver of the stroke survivor, and demonstrate proficiency communicating in English. Potential participants were excluded from the study if they were under the age of 18 years, not able to cognitively consent for themselves, or communicate proficiently in English. Stroke survivors with aphasia or limited communication capabilities were included in the study along with their spouses/caregivers. Ten participants across the Seattle metropolitan region completed the study, including eight stroke survivors and two spouses/caregivers. Of the stroke survivors, four were male and four were female, ranging in age from 49 to 78 years old (mean = 65 years), and ranging from 6 months to 12 years post-stroke (mean = 4.75 years). One male and one female spouse/caregiver participated in the interviews with their respective partners. Two participants had mild to moderate expressive aphasia, one participated in the interviews independently, and another participated to the greatest extent possible with the assistance of his spouse. Most

FIGURE 2 | Sample Commercial and Lab-Based sEMG Sensors: A brief demonstration and feature discussion for these four sEMG systems was conducted during each participant interview. Systems were available for physical inspection, but not applied to the participants. **(A)** MC10 Biostamp® **(B)** Thalamic Labs Myo™ Armband; **(C)** Delsys Trigno™; and **(D)** Epidermal Sensor System (patent pending).

participants ($n = 8$) had post-secondary vocational training or college degrees, with employment backgrounds including business and finance administration, teaching, musician, and aerospace engineering. One participant had previously worked in a research and development capacity with activity monitoring technology for nearly 20 years, and another had participated in a prior research study using sEMG for serious gaming. The remaining participants did not have prior experience with sEMG, though many had used or trialed related neuromuscular rehabilitation technologies such as electrical stimulation or biofeedback, as well as ubiquitous lay technologies such as commercial fitness or activity trackers, following their stroke.

Data Analysis

De-identified transcripts were analyzed inductively for their responsiveness to the research purpose, and coded using constant comparison until data saturation was reached and themes grounded in the participants' perceptions and experiences emerged (38, 39). The authors engaged first in open coding, followed by further, independent content analysis and focused coding and discussion among the team to consolidate focused codes into themes. All themes were created with >95% agreement, and any differences in interpretation were resolved by discussion until consensus was achieved. Interview participants engaged in member checking, by which they were provided an opportunity to review a summary of the findings and ask questions so the research team could confirm accuracy and avoid misinterpretation of the results (38). A "thick description" of participant perceptions and experiences, supported directly by verbatim quotations, is presented to allow reader-driven determination of data credibility (39). **Table 1** shows a detailed example of the structured coding process.

RESULTS

Three major themes emerged from the data: (1) "*Surface EMG has potential...but...*"; (2) "*Tracking incremental progress over days or years is important*"; and (3) "*Neurorehabilitation technology is cumbersome*". These themes inform an overarching construct that sEMG could be valuable for stroke survivors, but the process and products must be simple and meaningful to their recovery in order to achieve greater uptake in both clinical and community settings during rehabilitation. Within these themes, the participants identified several key features of

TABLE 1 | Qualitative coding structure.

Quote	Open Coding	Focused Coding	Theme
"If you can see things, that would be helpful in acute rehab, cause there is time there. You're just in bed a lot of the time, and that's the time to work, you know? I think seeing linkages between each part of this, like, if the home healthcare people use the same data that they use [in acute rehab], they can come in and say, 'Well, you were working on this particular muscle so this time let's give more attention there and then do a check and see how these others are doing'. And then you kind of feel that progression with your [program]."	Seeing is believing, a lot of downtime, downtime as worktime, information for therapists, data to drive rehabilitation, progression of rehabilitation	Visualizing objective data, downtime as worktime, technology can drive rehabilitation	sEMG has potential…but
"Remember they said if you don't have any recoverability within the first 3 months, if you don't have it by then…kiss it goodbye. So, I'm fighting. I am making little improvements, not big ones, but little ones. Only because I keep on fighting. You don't see that years out like I am."	Return to function, timeline on return, seeing progress, little improvements, motivation and persistence over years	Seeing actual change, motivation and persistence to keep working	Tracking incremental progress over days and years is important
"E: And [e stim], it's something he can't do by himself. So, I have to be available to do it with him, and then, you know, it's just very touchy so you have to replace [the pads] a lot during the thing, so it's not just like we can slap it on and let it go. We're both kind of there the whole time, so it takes a lot longer than it should, I think. D: What…have a turn on and be working E: And stay on. Exactly (laughing). It's not even the length of time, it's just having to fix it all the time. Makes us both crazy!"	Can't set up by yourself, need for caregiver presence, equipment is finicky, cost/use of replacement supplies, willing to put in the time, clinical effectiveness	Technology set-up and logistical challenges, time vs. effort	Neurorehabilitation technologies are cumbersome

This table demonstrates the iterative process of qualitative coding. Beginning with a quote on the left, each quote is annotated with open codes on first reading, which are subsequently streamlined into focused codes on later readings, and finally merged into overarching themes that describe how the focused codes relate to one another.

existing sEMG systems that were appealing, as well as features that presented barriers to use. Participants also offered innovative ideas and solutions for future iterations of sEMG technology and key insights for improved technology translation in healthcare.

Theme 1: "Surface EMG Has Potential…but…"

The first theme highlights perspectives that sEMG could offer motivation, reinforcement, and provide more precise data during recovery, but this data is only valuable if its output is both meaningful for stroke survivors and clinically useful for rehabilitation professionals. Participants also identified that timing of sEMG application is a key consideration. In general, participants felt that having sEMG data would help clinicians in care planning and decision-making, however, there was some disagreement among participants as to if this was a valuable use of clinicians' time. Ultimately, participants felt excited about the potential of sEMG technology and an integrated approach to rehabilitation that included clinicians, engineers, and patients. However, participants also expressed a simultaneous need for further clarity about the impact of sEMG data on their recovery.

For example, a majority ($n = 8$) participants felt that sEMG could be a useful way to deliver more objective data to support their self-perceived assessment of functional recovery (**Table 2**, Quotes 1-2). In regard to optimal timing, there were differing opinions as to whether sEMG would be valued in acute rehabilitation prior to return of visible movement. One stroke survivor thought sEMG would be more useful after voluntary movement returned, however, this was an outlying view (**Table 2**, Quote 3). The remaining participants felt sEMG data could be applied early, to facilitate a more integrated approach to monitoring recovery, and over half of the participants noted that sEMG technology would translate well between clinical and home settings during the recovery process (**Table 2**, Quotes 4-6).

A majority of participants ($n = 8$) also highlighted the potential importance of sEMG in providing objective information to their clinical teams, noting that it could fill a gap for medical providers in challenging or ambiguous situations, and assist in making accurate prognostic decisions, providing concrete feedback to survivors and caregivers, or improve rehabilitation productivity (**Table 2**, Quote 7). One couple, in drawing from their previous experiences with electrical stimulation, had an alternative view, feeling like time spent with set up or monitoring of sEMG could interfere with other therapy activities and reduce time for hands-on functional activities or exercises with therapists (**Table 2**, Quotes 8-9).

Among over half the participants ($n = 6$), there was recognition of sEMG as a means to invite a multidisciplinary, user-centered technology experience into rehabilitation and recovery. Participants were excited about the prospect of brainstorming sessions to leverage existing technologies and innovate with new ideas, and highlighted the importance of the technology user as a primary stakeholder with lived expertise in regard to these healthcare advances (**Table 2**, Quotes 10-11). Despite these perceived benefits, reservations among participants remained regarding the interpretation of sEMG outputs and appraising the value of a potential investment in sEMG during recovery (**Table 2**, Quotes 12-14).

TABLE 2 | Theme 1: 'sEMG has potential...but' Participant Quotes.

#	Quote	Description
1	"If Cherry sees improvement with a device, as opposed to thinking, 'Gee I thought I walked better today', You see what I mean. You've got hard data that says, 'yeah, you did walk better', okay, reinforcing her mind." (Archie, spouse).	Visualizing objective data, data-driven recovery, motivation
2	"If you were identifying some task-oriented thing and you thought, 'Well, I want to be able to reach into that cabinet', and then each day you could kind of check on how well did you do, I think it would give you data to help you…when you're here, and trying to get there." (Cherry, 77)	
3	"In my case, when their arm are like this, they're trying to get moving so I don't think those [sensors] would be very good until you get after [moving]. I think after, it would seem to help me see if I can do it or not do it" (Jane, 68).	Seeing change over time
4	"If you can see things, that would be helpful in acute rehab, cause there is time there. You're just in bed a lot of the time, and that's the time to work, you know? I think seeing linkages between each part of this, like, if the home healthcare people use the same data that they use [in acute rehab], they can come in and say, 'Well, you were working on this particular muscle so this time let's give more attention there and then do a check and see how these others are doing'. And then you kind of feel that progression with your [program], I think." (Cherry, 77)	Downtime is worktime, monitoring outside of therapy time
5	"And you'd probably take that same [technology] home with you, if you started out in acute rehab with using the equipment." (Archie, spouse)	Translation from clinic to home
6	"I think it's a great addition and I think once you're done with the bulk of therapy, this might be an easy or a good way to continue things at home." (Emily, spouse)	
7	"I think it would [help healthcare professionals do their jobs better] and also show progression if something does change. Then they get a database on each patient and can say, 'here's the normal range, here's where this one is, in this one area what can we do to strengthen'. I think it would increase productivity. It might not decrease the time, but you might be able to do a lot more. It would definitely help the therapists, and also your recovery" (Cherry, 77)	Helpful information for healthcare providers
8	"Too time-consuming…It's not the right type [to use in therapy]" (Daniel, 66)	May interfere with hands-on exercise or functional activities
9	"Yeah, you know, when we go in for therapy with you, when she spends a lot of time playing with the electrodes and the e-stim, and then we leave, it's just like you've used up one Medicare session and you don't feel like you've gotten enough done" (Emily, spouse)	
10	"It's important to involve users as well as the engineers. Because engineers come up with these great ideas, but it's the users who are actually much more precise. With aligning a prosthesis, the prosthetist has been trained and worked to really know how to do that, but if you give the amputee control over alignment, they'll come up much more precise than the prosthetist is, you know?" (Jill, 77)	User empowerment, lived experience, multidisciplinary approach
11	"That would be really cool to have a brainstorming session, so you can go through the logic and opportunities and bringing in IT people, physical therapists, mechanical engineers, and you've got yourself a powerful group to download information. Put a patient in there, you'll have some great, cheap innovations coming." (Anne, 62)	
12	"I think it's all sort of cool and interesting, but again the question is so what do I do with it? How do I set a goal for myself using it? And, how does it help me improve? How does looking at these graphs or seeing if I can make them look the way they need to look help me improve?" (Duke, 49).	Skepticism about value, interpreting the data
13	"Is it actually worthwhile doing this? Does it work for you? It may work for one person and not another…" (Anne, 62)	
14	"I would need more explanation of what the raw signals mean. What are they actually measuring, and what kind of output do you want, you know, do you want precision or do you want general, cause some people just wonder what's the count for the day, they weren't interested in what your highest was, or they're interested in just one piece of it." (Jill, 77)	

This table encapsulates relevant example quotes from the results which supported the development of Theme 1: 'sEMG has potential…but'.

Theme 2: "Tracking Incremental Progress Over Days or Years Is Important"

The second theme reflects participants' experiences of small changes or progress months and years after stroke, the potential role of technology like sEMG in detecting such change during acute and long-term recovery, and the need for more data to document objective changes that may inform neurorehabilitation policy and practice.

For example, all participants discussed their recovery journey, highlighting processes of both self-discovery as well as harsh realities, noting that they surprised themselves and their medical team with changes long after their stroke. Depending on how recently the stroke occurred, these changes were still emerging (**Table 3**, Quotes 1-4). Progress was slower than expected, and even with positive experiences in recovery, long adjustment periods and fear were common threads (**Table 3**, Quote 5). As a part of this incremental recovery, a majority of participants ($n = 7$) noted they would appreciate the precision offered by sEMG and the potential to identify small changes during rehabilitation (**Table 3**, Quotes 6-7). The participants felt that the capability to monitor muscle activity and see these small changes was a benefit that outweighed the potential for discouragement if minimal or no progress was observed in a particular muscle group (**Table 3**, Quote 8).

All participants also highlighted the challenges with transitioning back home after rehabilitation, and a desire to have more connectivity and more technology in a home setting. For example, sEMG could play a role during time at home outside therapy, or as a means to monitor and prevent further medical complications resulting from inactivity (**Table 3**, Quotes 9, 10). Both caregivers also noted the challenges that arise with the transition home, whether that be fatigue, logistics, or time for technology or other recovery activities (**Table 3**, Quotes 11, 12). Ultimately, for both treatment

TABLE 3 | Theme 2: "Tracking incremental progress over days or years is important."

#	Quote	Description
1	"With my hand and arm, it's tough, you know, but every once in a while, I'll still see something. I feel like if I can make myself do something like once or twice, you know, its brutally difficult the first couple of times, but once you can do it a few times or a handful of times you can start to get better at doing it consistently." (Duke, 49)	Progress takes time, small changes are a big deal, motivation to keep fighting
2	"I do exercise every day. Three times a day. I put my stimulator on my hand and it lifts my hand open because I couldn't do anything with my right hand. When I first got home, all I could do was…like that [pulls arm against body]. Now, I can do almost anything, but [my hand] still won't work, but I'm working on it." (Jane, 68)	
3	"Remember they said if you don't have any recoverability within the first 3 months, if you don't have it by then…kiss it goodbye. So, I'm fighting. I am making little improvements, not big ones, but little ones. Only because I keep on fighting. You don't see that years out like I am." (Anne, 62)	
4	D: "Umm, wait and see. I... can't really tell yet, how much I can be at this time. E: Your speech? D: Yes. And, it's not…as fluid as I will like. My understanding always there, but I can never, can get it out. E: The arm is the slowest coming back, by far. D: Yes. But I'm, legs are…in the past two days…E: The last week or so, you've been commenting a lot, just the strength and the feeling in it. D: Yeah, they're stronger" (Daniel, 66 and Emily, spouse)	
5	"I think I did the best I could, with both the arm and leg out of commission, You always think it's gonna be over the next morning or something, so that was kind of disappointing that didn't happen. But the people I worked with were all very positive and supportive, so that's good." (Cherry, 77)	Acceptance takes time, even with support
6	"Well I do think that having data of what else is going on, you're working with it in therapy, you know, and getting muscles to activate like it would on the other side, being able to learn to identify that little stuff is highly valuable. And I would really like that precision- to be able to be very precise about what is happening." (Jill, 77)	Identifying small changes with precision is important, hard to tell if something is working
7	"I think if you could see the muscle movement and if you could see that changing over time, that would be really motivating. To know that you're actually doing something and it's working, cause a lot of time, it's hard to tell" (Emily, spouse)	
8	D: "No, but I…use…I don't know. E: I think for me, it depends how long you were seeing nothing. If you worked on it for weeks or months and you still weren't seeing anything, that could be a little [discouraging]. D: Yeah E: But the potential for seeing progress, when there wasn't before, that could be motivating, or worth a try. D: Yes." (Daniel, 66 & Emily, spouse)	Potential benefits outweigh being discouraged
9	"If [technology] were in the home you get a lot more better because I like these [exercises], I do these every morning. Because you go to another therapist and they give you forty-five minutes and that's it…and then the week next you stay the same thing over and over, you don't get enough time" (Jane, 68).	Role of technology in the home for monitoring recovery and activity
10	"When I got home, they told me, do these exercises, and I did it some, but probably not as much as I should have, and I didn't really understand…And if we would have been monitoring while I was doing them, and they had seen how I wasn't really doing a whole lot, I might have done more, cause I was willing to do more, you know, I just didn't know to do more. And I ended up with a DVT. If [a system] gave you feedback that you were doing something, I think that would have really helped me." (Jill, 77).	
11	"Always remember that for people like us, time and energy is the thing that beats you down, it really is. Appointments are also kind of logistically challenging. It takes us three hours just to go for a doctor's appointment. Getting ready, down the e-chair into the garage, getting transferred, driving down and then of course they're always late. So, things that you could do at home, remotely…" (Archie, spouse)	The transition home is complicated and tiring, simplicity is key
12	"We have one of those [e-stim units] at home too, that we use on his arm. It's hard finding just the time and when we can both do it, and we're tired a lot (laughs). After a rough day, you know, he gets really tired from the therapy so even though it seems like it wouldn't be that hard to just sit down and do it, it seems to be for us though." (Emily, spouse)	
13	"Usually when you have a stroke, they figure that you're not competent for your own care. And they not only assume it, they project that out to you and everybody else around you. Which is hard, because you have a tough time communicating, and you can't function, and you're frightened. We became our own advocates, for technology and everything else." (Ben, 64)	Learning to advocate, using the technology that is available
14	"You have to be able to adapt and provide your own things for yourself. Whether it's training your body or just figuring out how to do it yourself. Whether it's with adaptive technology or with something you use to train yourself. It may be simple technology, but using what's available." (Anne, 62)	
15	"Another thing you might try would be using the data from this [technology] to improve the system. So you're covered and you can go work with the therapists who do the clinic and have them incorporate that into some of the stuff that they're doing, to show how the muscles are affected, something like that might be a really big training device, and a way to get insurance to understand, because you could see a lot of data" (Ben, 64)	Data showing incremental progress could improve the system
16	"It's a pretty significant investment. Cause of course I'm sure none of this is covered by insurance. If you look at it, think about a Botox injection, I mean, they're incredibly expensive. The insurance company gets billed five thousand dollars every time I have injections…and you know, I would say it helps on the margins, but I don't think it's been miraculous. And I think you run into the same sort of stumbling block with something like [sEMG]. Does it really have the potential to be a game changer? I think a lot of people are looking for what is gonna be a game changer. What's really gonna fix me? At least, that's how I thought about it at first, for better or worse." (Duke, 49).	

This table encapsulates relevant example quotes from the results which supported the development of Theme 2: "Tracking Incremental Progress over Days or Years is Important".

decisions as well as technology decisions, participants stressed the importance of involving the stroke survivor at every step, even in the early stages, to self-advocate for their needs (**Table 3**, Quotes 13, 14).

All participants discussed insurance frustrations during their stroke recovery. Over half the participants ($n = 6$) also noted that data describing these incremental changes noted during recovery could be essential for improving policy and access to neurorehabilitation services as well as technology such as sEMG. However, it was clear to participants that if sEMG will become a justifiable and viable rehabilitation technology, that it must demonstrate its significance to both users and insurance companies (**Table 3**, Quote 15, 16).

Theme 3: "Neurorehabilitation Technology Is Cumbersome"

The third theme reflects experiences of stroke survivors with other types of muscle tracking technology, as well as perceptions of current sEMG systems. Participants highlighted issues of cost and funding coverage, time, set-up logistics, and the tension between their desire to optimize time in therapy sessions vs. a willingness to try new technologies that may (or may not) enhance recovery. For example, even for a participant whose previous job was to create and test activity monitors, cost and accuracy were issues (**Table 4**, Quote 1).

All participants had purchased some type of rehabilitation technology out of pocket, and described similar sentiments about cost, maintenance, and reuse of supplies (**Table 4**, Quotes 2-4). Overall, the participants described a "buy and try" mentality, resulting in both successes and failures with technology (**Table 4**, Quotes 5-7). However, despite a willingness to search out and try, most participants ($n = 7$) expressed a preference for lower tech adaptive devices, or more ubiquitously available lay technology. Over half ($n = 6$) of the participants had tried wrist-worn commercial fitness trackers but reported mixed results. Those that responded favorably noted the device's potential for motivation, and those with less favorable opinions cited a lack of accuracy or customizability (**Table 4**, Quotes 8, 9). When sharing their experiences with sEMG or related technologies such as electrical stimulation, participants described the challenging logistics and cumbersome nature of these rehab technologies as a major barrier to use. Finding the correct sensor placement and need for caregiver assistance for setup were mentioned by half ($n = 5$) the participants (**Table 4**, Quotes 10-12). Training on proper placement and use of muscle technologies was also reported as a barrier by all the participants who had previously used wearable sensing devices ($n = 5$), even when self-cueing was performed by taking photographs or drawing on the skin. Participants noted the need for refresher training with their therapists when using this technology (**Table 4**, Quote 13).

Trends emerged, however no consensus from the participants was reached when discussing the benefits and drawbacks perceived from the demonstration of four sEMG systems. In general, participants felt the Delsys Trigno™ was a better research tool and impractical for clinical or home use, which reflects what it and other research-grade systems were designed for. Participants appreciated the flexibility and low profile of the ESS tape sensors and the Biostamp®, but preferred the Myo™ in terms of simplicity and ease of placement without the use of stickers. Half the participants raised the issue of difficulty removing sticker backing and applying sensors one-handed (**Table 4**, Quote 14). Aesthetics was less of an issue, with only one participant commenting about the sensor appearance (**Table 4**, Quote 15). Consensus was reached, however, in regard to user-centered feedback. All participants felt that a significant improvement for the future of sEMG systems would be the ability to incorporate real-time, multisensory feedback with flexible methods for receiving signal data outputs that are meaningful to the user (**Table 4**, Quotes 16-18).

Participants also had some lofty goals for the future of creative sEMG system design and multifunctional capacity. Design ideas included built-in lighting, navigation systems, and greater connectivity between body and technology, envisioned as a social media-style account for muscle tracking (**Table 4**, Quotes 19-21). Ultimately, participants were excited about the potential for sEMG technology to play a meaningful role in their stroke recoveries, despite the existing barriers of current systems and a lack of cost-effective, adaptable, user-centered systems. As one participant notably summarized, the issue with sEMG in rehabilitation populations is largely about product development stage, user knowledge, availability, and impact in a specialized market (**Table 4**, Quote 22).

DISCUSSION

Despite a significant body of research that describes the benefits that sEMG technology may provide in better understanding stroke recovery and enhancing neurorehabilitation outcomes, as well as standards for systematically implementing sEMG, translation to clinical and community settings has been limited (16, 18, 35, 41, 42). One aspect of this complex landscape is patient technology acceptance. Thus, it is important to more closely examine the perspectives of stroke survivors and their families, as central stakeholders in neurorehabilitation, in regard to sEMG technology features and functions. The recovery stories, setbacks and successes, and perceptions and presence of technologies represented in the themes that emerged from this study can play a central role in improving the translational capacity of sEMG systems.

First, our participants noted that little or no muscle monitoring technology was used during the acute and subacute phases of their recovery, these experiences underscore previous work documenting slow uptake of sEMG technologies outside research environments (15, 16). However, stroke survivors and their families indicated that this would be an ideal time to trial sEMG technology, when frustration and fear about return of muscle function is most prevalent and sEMG may detect muscle activity that is not visible or palpable. This early technology intervention is also supported in the literature, and capitalizes on the principles of neuroplasticity routinely cited as drivers of clinical practice in current stroke rehabilitation (43, 44). Further, given that detectable sEMG activity has been

TABLE 4 | Theme 3: "Neurorehabilitation technology is cumbersome."

#	Quote	Description
1	"I wish that I could wear a monitor now, to do a session and see how it is different from what it was, but I haven't wanted to spend the money to get something, and if I was to get one, I don't know that it would work, because I know how much better the monitors that we made were…very medically accurate. (Jill, 77)	Desire for accuracy, lack of money
2	"[Technology] requires a tremendous amount of money and a tremendous amount of effort. It looks cool and shiny and it does a lot of cool things, but how much does it cost? Can a patient afford that? Will insurance cover it because it is so costly? We have the same problems that everyone else does financially. We are looking at income versus outflow." (Anne, 62).	Out of Pocket cost, re-using supplies, insurance coverage are significant concerns
3	"Now they got my leg on this thing [e-stim/biofeedback], I was a candidate, but Medicare was no good, I had to pay for it all…it was almost six thousand dollars. Then, we had to buy a new computer because it went out and that cost me another four hundred dollars. It's hard, but it's worth it…at least now I can walk. I mean, I have to go very slow, but I can do it. You either gotta work back and then money. Money is a real problem." (Jane, 68)	
4	"If you have [money], it's fine. If you don't have it…one way we could actually get [our system] to run better would be to use new electrodes every time, but that would get expensive cause you have to keep buying those. So, we re-use them, but you know, the longer you use them, the worse they stick." (Emily, spouse)	
5	"I read magazines and I say, "Oh, this would be for me." And we'll go on the computer and see how it does it and everything. I'm always interested in technology and doing it for myself. I have all kind of gadgets that I can do with one hand." (Jane, 68).	Buy and try mentality
6	"From work, they had this one thing I could try, and I tried it. I didn't really perceive it was helping, so I decided not to keep doing it. And that may have been helpful, but it's hard to know…maybe this is what you get… you don't really know whether it's helpful or not." (Jill, 77).	
7	"You know, we are always trying to solve problems, there's not always good solutions for us. It's totally just looking for answers to our problems. What's going to help me recover? Whether that's a garbage can or whether it's these little [sEMG] tools. I'm willing to look at it and I'm willing to invest not only my time, my effort, that if I find the right tool, I'm willing to acquire it as an investment." (Anne, 62)	
8	"I just bought you a Fitbit, I thought that would be motivating with the walking and the steps. And we have a treadmill, so we're not there yet, but that's something we're hoping to use once he's strong enough. D: Well, it's…really beginning stages" (Emily, spouse, and Dan, 66)	Low tech solutions or lay technology use
9	It just doesn't cut it. I hear it's not accurate. It counts your steps, but it won't count half a step. Where if you have a short step like I do, then it doesn't count 'em. And they tried the heart rate monitor and it doesn't work. I was not impressed." (Ben, 64)	
10	"You'd put electrodes on your arm and then they actually gave me a laptop that had like a game on it. But it was one game and it was just basically moving one thing around. I mean, it was pretty cool, but it was a hassle to put the electrodes on and taking them off and getting them in the right place. They just sharpied on a mark where they were supposed to go. (Duke, 49).	Hassles with logistics, sensor placement, need for caregiver assist with setup and operation
11	"And the logistics of putting things on or off, That's a show stopper a lot of times. Cause I have to do it, of course. She can't do it if it's on her right arm. There's a lot to do just to get her set up." (Archie, spouse)	
12	"E: And [e-stim], it's something he can't do by himself. So, I have to be available to do it with him, and then, you know, it's just very touchy so you have to replace [the pads] a lot during the thing, so it's not just like we can slap it on and let it go. We're both kind of there the whole time, so it takes a lot longer than it should, I think. D: What…have a turn on and be working E: And stay on. Exactly (laughing). It's not even the length of time, it's just having to fix it all the time. Makes us both crazy!" (Emily, spouse, and Dan, 66)	
13	"It's hard because at first we would draw around the electrodes, but we get home, and if your arm's in a different position, it's not exact, and then you forget. You take a shower and they're all gone. And I took lots of pictures, you know, I'm there with my pictures trying to figure it out (laughs). This second round though, I feel better, at least about this stuff, than I did the first time. But really, it's a lot of just doing it and then if you can't get it to work, you go in, and they show you again." (Emily, spouse)	Being creative but needing training refreshers
14	"Sticking anything on and off just gets old after a while, right? So, anything they would come up with that just sits on the skin and can do it, I mean, I think it'll be a real leap forward. I mean, you only have fun ripping the hair out of your arm so many times (laughter) before you sort of just say, 'Well, what's the point of this!" (Duke, 49)	Hassle of stickers
15	"[They're] not pretty. I mean unless you put little rhinestones on it!" (Anne, 62).	Aesthetics may matter to some
16	"If it gives you a display, where you had something you can train yourself to, so if you're looking at something you can say, "Oh boy! I'm doing good because the pulses are the same on both legs instead of oh, this one was just going like that," so you get a video or an audio feedback of some kind." (Archie, spouse)	Needs for the future: multisensory feedback, multiple output styles
17	"If a graph was explained to me, I would love the graphs. I think with [others] you probably need characters or "yay" or something, or a positive sound coming out." (Cherry, 77)	
18	"If I'm trying, it meets me halfway, with a combination of visual and sensory [feedback]. You know, all the senses, Touch may be another option too" (Anne, 62).	
19	"I'd like something that has a little GPS finder, so there's some cool attraction that individuals may want. Are you more of an outdoor person, is there a flashlight involved? A flashlight would be handy too, you know, Are my shoes under here?!" (Ben, 64)	Multifunctional capacity
20	"Your next level is, is it voice-adaptable? Will it activate by voice? Voice activation would be ideal, because you can connect or sync up to the phone, or ring the doorbell, lock the door, you know, whatever you pick. Maybe color coding - does it turn blue when it's activated, or it turns yellow when you've achieved such a level." (Anne, 62)	

(Continued)

TABLE 4 | Continued

#	Quote	Description
21	"So, what you really want to do is have it integrated into some sort of central controller so that it could send you a text when you activated the muscle you wanted. Or an email, who knows what the next best thing will be. Tweet you, who knows! Set up a Twitter account for your muscle!" (Duke, 49).	
22	"I think it's about the quality of the technologies that are really out there sort of fully commercialized and fully on the market. And there's a lot of stuff that's kind of in conceptual phases or in beta test or in research studies, but there's not really that much that is sort of fully vetted and fully out there in the market to choose from. If something was demonstrably good at making improvements, I think it would be good if that was available, but I just think there's sort of a dearth of stuff available." (Duke, 49).	Where the industry is at, and where it can go

This table encapsulates relevant example quotes from the results which supported the development of Theme 3: "Neurorehabilitation technology is cumbersome".

seen in flaccid limbs of stroke survivors days after stroke and prior to onset of voluntary muscle contraction, having this resource more readily available in acute recovery phases could serve to build hope and motivation for stroke survivors, in addition to providing information to the medical team about neural pathway integrity (45). Interestingly, participants in this study also discussed the relative "downtime" during recovery, despite their willingness to work on exercises or activities outside of scheduled therapy visits. Rehabilitation clinicians have similarly noted these challenges that come with a relatively passive institutional rehabilitation culture, where stroke survivors have limited opportunities to practice real-world functional skills during down time from therapy or medical cares—which could signal a clinical practice gap in which sEMG may offer novel and individually tailored activity challenges to promote recovery (22).

Second, at home and in the community, stroke survivors demonstrated creativity, and resilience in adapting to their changing abilities, using a combination of high and low technology to improve participation and access. This is consistent with previous literature that describes the processes by which physical resilience is demonstrated following stroke, in part by participating in the hard work of rehabilitation, as well as capitalizing on technologies that may provide access or motivation during recovery (46, 47). However, while technology use with low tech tools such as adapted cutting boards or assistive mobility devices was ubiquitous, perceptions, and use of high-tech tools, including lay technologies for tracking fitness and activity, were quite mixed. These results are also consistent with previous literature describing general interest and excitement combined with skepticism about the features and function of rehabilitation technology (19–21). Further, while most participants were exposed to muscle tracking and training technologies such as electrical stimulation or biofeedback, use was inconsistent and often abandoned due to personal cost, cumbersome set-up, or lack of progress, which is also a common theme in previous work. This presents a unique challenge to clinicians to critically examine how and when these technologies are introduced, as well as to designers and manufacturers of sEMG to understand user and clinician perspectives in early development stages, respond to the relative simplicity and aesthetic appeal of lay technologies, and simultaneously address the precision and adaptive requirements to meet rehabilitation needs.

Third, the participants most strongly highlighted the need for technology to provide both significant and meaningful results. Current sEMG technology had potential in their eyes, and many participants were willing to try, but the financial investment and learning curve were possible barriers, especially if it did not result in impactful information or change from their own point of view. From a perspective of stroke survivor as consumer, this issue is likely one of the most important considerations for future sEMG system design and function. Interestingly, a lack of meaningful outcomes is a frequently cited reason for rehabilitation technology abandonment, however, user-centered, participatory design and implementation strategies are still not widely used in the development of such technologies, especially with older adults (48–51). It is important to consider, however, that sEMG systems may be less like traditional rehabilitation technologies but more closely resemble other wearable biomedical sensors that are engrained in routine clinical care, such as those that monitor heart rhythm (EKG) or brain activity (EEG). These systems also provide valuable results to clinicians and users, but do not require any action by the user aside from passively wearing the sensors. There appears to be a gap in research exploring user acceptance of these similar devices (52), but it remains unclear whether acceptance is not viewed as a major concern, whether differing perspectives may be due to the nuance of sEMG having the potential to elicit action or provide real-time feedback to users, or whether it is simply representative of a unique timeline and trajectory for clinical translation that sEMG may come to enjoy in the future. Regardless, this further highlights the need for additional collaboration between users, clinicians, and engineers during technology development and deployment processes.

Finally, the results of this study point critically to issues of knowledge and understanding of current rehabilitation evidence. Participants discussed the need for further information and education- both for themselves and their families, but also for their healthcare providers- in regard to the benefits and potential outcomes that may be enhanced by sEMG technology. Lack of knowledge or training, time, and self-confidence, as well as a need for meaningful therapeutic outcomes surrounding use of sEMG systems are indeed themes that have been reported previously from the perspective of clinician stakeholders, who often become technology gatekeepers during stroke rehabilitation (28, 35). This is concerning, given the extensive body of literature and standardized guidelines from the SENIAM project that support sEMG as a valuable rehabilitation tool, upon which comprehensive clinician training programs could be built (17, 18). Practical solutions to fill this knowledge gap for clinicians already exist, such as the American Board of Physical Therapy Specialties certification in Clinical Electrophysiology, but could also take the form of international multidisciplinary working groups, further expansion of electrophysiology content in professional rehabilitation training, and vetted teaching and learning modules that extend to a greater number of clinical practice areas.

In addition to technology recommendations from members of their rehabilitation team, a majority of participants largely sought out solutions on their own or at the suggestion of other stroke survivors in their peer groups, which are viewed as an important aspect of recovery (53). Improving education and information sharing among clinicians and stroke survivors appears to be a pathway by which sEMG could achieve greater uptake, provided a clear and compelling message about its utility during recovery could be delivered. This will be a challenge, given the difficulties with system change and novel technology implementation that have been reported in healthcare literature (36, 37). However, there is a unique opportunity to learn from these perspectives and use them to drive product and process improvements. By listening to stakeholders, it is possible for a re-branding of the potential of sEMG technology as a valuable tool that has the capability to provide a rapid, non-invasive, and data-driven look at post-stroke muscle activity which can impact prognostic outcomes, service recommendations, education, and empowerment for stroke survivors and their families.

Study Limitations

Although the stories shared by stroke survivors and their families who participated in this research provide a much-needed perspective on sEMG technology, there are several limitations to this study. First, the participants represent a small, convenience sample contained within a single metropolitan area, and may not represent the diverse perspectives of a larger or randomized group of stroke survivors. While there was a wide range of ages, genders, stroke types, and rehabilitation courses represented among our participants, all but one individual was Caucasian. Additionally, while a standard set of factual information was shared about four sEMG systems, this is not representative of all available sEMG technologies, so participant perspectives presented here are limited to these systems only. Further, given interview time constraints and to avoid fatiguing the participants, the interviewer did not fully connect or operate the systems in real-time. Participants had the opportunity to physically interact with the sensors, observe signal printouts, and verbally or visually attend to a feature comparison chart. Further work in this area should aim to mitigate these limitations, by intentionally recruiting racially diverse participants, conducting interviews across a wider geographic area, and involving the users in real-time set up and implementation of the sEMG systems over a longer study period to obtain perspectives after full immersion in the processes. Future research should also combine user and clinician perspectives together during rehabilitation care and further assess clinician training in neurorehabilitation technology to determine how closely perspectives align and how therapeutic relationships may affect responses to sEMG technology. Finally, while these perspectives are useful, further user, clinician, and engineering collaboration *before* technology development and deployment will strengthen resulting outcomes, as it is less helpful to constructively critique sEMG systems once they are already commercially deployed.

CONCLUSION

Perspectives of individuals with neurologic injuries and their caregivers are one central piece of a broader discussion of factors influencing improved translation of sEMG technology use into clinical settings. The stroke survivors in this study felt that sEMG would be a useful tool for motivation and acquisition of objective data, but that the user interface would have to be simple, available in multiple formats based on the preferences of the user, and provide meaningful feedback for participation in real-world activities, not just exercises. Participants highlighted essential features of sEMG systems, including low cost, flexibility, intuitive and independent use and interpretation, disposability, and comfort. Further translation of sEMG technology for neurorehabilitation into clinical and community environments holds promise, but sEMG system design and user interface needs refinement, and training and education opportunities for clinicians to leverage sEMG technology throughout all phases of rehabilitation following stroke is warranted. Including stroke survivors directly in translational efforts, particularly in creating sEMG system outputs and feedback that is meaningful and motivating to users, is essential to improve uptake in both clinical and community environments.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The University of Washington Human Subjects Division. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

All authors contributed meaningfully to the preparation of this manuscript. HF conducted all the interviews. HF and CP completed primary data analysis. KS and KP completed secondary data analysis. All authors contributed to the writing and editing of the manuscript and equipment used in the study is owned by the Steele Lab in the Department of Mechanical Engineering at the University of Washington. Photos of sEMG systems were taken by HF and are provided courtesy of the

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METHODS
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Analysis and Biophysics of Surface EMG for Physiotherapists and Kinesiologists: Toward a Common Language With Rehabilitation Engineers

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Recent decades have seen a move toward evidence-based medicine to inform the clinical decision-making process with reproducible findings from high-quality research studies. There is a need for objective, quantitative measurement tools to increase the reliability and reproducibility of studies evaluating the efficacy of healthcare interventions, particularly in the field of physical and rehabilitative medicine. Surface electromyography (sEMG) is a non-invasive measure of muscle activity that is widely used in research but is under-utilized as a clinical tool in rehabilitative medicine. Other types of electrophysiological signals (e.g., electrocardiography, electroencephalography, intramuscular EMG) are commonly recorded by healthcare practitioners, however, sEMG has yet to successfully transition to clinical practice. Surface EMG has clear clinical potential as an indicator of muscle activation, however reliable extraction of information requires knowledge of the appropriate methods for recording and analyzing sEMG and an understanding of the underlying biophysics. These concepts are generally not covered in sufficient depth in the standard curriculum for physiotherapists and kinesiologists to encourage a confident use of sEMG in clinical practice. In addition, the common perception of sEMG as a specialized topic means that the clinical potential of sEMG and the pathways to application in practice are often not apparent. The aim of this paper is to address barriers to the translation of sEMG by emphasizing its benefits as an objective clinical tool and by overcoming its perceived complexity. The many useful clinical applications of sEMG are highlighted and examples provided to illustrate how it can be implemented in practice. The paper outlines how fundamental biophysics and EMG signal processing concepts could be presented to a non-technical audience. An accompanying tutorial with sample data and code is provided which could be used as a tool for teaching or self-guided learning. The importance of observing sEMG in routine use in clinic is identified as an essential part of the effective communication of sEMG recording and signal analysis methods. Highlighting the advantages of sEMG as a clinical tool and reducing its perceived complexity could bridge the gap between theoretical knowledge and practical application and provide the impetus for the widespread use of sEMG in clinic.

Keywords: rehabilitation, surface electromyography, physiotherapy, kinesiology, clinical application, surface EMG tutorial

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INTRODUCTION

Surface EMG is currently an under-utilized clinical tool in rehabilitative medicine, despite its clear potential as a non-invasive measure of muscle activity. It is often considered more complex to analyze than intramuscular EMG, a technique commonly applied in clinical neurology, as parameters of direct clinical relevance cannot be readily extracted (visually or acoustically) from the recorded signal. However, with relatively basic signal processing, important information on muscle activation patterns and muscle properties can be obtained from surface electromyographic (sEMG) signals. This information can potentially provide an objective, quantitative method of assessing muscle function, movement patterns, and local muscle fatigue to inform the clinical decision-making process. Surface EMG features may also provide a more effective means of objectively capturing differences in motor control following surgical or therapeutic interventions, or training and rehabilitation protocols, when compared with more subjective measures based on visual observation, manual palpation, mechanical manipulation, or standard clinical tests. Application of sEMG in terms of real-time feedback can also be used as a tool to help patients gain greater awareness of their own muscle activity and support re-training of movement patterns. Recent developments in wearable sensing technologies enable movement and EMG data to be recorded in more natural environments outside the laboratory setting, during the activities of daily life. These technologies present a range of new opportunities for quantitative assessment and medium to long-term monitoring of movement. However, a basic understanding of signal processing is required to extract or interpret information from EMG or accelerometry signals recorded by the sensors. With smartphones and tablets placing high-powered data sensing and processing capability into the hands of all, and technology becoming an integral part of all professions, it is responsibility of educators and professional bodies to ensure that the next generation of therapists have the technical competency and know-how needed to make the most of this capability within their clinical practice and harness the opportunities it offers.

The speed at which technological innovations are adopted and disseminated is governed by several factors, including the perceived complexity and benefit of the innovation (1, 2). The slow uptake of sEMG as a clinical tool can be largely attributed to the perceived complexity of sEMG and an incomplete understanding of its capabilities and potential among practitioners (and more importantly, among clinical educators). Although these obstacles can be partially overcome through education, the mere availability of tutorials and documented technical information is not enough to encourage the widespread dissemination of sEMG as a clinical tool. A theoretical knowledge of sEMG alone is not sufficient, practitioners need to see how sEMG can benefit everyday practice to be convinced to adopt the technology. The benefit is best demonstrated either by students being taught how to use and apply it by their educators, or though observing it in routine use by experienced practitioners in the clinic. As highlighted by Jette (2), "People follow the lead of other people they know and trust when they decide whether to take up an innovation and change the way they practice." When correctly presented, the perceived complexity of sEMG can also be broken down, and the technical background needed to accurately record and interpret sEMG signals can be conveyed to students and practitioners in a relatively simple manner. Finally, providing opportunities for practical experience observing and experimenting with sEMG is then critical to bridge the gap from a theoretical knowledge of sEMG to having the ability and motivation to adopt sEMG in clinical practice.

The perception of sEMG as a specialized subject with limited relevance to clinical practice is likely to be first formed during the education and training of practitioners. Physiotherapy and kinesiology education varies considerably across different countries, ranging from an apprenticeship involving clinical or hospital-based training to professional masters or doctoral degree programs (3) (from here on, the term "physiotherapy" will be used to cover "physiotherapy, kinesiology, and physical therapy"). The standard curriculum in tertiary education may cover recording and analysis of sEMG. However, this is not universally the case, and even when taught, these topics are often not covered in sufficient detail to encourage a confident and independent use of sEMG in clinical practice. A gap exists between the theory covered in standard courses and the minimum signal processing and biophysics knowledge and experience required for application of sEMG in clinical practice. These concepts are required to master the recording and analysis methods for sEMG and to ensure the required clinical information can be obtained accurately and reliably. Although there are a number of resources that provide guidelines for sEMG signal processing, this information is sometimes presented using language and terminology that caters to readers with an engineering or technical background. Notable exceptions include the books by Criswell (4), Kamen and Gabriel (5), Barbero et al. (6), and Chapter 8 of Robertson et al. (7) which provide a detailed treatment of sEMG recording and analysis methods targeted specifically at practitioners (a full list of relevant resources targeted at practitioners is available in the "Further Reading" **Supplementary Material**).

The aim of this paper is to address technical barriers to the widespread adoption of sEMG in the clinic, specifically those related to the perceived complexity and benefit of sEMG. Examples are described to illustrate the wide range of clinical sEMG applications, from simple biofeedback (requiring minimal knowledge of sEMG concepts) to more advanced sEMG signal analysis that can provide additional detail on neuromuscular function (e.g., sEMG median frequency can provide information on muscle fatigue). We then identify key information that is needed to successfully record, process and interpret sEMG signals in a clinical setting, and aim to present it in an accessible way to a non-technical audience. The paper begins with an overview of the physics and physiology underlying the generation of sEMG signals and examples of clinical applications (section 2: Background and Applications). Basic signal concepts including time and frequency domain analyses are introduced in section 3: Basic Signal Concepts. The main factors to consider when choosing equipment and recording EMG signals are then outlined (section 4: EMG Signal Acquisition and

Recording) and key topics in signal processing relevant to sEMG analysis explained, i.e., sampling, filtering, and frequency domain analysis (section 5: EMG Signal Pre-Processing and Analysis). The topics covered could be incorporated into the curricula for physiotherapists to provide the foundational knowledge needed to reliably record and interpret sEMG signals to extract clinically meaningful information. Although the material covers topics that may be unfamiliar to readers coming from a non-engineering background, the only pre-requisite to understanding the material is familiarity with basic mathematical concepts, e.g., concept of an equation, sine, logarithm. This allows the material to be more easily understood by readers from a non-technical background when compared to other introductory signal processing texts, which often require a relatively strong mathematical knowledge.

This paper is designed as a tutorial to enable readers to bridge the gap between theory and how it is applied in practice though EMG signal analysis. To promote the practical application of the key concepts covered in this paper, EMG data is available in the **Supplementary Material** and accompanying MATLAB (requires license) and Octave (free) software code is provided to illustrate different signal processing concepts (https://doi.org/10.5281/zenodo.4001609). These data and software codes could form the basis of a practical tutorial or workshop on sEMG. The code provided can be used as a template to be adapted and used by readers in the analysis of their own signals. Although many sEMG recording systems supply software to provide estimates of signal features, such as sEMG amplitude or frequency content, it is often not clear to the user how these features are calculated. To the non-expert user, the appropriate choice of parameters to extract the signal features of interest may not be apparent. However, enabling users to develop and alter their own code allows them to explore how changing the analysis parameters can affect the features extracted from the sEMG. This empowers the user, providing transparency and the awareness of the processing methods rather than a "black box" type approach, and enables them to tailor their analysis to specific applications. Even when using standard software packages, it is important that users understand how the parameters chosen for signal analysis influence the results obtained.

Finally, by introducing these topics in a way that is accessible and clinically useful, we demonstrate a pathway for incorporating technical and scientific aspects of sEMG recording and analysis into the educational curriculum for physiotherapists. In this way, we aim to reduce technical barriers to the incorporation of surface EMG in clinical applications and provide a bridge between theoretical concepts and practical applications by both reducing the perceived complexity of sEMG and highlighting its benefits as a clinical tool.

BACKGROUND AND APPLICATIONS

EMG Generation

The EMG signal is the electrical activity generated by a contracting muscle which can be detected by placing an electrode[1] or pair of electrodes on the skin above the muscle of interest. During muscle activation, there is a flow of charged particles (ions) across the muscle fiber membrane. The rate of flow of charge is called the electrical current (I) and is measured in Amperes (electric charge per second). Electrical currents within the muscle alter the electrical potential in the surrounding tissue. The difference in electrical potential or voltage between two points is measured in Volts (V). The voltage detected at the skin surface is influenced by the resistance or impedance [quantified in Ohms (Ω)] to the flow of electric current provided by the surrounding muscle, subcutaneous tissue, and skin. The time-varying voltage distribution present on the skin surface due to the electrical activity of a muscle is termed the sEMG signal, see **Figure 1**, and can be used to provide information about the muscle contraction[2] (see section Practical Applications of Surface EMG in the Clinic). These basic principles of electricity are fundamental to the understanding of the more advanced EMG topics covered in this paper [see also Barry (8) and Kamen and Gabriel (5)].

Signals from the brainstem/spinal cord are transmitted to the muscle by motoneurons. When a motoneuron is activated (i.e., discharges), synaptic transmission at the neuromuscular junction results in a transient change in electrical potential, known as an action potential, across the muscle fiber membrane of each muscle fiber innervated by the motoneuron. The motor unit[3] action potential refers to the electrical potential recorded due to the activation of the muscle fibers innervated by a motoneuron. The sEMG signal is a summation of action potentials generated by motor units lying within the detection volume of the electrodes, **Figure 1A** [for detailed accounts of EMG signal generation see De Luca (9), Kamen and Caldwell (10), Moritani et al. (11), and Farina et al. (12)]. Each motor unit action potential (MUAP) waveform will have a distinct shape, **Figure 1B**, which represents the recorded electrical potential over time. The shape of the action potential will depend on the motor unit properties (e.g., number of muscle fibers innervated by the motoneuron and their cross-sectional area and fiber type) and the location and orientation of its muscle fibers relative to the position of the recording electrodes [for further details on MUAP properties see Barkhaus and Nandedkar (13) and Rodriguez-Falces (14)]. In order to increase the force generated by a muscle, there must be an increase in the firing rates of motor units which are already active and/or additional motor units must be recruited. At very low levels of muscle activation (e.g., $<10\%$ of maximum voluntary contraction, MVC) or with intramuscular EMG (detected with needles or wires inserted into the muscle), it is sometimes possible to distinguish individual motor unit action potentials, **Figure 1A** (ranging in duration from 5 to

[1]Sensor made of conductive material. The individual contacts within an electrode sensor can also be termed "electrodes" (but are here referred to as "electrode contacts").

[2]It is important to note that measuring the electrical activity of the muscle with sEMG is not equivalent to measuring the tension produced within the muscle, as the EMG signal precedes mechanical muscle activity. It is also possible for electrical and mechanical muscle activity to occur independently from one another.

[3]A motor unit is the smallest functional unit of a muscle, it consists of a motoneuron and the group of muscle fibers it innervates.

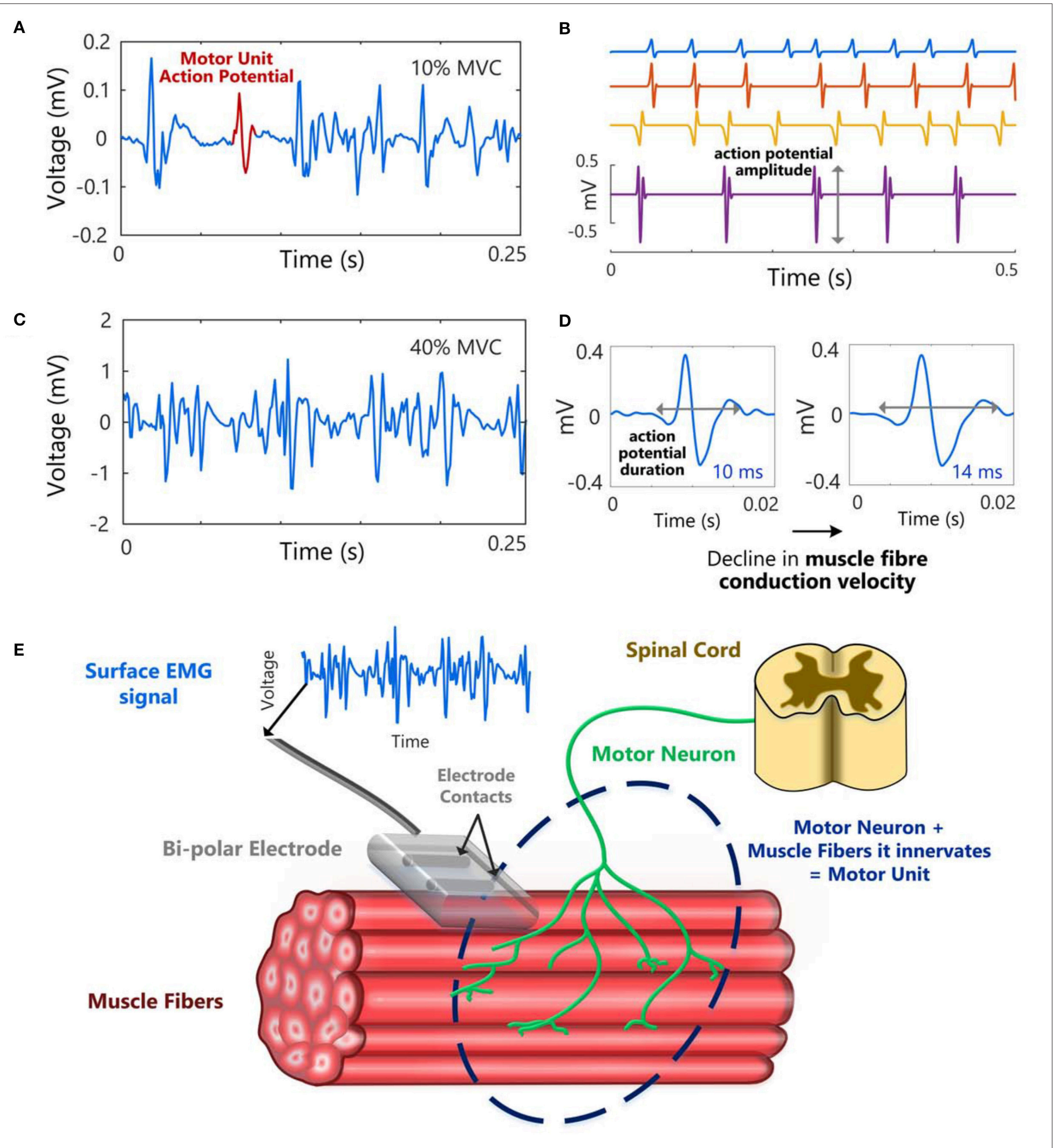

FIGURE 1 | Example of a surface EMG signal at a low force level (10% of maximum voluntary contraction, MVC) **(A)** and a higher force level, 40% MVC **(C)**, in the first dorsal interosseous muscle. **(B)** Single motor unit action potential trains with different inter-spike intervals (ISIs), i.e., different motor unit firing rates and **(D)** an illustration of the increase in action potential duration that can occur with a decline in muscle fiber conduction velocity. **(E)** A schematic to illustrate a motor unit, and how a surface EMG signal could be recorded from a muscle using a bipolar electrode (two electrode contacts).

30 ms, **Figure 1D**). At higher muscle contraction levels (e.g., 10–100% MVC), it is rarely possible to visually distinguish individual motor units, as the number of MUAPs contributing to the signal increases. The action potentials from all active motor units sum together generating a random-looking EMG signal at the skin surface, **Figure 1C**. The firing times of individual motor units can

TABLE 1 | Examples of sEMG applications in assessment and treatment, see Chapter 10 in Criswell (4).

Assessment

Assess level of muscle activation:	sEMG evaluation:
• Unwanted muscle activation during rest	• Evidence of MU activity in baseline sEMG recording
• Relative activation of different muscles across the range of motion [a]	• Variation in sEMG amplitude across the range of motion [a,b]
• Presence of unwanted muscle activation/inhibition during muscle contractions	• Excessive/insufficient muscle activation (higher/lower than expected sEMG amplitude) relative to the task or in relation to other synergists [b,c]
• Inappropriate muscle co-activation during bilateral movements	• Differences in sEMG activity between homologous muscles on the involved and uninvolved sides during bilateral movements [b,c]

Assess timing of muscle activation:	sEMG evaluation:
• Altered recruitment/derecruitment of muscles during eccentric and concentric phases of movement • Inappropriate timing of agonist/antagonist muscle activation during joint stabilization	• Delayed muscle onset during movement • Premature muscle onset during movement • Muscle active for an excessive (or insufficient) time period during movement

Assess muscle fatigue:	sEMG evaluation:
• Indirect estimate of changes in muscle fiber conduction velocity (MFCV) associated with peripheral fatigue	• Rate of decline of the mean/median frequency of the sEMG signal (see section Surface EMG Spectral Features (Frequency Domain)) during a fatiguing contraction and subsequent recovery (normalized to baseline value)
• "Global" estimate of MFCV	• Estimated from the delay between sEMG signals from spatially displaced electrodes
• Changes in muscle activation (motor unit firing rate/recruitment) to compensate for reduced force generating capacity	• Increase in sEMG amplitude with respect to baseline value

Treatment

Objective:	Use of sEMG:
• Uptraining muscle(s) (i.e., increase sEMG amplitude)	• sEMG activity can be provided as feedback to the patient as an aid to increase awareness of their level of muscle activation • Begin with training an isolated muscle, recording also from other muscles to ensure they are not inappropriately recruited to the contraction • Threshold level can be set a for sEMG activation and patient encouraged to exceed this threshold • Threshold can be gradually increased to encourage patients to increase the strength of the muscle contraction • A threshold could also be used in endurance training, where the subject must maintain a target level of muscle activation

(Continued)

TABLE 1 | Continued

Treatment

Objective:	Use of sEMG:
• Relaxation or down-training muscles (i.e., reduce sEMG amplitude)	• Record from muscles that are chronically hyperactive to promote relaxation • Threshold can set be for muscle activation and encourage patient to relax the muscle to keep below this threshold • This threshold can be gradually lowered over time to increase relaxation ability

[a] *Resources are available showing the normal template for muscle activations during different movements, for example the atlas in Part III of CRAM's provides a "benchmark" for the relative activation of certain muscles during static load conditions (e.g., during normal shoulder abduction, there should be a balanced activation of the upper and lower trapezius).*

[b] *Caution should be exercised when interpreting sEMG amplitude due to intersubject and intrasubject variability associated with factors such as electrode contact, electrode placement, anatomical factors, temperature etc. which can influence the signal amplitude.*

[c] *Normalization of sEMG amplitude with respect to a reference value is usually recommended, see Besomi et al. (22). However, sEMG signals between homologous muscle groups can be approximately compared (e.g., between left and right upper trapezius).*

be extracted from sEMG signals recorded with two-dimensional arrays of electrodes using specialized sEMG decomposition algorithms (15–17). This method provides information on the discharge times of individual motoneurons, with a greater yield of detected motor units than can typically be obtained using invasive intramuscular EMG. sEMG decomposition is a specialized topic which will not be covered in this paper, for further details readers are referred to de Luca et al. (18), Drost et al. (19), Stegeman et al. (20), and Farina and Holobar (21).

Practical Applications of Surface EMG in the Clinic

In the assessment and diagnosis of neuromuscular disorders, EMG is typically invasively recorded within the muscle using needle electrodes (either concentric or monopolar). Intramuscular EMG recordings can isolate single motor unit activity and are used to detect abnormalities in motor unit firing patterns or in action potential shape, and pathological spontaneous activity in relaxed muscles. However, due to the small detection volume of needle electrodes, intramuscular EMG recordings reflect the activity of a small number of motor units whose muscle fibers are located close to the detection site. Moreover, this technique is usually limited to low levels of isometric muscle contraction with a relatively small number of active motor units in order to reliably discriminate or extract the activity of individual motor units. Physiotherapists are often more interested in extracting information on temporal patterns of activity from the muscle as a whole or from groups of muscles, often during functional movement. Surface EMG provides a non-invasive, global measurement of muscle activity, which may be more suitable for applications in movement analysis that require frequent assessments or information on the patterns of activation of multiple muscles (e.g., in sport, rehabilitation, and occupational medicine). Surface EMG can be a valuable tool in both the assessment and treatment of patients and can be used to objectively, and quantitatively, measure progress, and evaluate treatment outcomes.

Examples of applications of sEMG signals in the assessment and treatment of patients are summarized in **Table 1**. Surface EMG recorded from simultaneously active muscles can provide the therapist with information on the symmetry and relative activation of these muscles during different movements. For example, sEMG recorded from the left and right erector spinae muscles during a low back evaluation or from the vastus medialis and lateralis during a patellar subluxation evaluation can be used to determine whether there is balanced activation from paired muscles [Chapter 4 in Schwartz and Andrasik (23)]. Surface EMG can also be used as a therapeutic aid in the treatment of patients and enable them to gain more awareness and control of their own muscle activity. The amplitude of the sEMG signal can be shown to the patient and therapist (i.e., biofeedback) to provide an objective measure of the degree of muscle activation, **Figure 2A** (24). Surface EMG biofeedback can be used in rehabilitation protocols to help patients self-regulate elevated muscle activity, strengthen/train weak, inhibited or paretic muscles, and facilitate a reduction in tone in a spastic muscle (25). Schwartz and Andrasik (23) illustrate several applications of sEMG biofeedback, including an example in patients with shoulder problems. In this example, it is suggested that sEMG could be recorded from the upper and lower trapezius during shoulder abduction and a virtual channel constructed to display the relative activation of the lower trapezius (i.e., amplitude of the lower trapezius sEMG divided by the sum of the amplitudes of the upper and lower trapezius sEMG). This channel could be displayed to the patient visually to target the lower trapezius (increase recruitment), which can become inhibited and limit full range of motion in shoulder abduction. In a similar way, the inclusion of EMG biofeedback in conventional exercise programs can facilitate recovery after surgery (26, 27) and can also improve the effectiveness of training programs [e.g., pelvic floor muscle training (28–30)]. Surface EMG biofeedback can also be useful in cases where muscular tension causes pain, as the visual stimulus can help the patient to relax or deactivate the muscles [e.g., alleviating neck (31, 32) and low back pain (33)], **Figure 2B**. Muscle activation can be assessed using sEMG during different exercises in order to identify abnormal patterns of activation, and aid in locating the source of chronic pain (34). Visual feedback on muscle activation has also been shown to improve gait quality in both hemiplegic patients and in children with cerebral palsy (35, 36).

Surface EMG can also offer insights into diseases of the central nervous system which can affect the regulation and coordination of movement across the body. This can manifest as a reduction in (paresis/weakness), or loss of (paralysis), the desired motor output. Other diseases of the central nervous system can cause involuntary movements of the body (e.g., chorea, dystonia, seizures in epilepsy, tremor in Parkinson's disease, and essential tremor). Surface EMG offers a non-invasive alternative to intramuscular EMG in the detection of involuntary muscle twitches arising from spontaneous motor unit activity (i.e., fasciculation potentials) (37, 38). Surface EMG recordings are also commonly used in rehabilitation and biomechanics to investigate how movement is coordinated between multiple muscles during different tasks (e.g., during rest, gait, and fine hand movements) with the aim of differentiating between normal and pathological motor control in different conditions or identifying changes in response to interventions such as exercise or when using a device such as an exoskeleton. The amplitude of the sEMG signal can be used to examine the timing of muscle activity and the relative intensity or interaction between simultaneously active muscles, see section Surface EMG Amplitude Features (Time Domain), **Table 1**, **Figure 2A**.

In addition to providing information on muscle activation, in certain conditions sEMG can also be used to indirectly monitor changes in muscle force and in the underlying muscle fiber conduction velocity (MFCV). During isometric[4] muscle contractions, the sEMG amplitude can be used to infer information about muscle force [with important caveats, see de Luca (39)]. Surface EMG recordings can be combined with accelerometry or force data to provide a more complete picture of muscle function during different motor tasks. Simultaneous sEMG and muscle force recordings during isometric muscle contractions may provide a more objective method of assessing local muscle fatigue in the clinic when compared with subjective mechanical techniques. Changes in the amplitude and the mean/median frequency of the sEMG signal can also provide insight into the relative prevalence of central[5] and peripheral fatigue[6] in neuromuscular disorders (40). An inability to sustain a voluntary, submaximal muscle contraction combined with a minimal decrease in the sEMG median frequency could indicate that the impairment is central in origin, arising from a suboptimal voluntary drive from brain to muscle. The mean or median frequency of the sEMG signal provides an indirect assessment of changes in muscle fiber conduction velocity, however, a more direct, "global" estimate of muscle fiber conduction velocity (MFCV) can also be calculated using sEMG [estimated as the time taken for a sEMG signal to travel between two spatially displaced recording electrodes, (41, 42)]. This technique to estimate MFCV can be applied proficiently even during the execution of highly dynamic movements [e.g., cycling Farina et al. (43) and Sbriccoli et al. (44)]. Surface EMG has been used to assess differences in MFCV in several neuromuscular disorders (e.g., Duchenne muscular dystrophy, myotonic dystrophy) (38).

More recently, non-linear methods, such as recurrence quantification analysis and entropy, have been used to characterize the degree of similarity and repeating structure within sEMG signals (45, 46), see reviews by Clancy et al. (47) and Mesin et al. (48). These non-linear features have been

[4]A muscle contraction in which muscle tension is produced with no change in muscle length. It is often assumed that this is the case when there is no change in joint or limb position.

[5]Central fatigue encompasses decreases in descending motor commands from the brain to spinal motoneurons, reduced excitatory afferent input, and decreases in motoneuron responsiveness.

[6]Peripheral fatigue refers to changes occurring beyond the motoneuron, including changes within the muscle fibers.

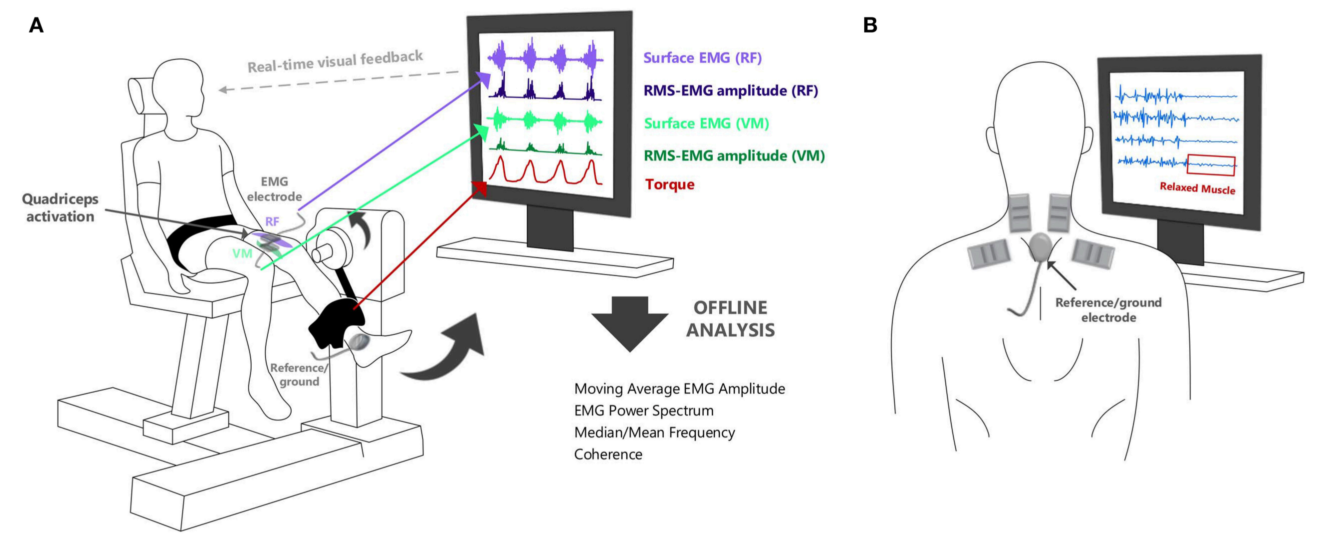

FIGURE 2 | (A) Surface EMG can be used to provide real-time feedback of muscle activation during neuromuscular assessments. It can show the relative timing of activation from selected muscles in different tasks. **(B)** Visual biofeedback from surface EMG can also aid in muscle training to ensure that rehabilitation tasks are optimally performed (and the correct muscles are "relaxed" or "activated" as required by the task).

shown to capture differences in sEMG signals under conditions where normal motor unit synchronization is enhanced, e.g., during muscle fatigue and in subjects with Parkinson's disease (49–52). Lastly, sEMG can be used in conjunction with electrical stimulation to record the amplitude of a compound muscle action potential[7] (CMAP). The CMAP amplitude is used to diagnose neuromuscular transmission disorders and can also be used to estimate the number of functional motor units within a muscle [for a detailed account of clinical applications see Zwarts et al. (53)].

In recent years, sEMG electrode arrays or grids have become more widely used, offering several advantages over traditional/conventional sEMG recordings. Electrode arrays can be used to locate the innervation zone of a muscle, accurately estimate muscle fiber conduction velocity, map motor unit action potential propagation across a muscle, and inform on the length and orientation of the muscle fibers. Using high density sEMG arrays the sEMG signal can be sampled across different points above the muscle, so that the spatial distribution of the sEMG signal can also be analyzed. Surface EMG recordings from electrode arrays can be decomposed using specialized algorithms to provide information on single/individual motor unit activities. Though sEMG arrays currently have limited clinical use, they offer significant potential for applications in neurology to monitor changes in the characteristics of the motor unit action potential waveform and motoneuron firing patterns in different neuromuscular disorders. However, a main drawback of sEMG array recordings is that they are more complex to analyze and interpret, requiring specialized algorithms to extract individual motor unit activities, and to assess the accuracy of the detected motor unit firing trains. For many applications in sport and rehabilitative medicine, much of the required information can be obtained from traditional bipolar sEMG (e.g., assessment of muscle activation and fatigue). The placement of conventional sEMG electrodes is relatively straightforward and recorded sEMG signals can be successfully processed and analyzed with some basic knowledge of signal processing (with the key topics outlined in this paper). The varied clinical applications of sEMG are discussed in detail in Kamen and Gabriel (5), Criswell (4), and Barbero et al. (6), Merletti and Farina (54) and in Chapter 8 of Robertson et al. (7).

[7]A CMAP is generated when the motor nerve supplying the muscle is electrically stimulated, causing the muscle to contract. It is the summated electrical response of the activated motor units within the muscle.

BASIC SIGNAL CONCEPTS

Description of a Signal

Any physical quantity (e.g., temperature, voltage, current) that varies over time can be described as a signal and can be represented visually on a graph depicting its waveform or pattern over time, **Figures 3A,B**. A simple sine wave is described by three characteristics: amplitude (A), frequency (f), and phase (ϕ), **Figure 3D**.

Sine waves are periodic signals, which means that they repeat in time after a period of T seconds (s), with a frequency of $1/T$ "cycles per second" or Hertz (Hz), **Figure 4**. The period and frequency of a waveform are inversely related to one another ($f = \frac{1}{T}$), so as the period of a waveform decreases, its frequency will increase and vice versa. Sine waves can have different frequencies and amplitudes and can also be shifted in time relative to one another, i.e., have different phases, **Figure 4**. Sine waves of different frequencies and amplitudes are created in Example ii in

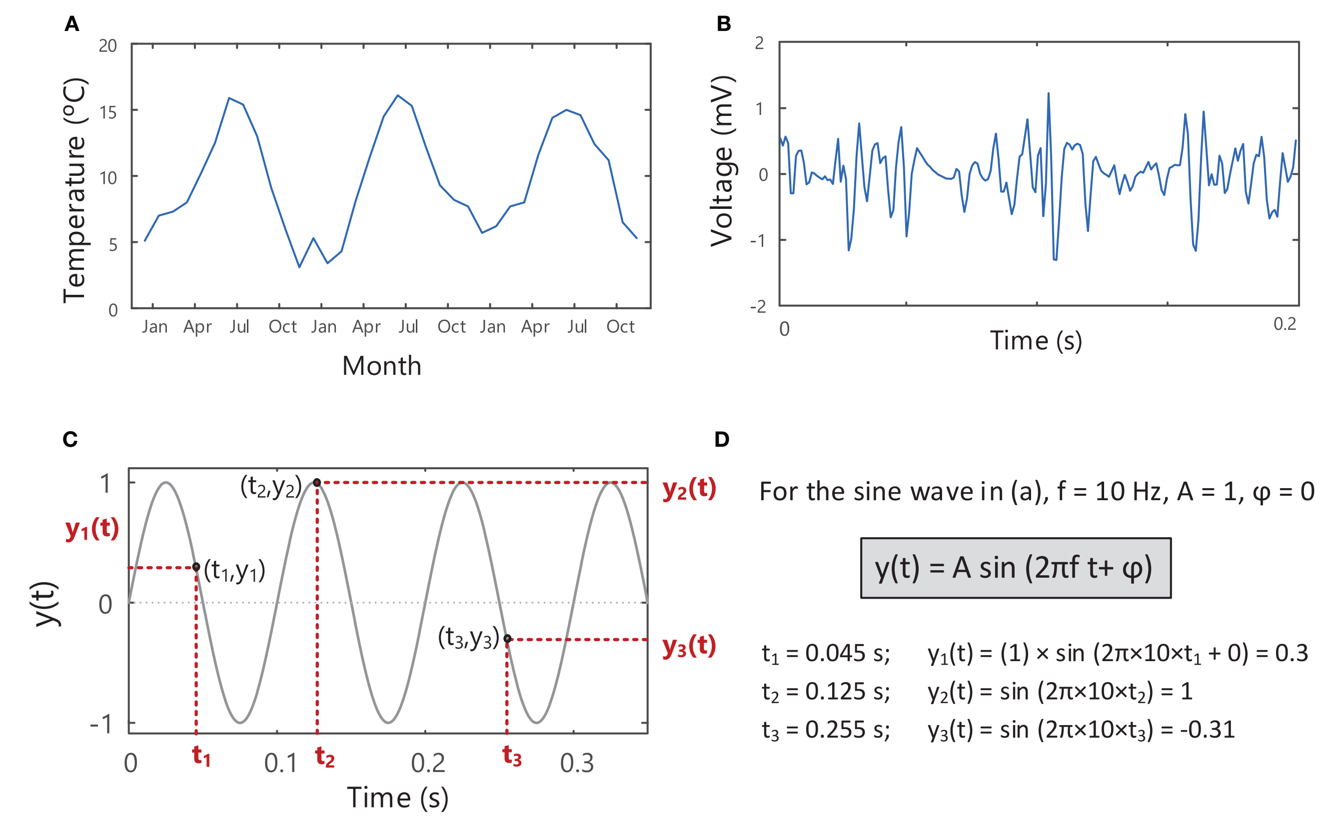

FIGURE 3 | Signals describing the variation of a measurable quantity over time, e.g., **(A)** temperature and **(B)** voltage. **(C)** A sine wave with an amplitude of 1, frequency of 10 Hz and phase of zero, showing the variation in the signal over time. The instantaneous value of the sine wave, y(t), shown in **(C)** can be found at each point in time, t, using the equation in **(D)**. See Example (i) in Tutorial Code.

Tutorial Code in the **Supplementary Material** (https://doi.org/10.5281/zenodo.4001609).

Frequency Domain Analysis

Signals can be represented in the time domain, **Figures 3**, **4**, or can be transformed to the frequency domain by applying the Fourier Transform[8]. Time domain analysis of EMG signals can be used to identify when a muscle is "active" or "inactive" or to provide information on the relative level of muscle activation [section Surface EMG Amplitude Features (Time Domain)]. Applying the Fourier transform to EMG signals provides information on how the signal power is distributed across different frequencies, i.e., it allows the signal to be examined in the frequency domain [section Surface EMG Spectral Features (Frequency Domain)]. The Fourier Transform works on the principle that any periodic signal can be represented as a sum of sine and cosine waves of different amplitudes, frequencies, and phases. The amplitude (A) or power of each sinusoidal component can be examined as a function of frequency, providing the amplitude and power spectrum of the signal, respectively, **Figure 5**. The area under the power spectrum (measured in V^2)[9] corresponds to the total energy contained within the signal.

For a perfect sine wave, all the energy in the signal is contained at one frequency (the fundamental frequency), **Figure 5A**. More complex signals, such as electroencephalographic (EEG) or EMG signals, have a broad frequency content with signal power distributed across a range of frequencies. Most of the sEMG signal power is contained between 10 and 400 Hz, **Figures 5D,E**, with frequency components outside of this bandwidth primarily due to noise at the electrode-skin interface and electrical interference. Higher frequency components up to 5,000 Hz can be observed in intramuscular EMG signals.

The length of the signal segment or epoch (T_r) determines the "frequency resolution" of the Fourier-transformed signal and the lowest detectable frequency component ($1/T_r$). For example, when 0.25 s of the sEMG recording in **Figure 5D** is examined in the frequency domain it will have a frequency resolution of $1/0.25\text{ Hz} = 4\text{ Hz}$. Similarly, a 0.1 s sEMG recording will have a

[8] The Fourier Transform is a mathematical function or technique that enables a signal to be separated and represented in terms of sine (or cosine) waves of different frequencies (which sum to reconstruct the original signal).

[9] The term power spectrum and power spectral density are often used interchangeably. To obtain the power spectral density (measured in V^2/Hz), the power spectrum is normalized by dividing by the frequency resolution (i.e., in the case of a 1 Hz frequency resolution, the magnitude of the power spectrum remains the same).

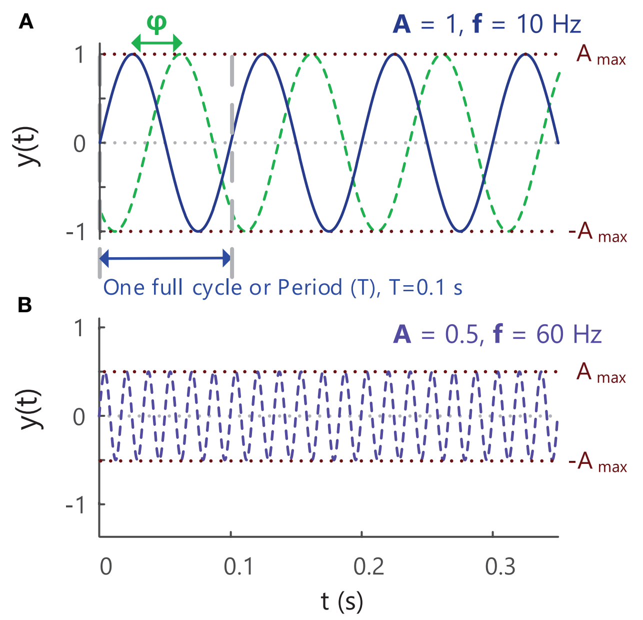

FIGURE 4 | (A) A sine wave with an amplitude of 1, frequency of 10 Hz and phase of zero, showing the variation in the signal over time. A second sine wave with the same amplitude and frequency but different phase ($-\pi/2 = -90°$) is indicated with the green dashed lines. As the value of a sinusoidal signal at any point in time is based on circular motion, the phase of a signal is expressed as an angle in radians or degrees (start of period = 0°, end of period = 360° or 2π radians). **(B)** A sine wave with an amplitude of 0.5, frequency of 60 Hz and phase of zero. See Example (ii) in Tutorial Code.

frequency resolution of 10 Hz (its frequency components will be 10 Hz apart), **Figure 5E**. It will thus be too short in duration to detect frequency components below 10 Hz, or frequencies lying between 10 and 20 Hz, 20 and 30 Hz, and so on.

EMG SIGNAL ACQUISITION AND RECORDING

Careful skin preparation and choice of electrode type, electrode placement and recording configuration, including filter settings and amplifier gain, are essential to record high quality EMG signals with low noise. Key information needed to optimize the quality of recorded sEMG signals is summarized below, and more detailed information on EMG instrumentation standards can be found in Tankisi et al. (55), Gitter and Stolov (56), Gitter and Stolov (57), and Merletti and Cerone (58).

Skin Preparation

One of the most important steps in optimizing the quality of sEMG recording is the preparation of the skin surface before electrode placement. The skin should be exfoliated to remove dead skin cells, shaved if necessary and cleansed (if an abrasive gel is used for exfoliation, this should be removed before electrode placement). A conductive gel can be rubbed on the skin (and then removed from the surface, to avoid short-circuiting[10] the electrode contacts) or placed on the electrode contacts. These steps reduce the electrode impedance[11] and ensure it is similar across all electrode contacts. The interface or contact point between the electrode and skin generates random noise, part of which can be reduced by reducing the electrode impedance. This noise occurs due to the change in current carrier at the electrode-skin interface, from ion[12] current (human body) to electron current (electrode).

Choice of Electrode

There are two main configurations of sEMG electrode: traditional bipolar sEMG and multi-channel sEMG arrays or grids. Bipolar surface electrodes are simple to apply, and relevant parameters are relatively easy to extract from the recorded EMG signals to give a general overview of the muscle activation. More detailed information can be extracted from sEMG recorded with electrode arrays or grids (e.g., identify innervation zone of the muscle, measure action potential propagation velocity, assess the distribution of motor unit activity across a region of the muscle, detect single motor unit activity). However, the procedure for recording and analyzing sEMG data from electrode grids is more complex, and specialized decomposition algorithms are required to extract the firing times of individual motor units. Considerations for the choice of electrode (both surface and intramuscular) are outlined in detail in Soderberg and Knutson (59) and Besomi et al. (60).

The selectivity of sEMG electrodes is determined by the distance between electrode contacts (inter-electrode distance, IED), and the area of the detection surface (contact area between electrode and skin surface), see Example (xi) in Tutorial Code. The sEMG recorded by the electrode is the average of the voltage at the skin surface underneath the electrode contact (61). Large electrodes will thus introduce more "averaging" of the EMG signal. The detection volume of the electrode will be greater for larger IEDs, **Figure 6A**. When recording EMG from small superficial muscles (close to the skin surface), or from muscles with a small surface area beneath the overlying skin, the selectivity of the recording electrode can be increased by decreasing the IED. Orientating the electrode along the direction of the muscle fibers further increases the selectivity of the EMG recording. In applications requiring selective recording of small muscles, larger IEDs with large pick-up volumes may detect unwanted EMG signals (or cross-talk) from muscles other than the muscle of interest (63). In these cases, intramuscular or wire EMG may be preferred to provide a more selective EMG recording (64). Recordings from electrodes above large amounts of subcutaneous fat tissue are more susceptible to cross-talk from surrounding muscles (65, 66). The SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of

[10]Too much conductive gel will allow current to flow along the gel, directly connecting the electrode contacts to each other, i.e., short-circuiting.
[11]Resistance to the flow of the electrical current at the contact point between the metal electrode and the skin surface.
[12]An ion is an atom or group of atoms with an electric charge. Ions (e.g., sodium, chloride, potassium, calcium, and magnesium ions) enable the flow of electrical signals through the body.

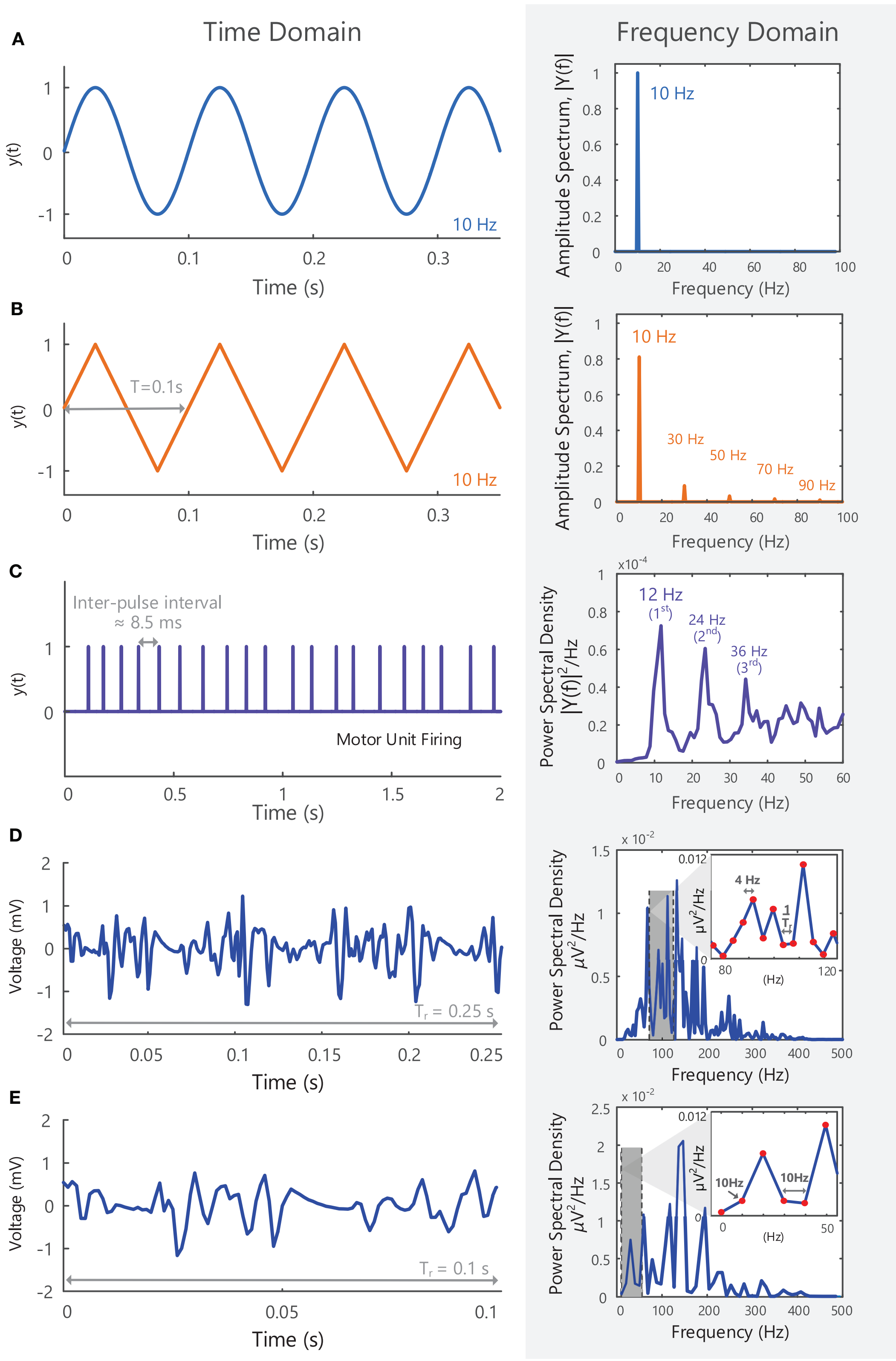

FIGURE 5 | (A) A 10 Hz sine wave with an amplitude of 1, shown in the time domain, y(t), and in the frequency domain, Y(f), after applying a Fourier Transform. All the power within the signal is contained at a single frequency (i.e., fundamental frequency or first harmonic–10 Hz). **(B)** A triangle wave with a repetition rate

(Continued)

FIGURE 5 | of 10 Hz shown in the time and frequency domain, y(t) and Y(f), respectively. As a non-sinusoidal wave, it contains frequency components at multiples of the first harmonic (note: triangle waves contain only odd harmonics). See Example (iii) in Tutorial Code. **(C)** The firing of a single motor unit over 2 s, shown in the time and frequency domain. The motor unit fires at an average frequency of 12 Hz (fundamental frequency of the spike train), but spectral peaks at multiples of 12 Hz can be observed in the frequency domain. **(D)** A 0.25 s EMG signal in the time and frequency domain. The length of the signal determines the frequency resolution ($1/T_r$ = 4 Hz) and the lowest frequency that can be detected in the frequency domain (4 Hz). **(E)** A 0.1 s EMG signal is too short to observe frequencies lower than 10 Hz and can only detect frequency components that are multiples of 10 Hz.

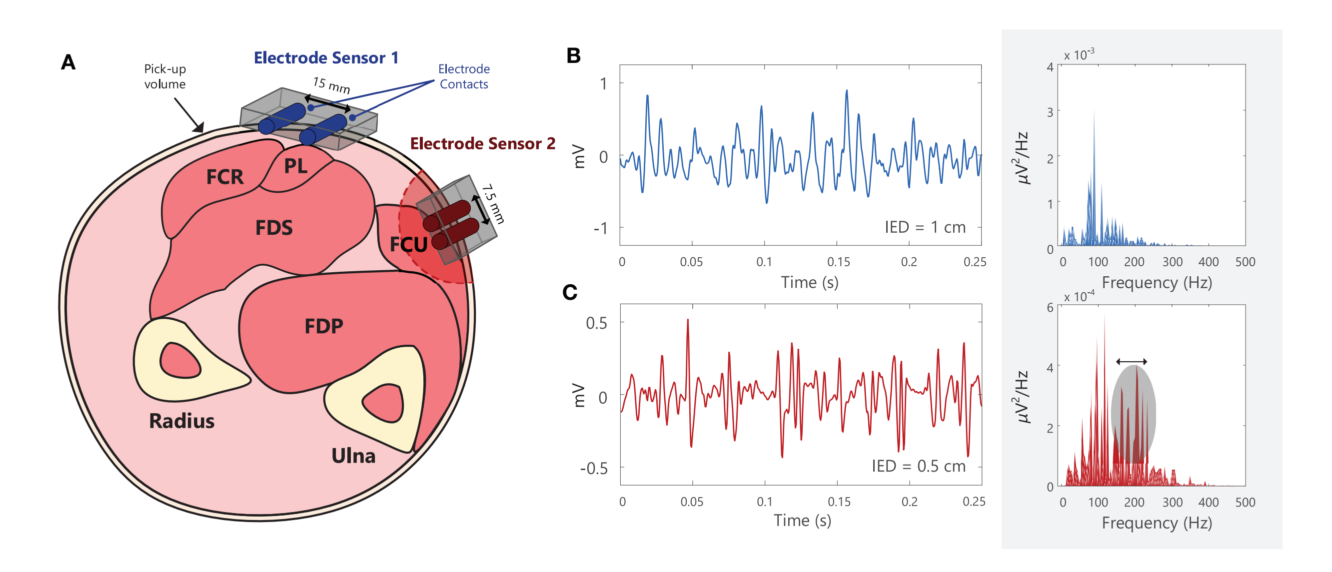

FIGURE 6 | (A) Schematic of the cross-section of the forearm, with the approximate locations of different muscles: flexor carpi radialis (FCR), palmaris longus (PL), flexor digitorum superficialis (FDS), flexor digitorum profundus (FDS), and flexor carpi ulnaris (FCU) (62). Note that electrode contacts should be placed approximately parallel to the muscle fiber direction. Electrode sensor 1 is placed over PL, but it will detect muscle activity (or crosstalk) from the adjacent/deep muscles, FCR and FDS. Electrode sensor 2 has a smaller inter-electrode distance (IED) than Electrode sensor 1 and will thus have a smaller pick-up volume. **(B,C)** Two EMG signals recorded using different electrodes with different IEDs, shown in both the time and frequency domains. EMG signals recorded using smaller IEDs can capture more high frequency components when compared with larger IEDs. Note that this diagram is for illustrative purposes and that the power spectra of the EMG signals cannot be directly compared between **(B)** and **(C)**, as they were recorded in different muscles, under different conditions, using different electrodes. See Example (xi) in Tutorial Code.

Muscles) guidelines make a general recommendation of 10 mm for the electrode contact diameter and IED of 20 mm for bipolar electrodes (i.e., 2 electrode contacts) (67), however, these will vary according to the experimental goals. Barbero et al. (6) and Criswell (4) present comprehensive atlases outlining the correct placement for an electrode pair (bipolar electrode) when recording sEMG from a range of different muscles [the Atlas in Barbero et al. (6) describes the innervation zones of 43 muscles]. For electrode arrays or grids the electrode contact diameter should generally be < 5 mm and the IED < 10 mm in order to effectively sample the EMG signal across the skin surface (68). Importantly, the selected IED will determine the frequency components that can be detected and the bandwidth of the recorded EMG signal, **Figures 6B,C**. Smaller IEDs used in sEMG grids enable higher frequency signal components to be captured, **Figure 6B**, making it easier for decomposition algorithms to discriminate the action potential waveforms of different motor units.

Information on recommended electrode placement procedures for different muscles and muscle areas can also be found in the SENIAM guidelines (http://seniam.org/sensor_location.htm). Typically, the preferred location of the electrode is on the midline of the muscle, midway between the nearest innervation zone[13] and the myotendinous junction (39).

Choice of Amplifier

EMG signals must be amplified (increasing the signal amplitude) and filtered before they are sampled and stored for processing. In order to reach the amplitude required for signal sampling and conversion from analog to digital format (i.e., going from a continuous to a discrete/sampled signal), surface EMG signals must be amplified (typically by a factor of 1,000–1,500, i.e., raw sEMG signals are in the range of microvolts and are amplified to the range of millivolts). In active electrodes, the pre-amplifier is located on or within the electrode itself, **Figure 10B**, rather than in an external circuit (as in passive electrodes). The use of active electrodes reduces the amount of signal noise being amplified, which is important in experiments where there is

[13] A region of a muscle where there is a concentration in the distribution of neuromuscular junctions (i.e., synaptic connections between an axon terminal of a motoneuron and a skeletal muscle fiber).

a high likelihood of EMG signal contamination from motion artifact (e.g., sEMG recorded during movement or exercise). Motion artifact can be further reduced with wireless electrodes.

Bioelectric or biological amplifiers, such as those used in EMG recording, **Figures 7A,B**, are usually differential amplifiers. This means that they amplify the voltage difference ($V_d = V_+ - V_-$) between two points (electrodes) by a factor of A_d (the amplifier differential gain) to obtain the output voltage, V_{out}, **Figure 7C** (i.e., $V_{out} = A_d \ V_d$). Signals appearing identically at both the V_+ and V_- inputs at the same time will not be amplified. An example of an unwanted signal that could appear simultaneously at both amplifier inputs (i.e., a common-mode signal) would be electrical interference from power lines, which occurs at a frequency of 50 or 60 Hz, e.g., **Figure 10C**. Amplifiers also suppress EMG signals from distant muscles, which appear at the amplifier as common-mode signals. Ideally noise or interference signals would be completely rejected by the amplifier, however, in practice these unwanted common-mode voltages will receive some small amplification and the output voltage of the amplifier, V_{out}, will contain some unwanted common-mode signals. A difference in the electrode impedance at the V_+ and V_- inputs (due to inadequate skin preparation) can also increase the level of unwanted common-mode signals [see Equation 7 in Terminology Matrix in the CEDE project, (69) and https://www.robertomerletti.it/en/emg/material/tech/]. The ability of an amplifier to accurately reject common-mode signals (e.g., noise or interference) is quantified by the common-mode rejection ratio (CMRR), which is expressed in decibels[14], Example (xiii) in Tutorial Code. When choosing an amplifier, the common-mode gain should be as small as possible and CMRR should be as large as possible (in practice the CMRR of the chosen amplifier should be >100 dB).

When setting the gain (A_d) of an amplifier, care must be taken to ensure that the output voltage of the amplifier, V_{out}, does not exceed the power supply voltage of the amplifier (e.g., ±10 V in **Figure 7D**). In the example shown in **Figure 7D**, the amplifier gain is 25, resulting in an output voltage that exceeds the power supply voltage. As a result, the output signal is clipped or limited at ± 10 V. Ideally, the gain of an amplifier should be as large as possible without exceeding the power supply voltage. Real amplifiers will also exhibit an "offset voltage" between the two terminals which results in an offset in the output voltage, see **Figure 7E**. This offset can be removed by high-pass filtering (see section Filtering) the EMG signal as typically takes place during the pre-amplification stage.

Finally, another important parameter to consider when choosing a bioelectric differential amplifier is the input impedance[15]. An internal input impedance, Z_i, is present at each of the two input terminals (V_+ and V_-), typically consisting of a resistive component, R_i, and a capacitive component, C_i. The input impedance, Z_i, acts as an obstacle to current flow between the input terminal and ground (reference), **Figure 7B**. An amplifier must have a high input impedance to optimally observe and record EMG activity without disturbing the voltage at the electrode. Amplifiers with high input impedance are also desired to minimize contamination from power line interference (see section Power Line Interference). Input impedance varies according to the frequency of the input signal and is therefore usually specified for a particular frequency. The amplifiers used in sEMG systems should have an input impedance >300 MΩ at 50 Hz (although minimum acceptable values will vary according to the type of electrode used). It should be noted that the choice of amplifier should be determined by the input impedance, Z_i, and not the input resistance, R_i, which is just one component of Z_i.

EMG Signal Sampling and Analog-to-Digital Conversion (A/D Conversion)

The final stage in recording EMG signals involves sampling the analog EMG signal so that it can be stored and processed as a digital signal. The EMG signal detected by the electrode is a continuous (analog) signal. In order to be stored and later processed, the analog signal must be first sampled to capture values at evenly spaced intervals or at a particular sampling frequency. To retain all the information contained within a signal, the signal must be sampled at a rate greater than twice the highest frequency component contained in the signal bandwidth (Nyquist's theorem[16]), **Figure 8A**. As the highest frequency component in the sEMG signal is ∼450–500 Hz, sEMG signals are typically sampled at a minimum of 1,000 samples/s or Hz. If a lower sampling rate is chosen, the spectrum of the original signal may not be accurately represented, **Figure 8B**. Good practice specifies that signals should be recorded well-above this minimum sampling rate, for example at 2,000 Hz for typical sEMG signals. Before sampling the analog EMG signal, the signal should be low-pass filtered with an anti-aliasing filter[17] with a cut-off frequency at or below half the desired sampling frequency. For example, if an EMG signal is to be sampled at 1,000 Hz, it should be low-pass filtered with a maximum cut-off frequency of 500 Hz. This attenuates/reduces frequency components >500 Hz, as these frequencies cannot be adequately represented by a sampling frequency of 1,000 Hz and would distort the EMG spectrum if not filtered out prior to sampling, **Figure 10B**. See section Filtering for further details on filtering and Nilsson et al. (70) for more information on the digital sampling of physiological signals.

Sampling converts the continuous analog signal into a discrete signal (a time series consisting of a sequence of distinct voltages). Each discrete voltage value can then be converted into a binary number consisting of a number of 1 and 0 s (or "bits") that can be stored and further processed. Analog-to-digital signal conversion can introduce noise into the signal, as the true value of the analog

[14]A unit used to express the ratio or relative magnitudes of two electrical signals on a logarithmic scale.

[15]A measure of the opposition to the flow of current into each input terminal of an amplifier, as a function of frequency.

[16]The Nyquist theorem states that an analog signal can be converted to a digital signal and reconstructed without error if the sampling rate is greater than twice the highest frequency component in the analog signal.

[17]Aliasing is the distortion of amplitude/power spectrum of a signal when the signal is sampled at a rate that is too low to accurately reconstruct the original signal.

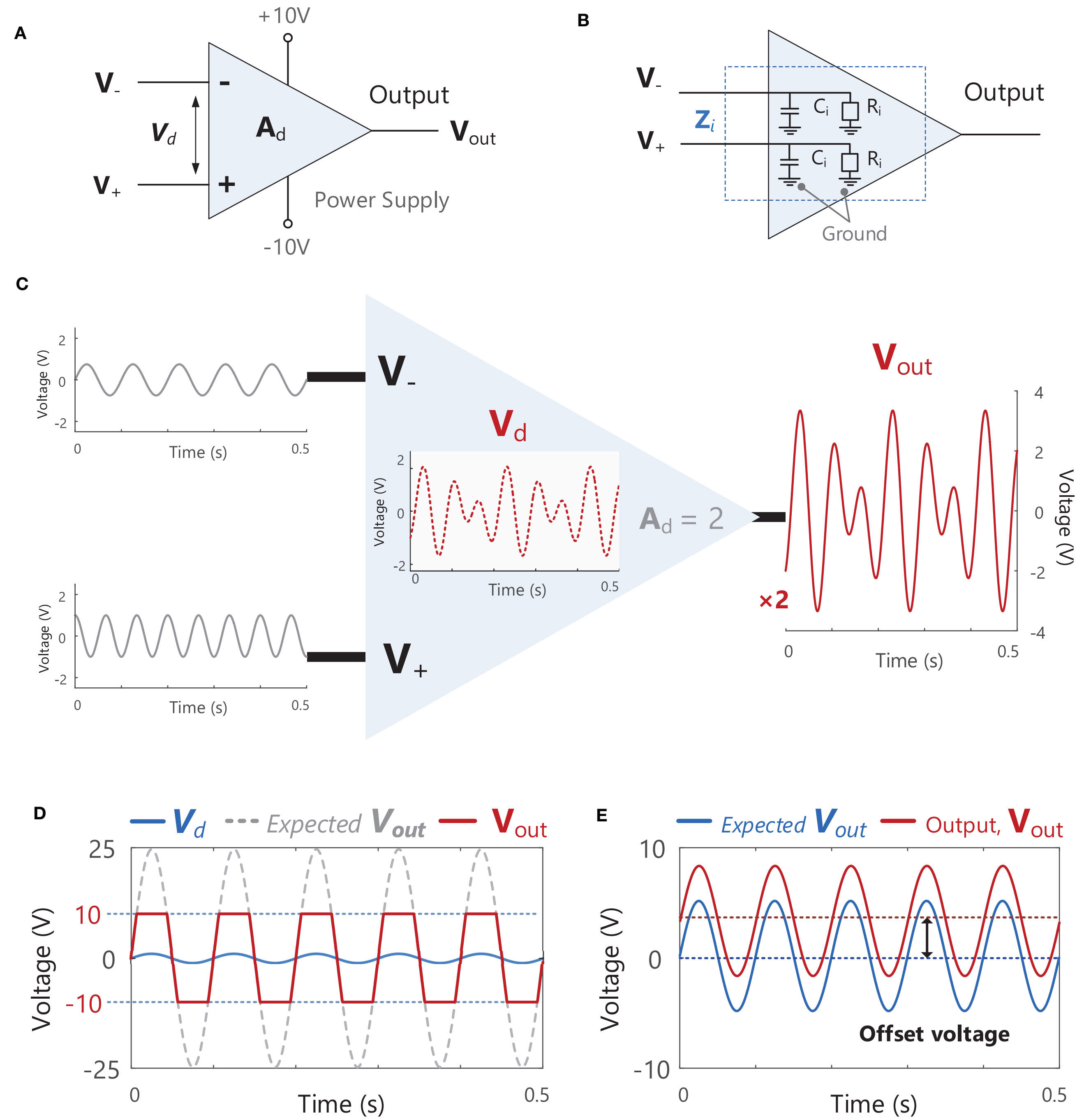

FIGURE 7 | (A) A schematic of an ideal differential amplifier with two inputs V_- and V_+, an output V_{out} and power supply connections (+10 and −10 V). **(B)** A schematic of the internal input impedance, Z_i. present at both amplifier inputs V_- and V_+. Z_i consists of a resistive component, R_i, and a capacitive component, C_i. **(C)** A schematic illustration the function of a differential amplifier, which receives two input signals at V_- and V_+, calculates the difference between these signals, V_d ($V_d = V_+ - V_-$), and multiplies (amplifies) V_d by the gain of the amplifier, A_d (in this example the signal is increased by a factor of 2). See Example (xii) in Tutorial Code. **(D)** If the gain of the amplifier is increased to a level where the expected V_{out} exceeds the level of the power supply voltage (e.g., ± 10 V in the amplifier shown in **A**), the actual V_{out} will be "clipped" or "limited" at the power supply voltage. **(E)** An example of an offset voltage being present in the amplifier output, V_{out}.

signal will have to be rounded to the closest available discrete binary value at each sampling instance. These two values will never be exactly the same, and the small difference between them is termed the quantization error [for more details see Terminology Matrix in the CEDE project, (69)]. Choosing an analog-to-digital (A/D) converter with a higher number of bits

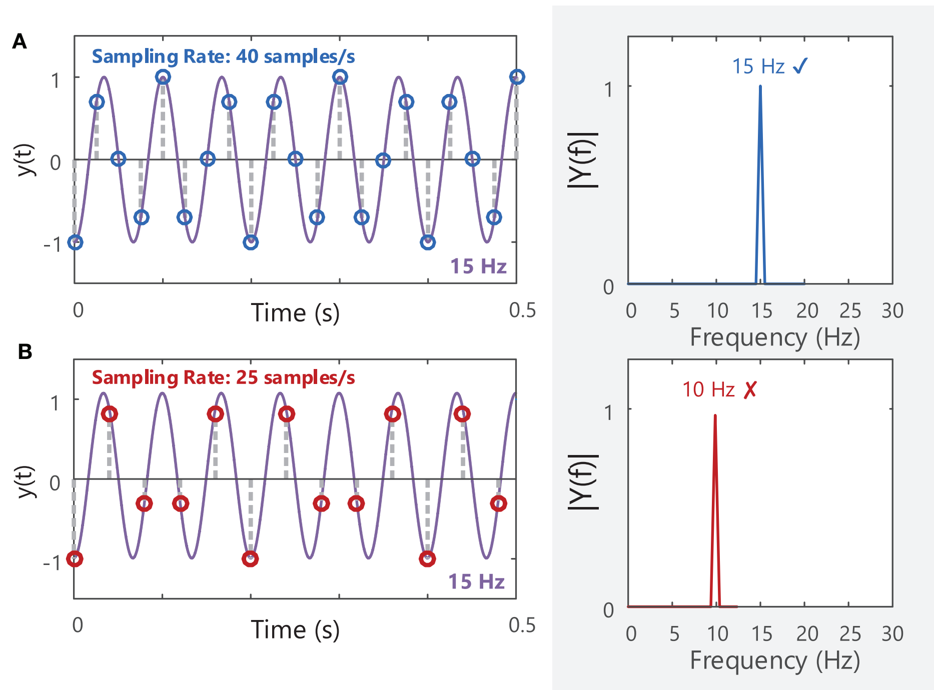

FIGURE 8 | (A) A 15 Hz sine wave sampled at a rate of 40 samples/s will produce a corresponding peak at 15 Hz in the frequency domain (40 Hz is above the Nyquist frequency of 30 Hz). **(B)** The same sine wave sampled at 25 Hz (below the Nyquist frequency for the 15 Hz sine wave) will have a distorted amplitude spectrum, and the fundamental frequency of the signal is mis-identified as 10 Hz. See Example (iv) in Tutorial Code.

will reduce quantization errors (A/D converters should typically have a resolution of at least 12 bits, **Table 2**), but will also increase the storage size of the output sEMG file.

Noise in EMG Recordings

The choice of electrode and amplifier will determine the level of noise in the EMG signal. Random fluctuations in voltage can be observed in the voltage output from the amplifier, even when an electrode is placed on a fully relaxed muscle. This baseline noise arises from voltage fluctuations generated at the electrode-skin interface (see section Skin Preparation) and within the internal stages of the amplifier and its circuit components (the minimum baseline noise that can be achieved is typically >8 µV peak-to-peak). If the amplifier and analog to digital conversion meet recommended standards, the signal-to-noise ratio of an EMG signal will be primarily determined by the properties of the electrode-skin interface. Careful preparation of the skin surface prior to electrode placement is therefore essential to minimize baseline noise and optimize the signal-to-noise ratio in the sEMG signal [quality of contact can be reduced by over a factor of 10 with adequate skin preparation, (71)]. Sources of noise in sEMG signals are outlined in **Table 3**, and more detail on noise and artifacts in EMG signals can be found in Türker (77) and Merlo and Campanini (78).

Power Line Interference

One of the most common sources of unwanted fluctuations in voltage that contaminate or interfere with the detected sEMG signal is power line interference. Alternating currents (AC) in power lines and electrical wiring/equipment produce electromagnetic fields that fluctuate at the same frequency as the AC power supply (50 Hz in Europe and 60 Hz in the USA) and its harmonics (100, 150, 200 Hz in Europe and 120, 180, 240 Hz in the USA). These electromagnetic fields can induce currents in the electrode leads and the subject's body through parasitic capacitive coupling[18] and electromagnetic induction[19] (mostly in the closed loop formed by the electrode leads, the subject, and the amplifier). These currents produce an interference potential or voltage on the skin (which can reach an amplitude of several volts) that is detected by the recording electrode, appearing as a common-mode input to the differential amplifier.

The magnitude of this power line artifact can be reduced by minimizing any difference in the electrode-skin impedance between the two amplifier input terminals through adequate skin preparation, and by choosing an amplifier with a high input impedance. If the electrode-skin impedances at the two terminals (Z_{e1} and Z_{e2}, respectively) are unequal, a portion of the unwanted common-mode interference signal will differ between V_+ and

[18]The unwanted transfer of electrical current from one current-carrying conductor (e.g., electrical wiring) to another conductor that is physically close (e.g., the human body), due to the interaction of the electric fields surrounding the conductors.

[19]The production of a current in a conductor that arises due to the voltage produced by the changing magnetic field from another nearby current-carrying conductor.

TABLE 2 | Summary of sEMG guidelines.

Stage	Guidelines
Choosing equipment (sEMG electrode, bioelectric amplifier, hardware filters, A/D converter)	• IED should be chosen based on the selectivity of the recording required (i.e., small IED when recording from muscles with a small surface area to avoid contamination from cross-talk) • Active or wireless electrodes may be preferred in experiments in which there is a high likelihood of motion artifact • Considerations for the choice of sEMG electrode are outlined in detail in Soderberg and Knutson (59) and Besomi et al. (60) • Hardware filters should typically band-pass filter the analog sEMG signal between 1 and 1,000 Hz (with a minimum sampling frequency of 5,000 Hz) (55, 70) • Bioelectric amplifiers with high input impedance are preferred [at least 300 MΩ at 50 Hz if small electrodes, e.g., 3 mm diameter, and floating amplifiers are used, and at least 80 MΩ at 50 Hz if small electrodes and battery-powered amplifiers are used, Merletti and Cerone (58)]. • An anti-aliasing filter (with cut-off frequency less than half the desired sampling rate) should be applied before A/D conversion • Choosing an analog-to-digital (A/D) converter with a higher number of bits can reduce quantization errors (the most commonly used A/D converters have resolutions of 12 or 16 bits)
Skin preparation	Skin should be exfoliated to remove dead skin cells, shaved if necessary and cleansed (see section skin preparation)
Electrode placement	Electrodes should be placed according to the SENIAM guidelines (http://seniam.org/sensor_location.htm), and are typically orientated along the direction of the muscle fibers and located on the midline of the muscle. The Atlas of Muscle Innervation Zones by Barbero et al. (6) provides quantitative evidence of the optimal placement of bipolar electrodes for 43 different muscles. An Atlas for Electrode Placement is also available in Criswell (4)
Noise and power line interference reduction	• Adequate skin preparation is one of the most important steps to reduce noise and interference in the sEMG signal • Power line interference can be reduced by moving power cables and equipment away from the subject, using wireless electrodes, shielding the electrode leads, keeping electrode leads short and/or twisting the leads together (minimize the closed loop area) and turning off fluorescent or LED lighting, section Power Line Interference
sEMG signal sampling	• Surface EMG signals must be sampled at a frequency >1,000 Hz (i.e., greater than twice the highest frequency component in the sEMG signal, typically around 500 Hz) If down-sampling sEMG signals to a lower sampling rate, the sEMG signal must be low-pass filtered with a cut-off frequency at or below half the desired sampling frequency to avoid aliasing or distortion of the signal, see section EMG signal sampling and analog-to-digital conversion (A/D conversion)
sEMG signal filtering (software)	• Surface EMG signals are typically band-pass filtered between 20 and 500 Hz with roll-off of 40 dB/decade, e.g., **Figure 10C** • Before down-sampling a sEMG signal, an anti-aliasing filter (with cut-off frequency less than half the desired sampling rate) should be applied to the signal • A notch filter centered at 50 or 60 Hz can be used to reduce power line interference when only an approximate estimate of EMG amplitude is required
sEMG Time/Frequency Domain Analysis	• sEMG signals are non-stationary and should be analyzed over short time epochs (0.5–1 s) when estimating the signal amplitude or the signal power spectrum during isometric contractions, see section EMG Signal Pre-processing and Analysis. Shorter time epochs should be used when analyzing dynamic contractions • sEMG signal amplitude is typically estimated using the root-mean-square (RMS) or the average rectified value (ARV) of the raw sEMG signal • Changes in the mean frequency or the median frequency of EMG power spectral density can be used to infer changes in MFCV (though are not a direct reflection of MFCV and are sensitive to other factors such as motor unit synchronization and recruitment)
sEMG signal normalization	Procedures for normalizing sEMG data are outlined in detail in Besomi et al. (22)
Reporting sEMG data	Standards for reporting EMG data are outlined in https://isek.org/wp-content/uploads/2015/05/Standards-for-Reporting-EMG-Data.pdf. Report the information requested in pages 103–105 of volume 8 of the SENIAM recommendations and in Merletti and Cerone (58)

V_-. This difference will be amplified by the differential gain A_d of the amplifier[20].

Other methods used to reduce power line artifact include moving power cables and equipment away from the subject, using wireless electrodes, shielding the electrode leads, keeping electrode leads short, and/or twisting the leads together (minimize the closed loop area), turning off fluorescent or LED lighting, and using the driven-right leg technique[21].

[20] Minimizing the difference between Z_{e1} and Z_{e2} and maximizing the amplifier input impedance, Z_i, reduces the power line interference: $V_{interference} = \frac{A_d V_{CM}\ (Z_{e1} - Z_{e2})}{Z_i}$.

[21] A method whereby the common-mode voltage (due to power line interference) on the body is negatively fed back to a third electrode, which is placed on the body to "cancel out" or reduce the power line interference.

EMG SIGNAL PRE-PROCESSING AND ANALYSIS

The sEMG signal can be used to infer information about the behavior of the underlying motor unit population. Useful information can be obtained from the time-domain EMG signal, and by examining the power spectrum of the sEMG signal in the frequency domain, **Figures 5D,E**. In the time domain, the amplitude of the sEMG signal can be used to determine whether a muscle is activated, i.e., "on" or "off." An increase in the amplitude of the sEMG signal can also indicate that additional motor units are being recruited or motor units are discharging faster to increase force production. In the frequency domain, alterations in the amplitude, or power spectrum of the sEMG can provide insights into changes in muscle fiber conduction

TABLE 3 | Sources of noise in the EMG signal.

Noise source	Frequency range	Noise reduction
Cable motion artifact	1–50 Hz	Ensure good contact between the electrode and skin. Use of short cables from the electrodes to the amplifier and securing these cables to minimize movement during the experiment. Use of the following electrode types: Ag-AgCl electrodes, wireless electrodes, and active electrodes[a] (72). High-pass filtering with a cut-off frequency between 10 and 20 Hz
Electrode motion artifact	<20 Hz	Minimize the electrode–skin impedance with appropriate skin preparation (i.e., skin abrasion) (73, 74) High-pass filter the EMG signal with a cut-off frequency between 10 and 20 Hz [though higher cut-off frequencies may be more appropriate to filter sEMG recorded during dynamic movements (75)]
Electrode-skin Interface	<8 Hz, >1,000 Hz	Minimize the electrode–skin impedance. Choose a signal amplifier with a high input impedance
Power line interference	50 Hz in Europe and 60 Hz in North America and their harmonics (i.e., 100, 150, 200 Hz. etc., and 120, 180, 240 Hz, etc.)	Shield the EMG recording apparatus move it away from electrical equipment and power lines. Remove unnecessary electrical equipment nearby Magnetically induced power line interference can be reduced by keeping the electrode leads short and/or by twisting the leads together, such that the loop area enclosed by the electrode leads, subject and signal amplifier is minimized Experiments may be conducted within a Faraday cage, where available, to minimize electromagnetic interference
Electronic instrumentation	Typically, 10–500 Hz	Use of state-of-the-art recording systems
Quantization noise	Frequency independent (white noise)	Data acquisition system with sufficient A/D resolution [12-bit A/D convertor is typically regarded as the minimum acceptable for sEMG, with 16-bit or 32-bit A/D convertors preferred (76)]
Electrophysiological sources of noise (e.g., ECG artifact)	Typically, 0.1–100 Hz	Application of adaptive filtering in post-processing stage

[a]An active electrode processes the EMG signal (filters and amplifies) within the electrode itself.

velocity[22] and are often used in the assessment of muscle fatigue (79). Standards for reporting EMG data are outlined in Merletti (80) (https://isek.org/resources/).

Power Spectral Density Estimation

The frequency content of an EMG signal can be examined by applying the Fourier Transform, as described in section Frequency Domain Analysis. EMG signals are typically analyzed over short time intervals or epochs (0.5–1 s) in the time and frequency domains, as they are generated by non-stationary processes[23]. In the frequency domain, these short duration signals have a noisy power spectrum, **Figure 9B**. To obtain a smoother power spectrum representation of the EMG signal, the total signal length can be divided into short segments or epochs containing a fixed number of samples, *L*, which can overlap in time. The power spectral density can then be estimated for each signal epoch, and these local estimates averaged to obtain the power spectral density of the entire signal length, see **Supplementary Material**: Advanced Topics, section A.1 and **Figure 9** for more details. A "smoother" power spectral density estimate can be obtained by decreasing the length of *L* or increasing the overlap between successive signal segments, **Figures 9E,F**.

Filtering

The quality of a recorded EMG signal is influenced by the signal-to-noise ratio, which describes the relative power of the "true" EMG signal to that of unwanted or artifactual signal components (noise, interference etc.) in the overall signal. Methods for reducing noise contamination in the EMG signal are outlined in Section(s) Choice of Electrode, Choice of Amplifier, and Noise in EMG Recordings, and in Clancy et al. (76). However, even with well-designed instrumentation and careful skin preparation, there will be some noise and/or interference (i.e., unwanted signals) present in the EMG signal detected from the skin surface. Although noise arising from the electronic circuitry is present across a broad frequency range (from 0 Hz to several thousand Hz), electrical signals from other noise sources can have most of their energy contained within specific frequency bands. For example, most of the power in electrical signals occurring due to motion artifact[24] will lie below 20 Hz, **Table 3**. Different types of filters [low-pass, high-pass, band-pass, and notch filters, for definitions on each filter type see the Terminology Matrix in the CEDE project (69)] can be used to shape the EMG power

[22]The speed at which an action potential propagates or travels along a muscle fiber.
[23]EMG signals exhibit non-stationarity as the statistical properties of the processes that generate the signal will change over time. However, it is often assumed that the processes generating the EMG signal are stationary over short time intervals (i.e., it exhibits quasi-stationarity).

[24]Unwanted voltage fluctuations present in the surface EMG signal due to movement between the electrode and the underlying skin or the movement of cables connected to the recording electrode.

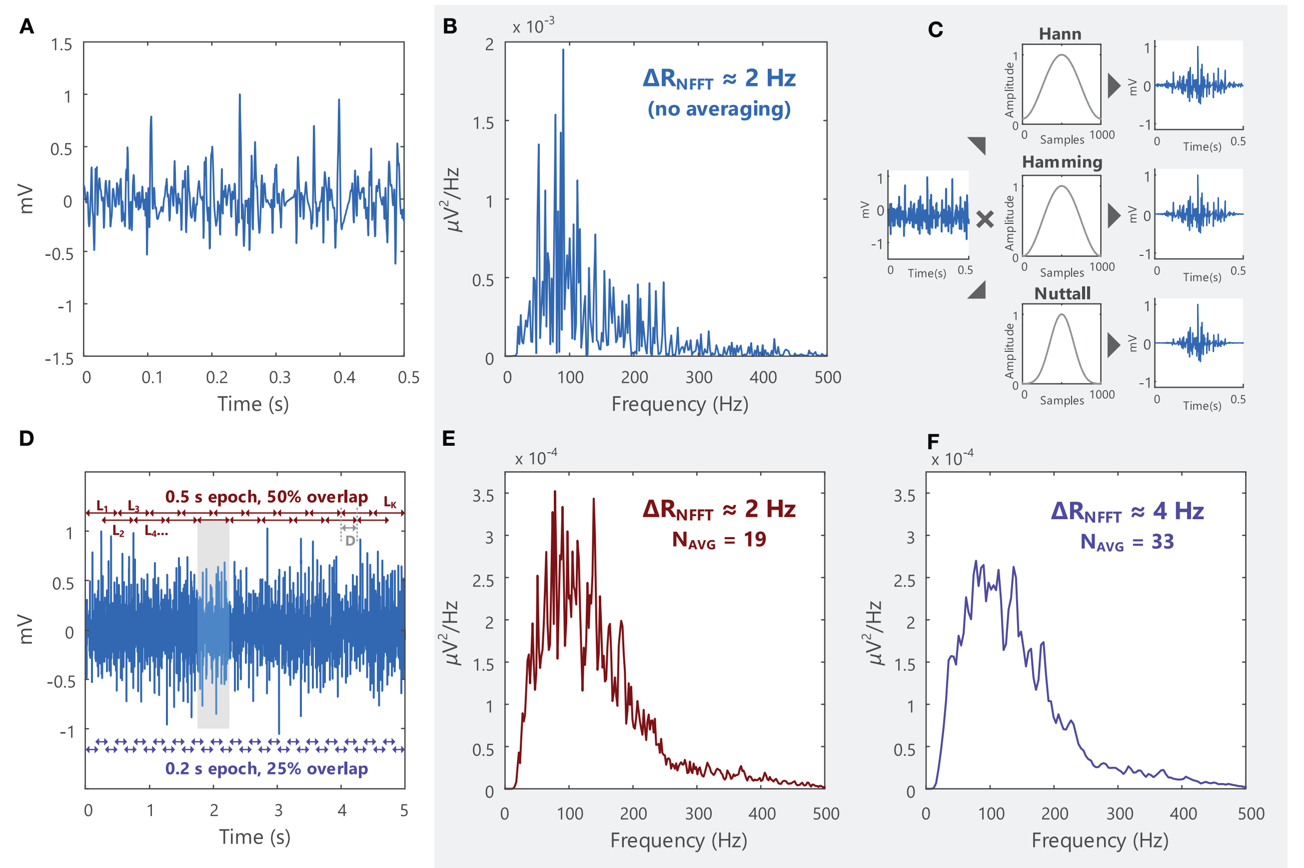

FIGURE 9 | (A) An EMG signal sampled at 2,000 samples/s in the time domain and **(B)** the power spectrum of the signal in the frequency domain. The signal spectrum contains several spurious peaks. **(C)** Welch's method breaks the total signal (5 s long, shown in **D**) into shorter segments (0.5 s) and multiplies (convolves) each segment by a window function (some examples are the Hann, Hamming, and Nuttall windows) before averaging all the modified segments. See Example (viii) in Tutorial Code. **(D)** In Welch's averaging method, the EMG signal is divided into a number of segments (K). K depends on the length of the segment (L) and the degree of overlap between successive segments, Equation 3 in **Supplementary Material**. Each successive segment starts D samples after the previous segments. **(E)** By obtaining an average power spectral density across K segments, the spurious peaks in **(B)** are reduced. **(F)** The smoothness of the power spectral density function can be increased by increasing K (i.e., increasing the number of averages, N_{AVG}), which can be achieved by decreasing the length of L or increasing the overlap between segments. See Example (vii) in Tutorial Code.

spectrum and to remove or attenuate frequency components that are likely due to noise, **Figure 10** and Example (x) in Tutorial Code. The signal-to-noise ratio in the detected EMG signal can be improved using hardware, **Figure 10B**. Software filters and other signal processing techniques can also be applied to the recorded EMG signal to further attenuate (i.e., reduce) unwanted frequency components.

Surface EMG signals are typically band-pass filtered between 20 and 500 Hz (with roll-off of 40 dB/decade or 12 dB/oct [25], see **Figure 10A**) to remove the electrical noise at frequencies below a cut-off frequency of 20 Hz and above a cut-off frequency of 500 Hz. Power line interference can be reduced with a notch filter centered at 50 or 60 Hz, see **Figure 10A**. However, this approach removes both wanted and unwanted signal components, and is thus only recommended when an approximate estimate of EMG amplitude is required. For other EMG applications, more advanced adaptive filtering methods may be necessary to remove interference and preserve spectral content, for example to remove electrocardiographic signal (ECG, the electrical activity of the heart) artifacts from recordings from back or diaphragm muscles (81). If the sampling rate of the EMG signal is to be reduced before further processing (i.e., down-sampled), the signal should be low-pass filtered with a cut-off frequency at or below half of the new lower sampling frequency. This is a necessary step in order to suppress high-frequency signal components and prevent aliasing or distortion of the signal, see section EMG Signal Sampling and Analog-to-Digital Conversion (A/D Conversion). Further information on filtering physiological signals can be found in MacCabee and Hassan (82).

[25] Filter roll-off describes the steepness of the transition between frequencies that pass through the filter unattenuated (passband) and frequencies that are removed by the filter (stopband), see **Figure 10A**. It is measured in either decibels/decade or decibels/octave, where a decade is a 10-fold increase in frequency and an octave is a 2-fold increase in frequency.

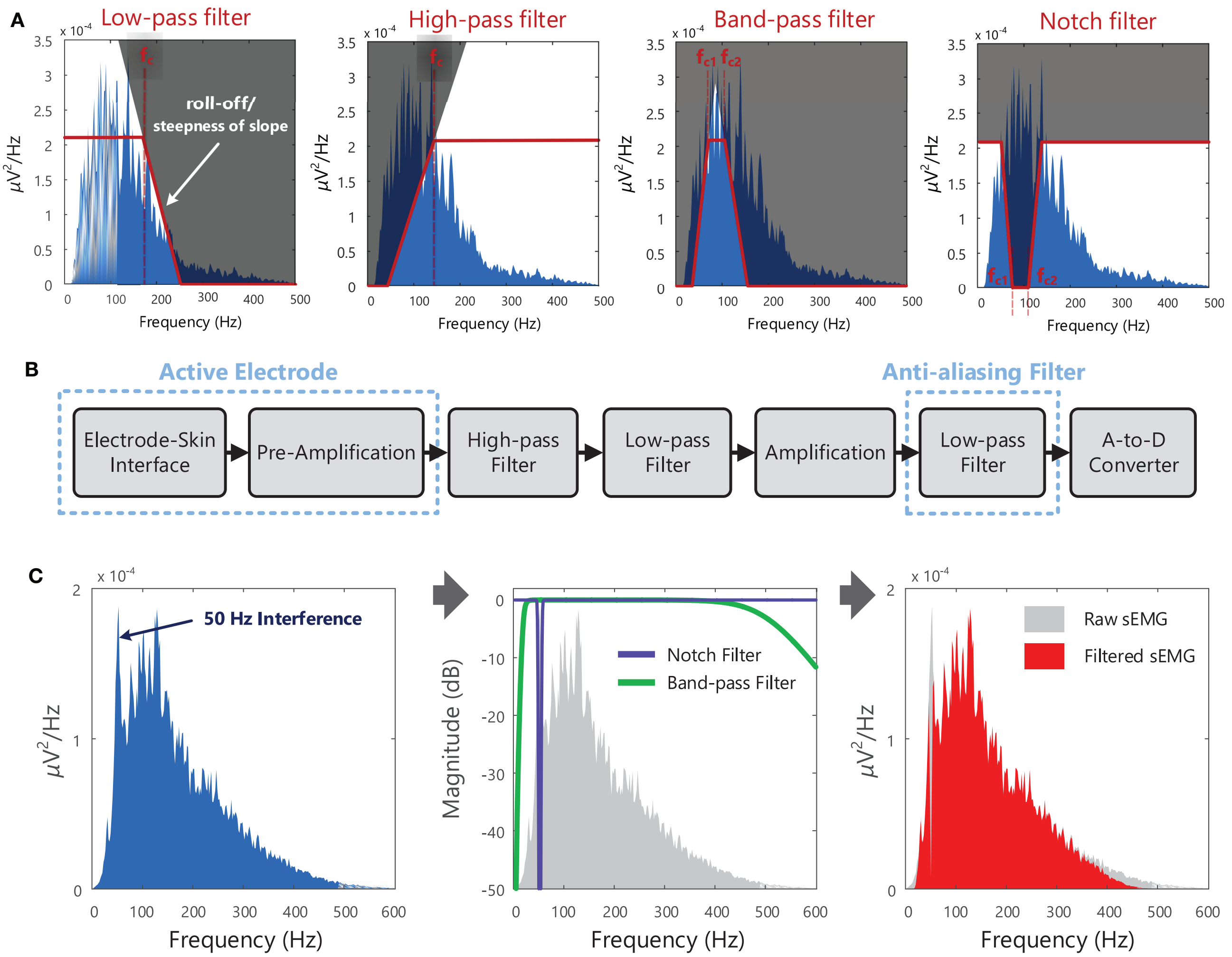

FIGURE 10 | (A) Different types of filters that can be used to shape the EMG spectrum, to keep, remove, or attenuate certain frequency components of the EMG signal + noise. In the example shown, the low-pass filter has a cut-off frequency (f_c) of 170 Hz and the high-pass filter has a cut-off frequency of 140 Hz. The band-pass and notch filters have lower cut-off frequencies (f_{c1}) of 70 Hz and upper cut-off frequencies (f_{c2}) of 108 Hz. **(B)** Schematic of the typical stages in recording surface EMG signals, with filtering at several points along the process (filters that operate on the analog signal, i.e., hardware filters). With active electrodes, pre-amplification is performed within the electrode itself (rather than the amplification being performed in an external circuit), see section Choice of Amplifier. EMG signals are low-pass filtered before sampling to suppress high-frequency components and prevent the distortion of the spectral content, see **Figure 8**. See Examples (ix) and (x) in Tutorial Code. **(C)** An example of a noisy sEMG signal contaminated with 50 Hz interference, the frequency response of a 50 Hz notch filter and a 20–500 Hz band-pass filter (the figure indicates how much the sEMG signal is attenuated by the filter, in dB, at each frequency), and filtered sEMG spectrum (after notch and band-pass filtering the raw sEMG signal). Note that notch filters are typically used when only an approximate estimate of EMG amplitude is required.

Surface EMG Amplitude Features (Time Domain)

The amplitude of an EMG signal varies randomly above and below 0 V, thus there is no information gained from the average of the raw EMG signal (i.e., the mean is zero[26]). To quantify the amplitude of a sEMG signal, a transformation or function must be applied to the raw EMG signal, **Figure 11A**. The two most common functions are the root mean square value (RMS) and the average rectified value (ARV) (or mean absolute value, MAV) of the EMG signal amplitude (see Example (xvi) in Tutorial Code). The RMS of the EMG signal is an estimate of the standard deviation of the signal, i.e., a measure of how much the signal differs from zero (for an EMG signal with a mean of 0 V). It is equal to the square root of the total power contained within the EMG signal. The ARV of the EMG signal calculates the mean of the rectified or absolute value[27] of the EMG signal amplitude, **Figure 11B**. The ARV is proportional to RMS of the

[26]If the mean value of the EMG signal is non-zero, the mean should be subtracted from the signal before any further processing, as it is an artefact introduced by the recording instrumentation and electronics (see voltage offset).

[27]All negative (minus) voltage value become positive.

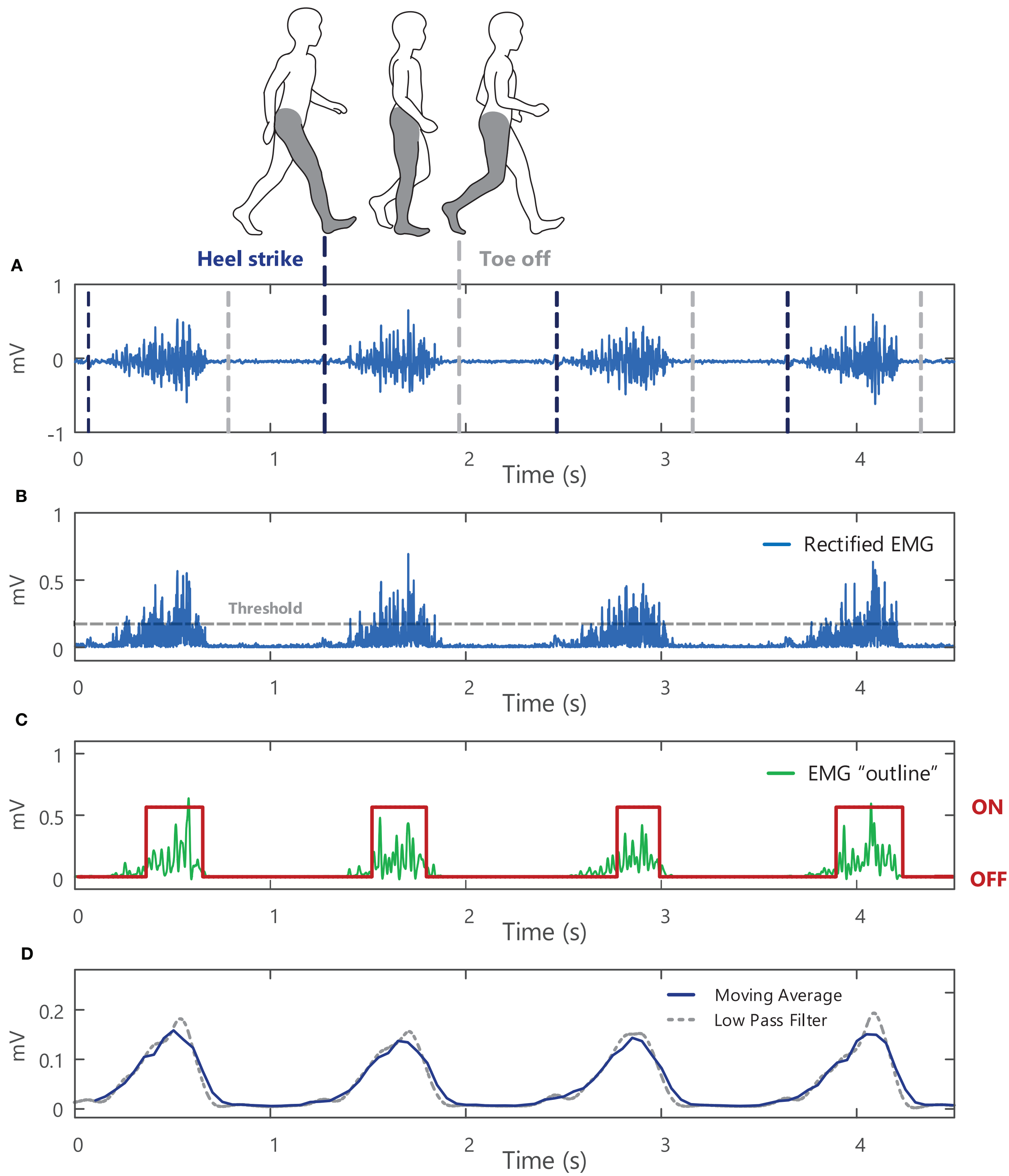

FIGURE 11 | (A) A raw surface EMG signal recorded from the soleus muscle during walking, with vertical lines to indicate where heel strike and toe off occur during the gait cycle. **(B)** The absolute value or rectified surface EMG signal. **(C)** The outline or "shape" of the rectified EMG signal obtained by low-pass filtering the EMG signal at 50 Hz (after applying the Teager-Kaiser Energy Operator to the signal) with muscle onset times shown in red. **(D)** A 0.2-s moving average of the rectified surface EMG signal (with 25% overlap) and an average obtained using a 5-Hz low-pass filter (with the filter applied twice so that there is no time delay in the filter output, see Example (xiv) in Tutorial Code).

EMG amplitude when the level of muscle activity is sufficiently high (83).

The sEMG signal amplitude is typically calculated over short time intervals or windows during which the signal can be assumed to be approximately stationary. For isometric contractions this corresponds to windows or epochs of ~0.5–1 s, with shorter duration epochs typically used to capture amplitude changes during dynamic contractions. Using a moving average window, EMG amplitude is estimated for a short section (or window) of the EMG signal. The EMG window under analysis is then shifted forward in time, incrementally, to obtain an estimate for each sequential section of the signal. The moving average is a simple method to smooth sEMG data, acting as a low pass filter and reducing random fluctuations, **Figure 11D**. Short duration windows or epochs allow rapid changes in muscle activity to be detected, whereas longer epochs produce a stronger smoothing effect. Calculating the moving average with epochs that overlap in time (50% overlap or more between successive windows) can further reduce the overall variability of the EMG amplitude profile but can reduce the ability to detect sudden changes in signal amplitude. Alternatively, the rectified EMG signal can be low pass filtered to obtain the "shape" and outline changes in the amplitude of the EMG signal, **Figure 11C**. Lower cut-off frequencies will result in a smoother EMG amplitude profile (e.g., the 5 Hz low-pass filter in **Figure 11D** results in a smoother signal than the output obtained with a 50 Hz low-pass filter, **Figure 11B**).

An increase in the amplitude of the sEMG signal can indicate an increase in muscle activation (provided there is no cross-talk from other muscles, see section Choice of Electrode), with additional motor units recruited to increase force production and/or a change in motor unit firing rates. In Example (xv) in Tutorial Code, the sEMG signal is shown at three different levels of voluntary muscle contraction force, exhibiting an increase in the RMS/ARV of the EMG signal amplitude as the level of muscle force is increased. Both the amplitude and frequency characteristics of the raw EMG signal are sensitive to many factors, some of which can be experimentally controlled (extrinsic factors, e.g., electrode type and orientation/location, see section Choice of Electrode), and others which typically cannot be controlled (intrinsic factors) and depend on the physiological, anatomical, and biochemical characteristics of the muscle under investigation (e.g., muscle fiber length/cross-sectional area/orientation/composition, level of subcutaneous fat, number of motor units). de Luca (39) provides a comprehensive description of the different factors influencing the sEMG, covering both causative factors (those that determine the basic composition of the EMG signal detected) and deterministic factors (those that directly influence the information content of the EMG signal). EMG signals recorded under different conditions (different subjects/muscles/measurement sessions/electrode positions) are thus essentially measured on different scales. For example, the RMS amplitude of the sEMG signal recorded during a given measurement session could be less than that recorded from the same subject, force level, and task on a different day [or on the same day due to changes in electrode position, in temperature, Winkel and Jørgensen (84), or in the electrode tissue interface]. To enable comparisons between different recording conditions and subjects, the sEMG amplitude must typically be normalized[28] to a reference value[29], which converts the raw EMG signal from volts (absolute scale) to a percentage of the reference value (relative scale) (85), see also Besomi et al. (22). This reference value is often chosen as the EMG amplitude recorded during a maximal voluntary contraction in the muscle of interest for each subject (i.e., 100% MVC). However, other signal normalization techniques may be more appropriate for certain subject groups, muscles, or experimental protocols (for example, maximal effort contractions may not be possible for older subjects or patient groups) (85, 86). Normalization to the EMG amplitude during submaximal contractions or to the M-wave amplitude[30] are other commonly used reference values.

A moving average of the normalized, rectified EMG signal amplitude can be used to determine whether a particular muscle is activated during a task. One method for establishing whether a muscle is "active" or "inactive" involves setting a threshold for muscle activation, e.g., **Figure 11B**. The threshold is typically chosen as a percentage of the mean RMS amplitude of the EMG signal (other estimates of the signal standard deviation can also be used), and when the RMS of the EMG signal goes above this threshold, the muscle is "on." Transformations can be applied to the EMG signal to improve the accuracy in the muscle activation onset timing. In Example (xiv) in Tutorial Code the Teager-Kaiser Energy Operator transformation is applied to the EMG signal and a threshold is set for muscle activation (87) [the Teager-Kaiser Energy Operator can also be applied to accelerometry data (88, 89)]. When the normalized EMG signal is greater than this threshold, the muscle is considered active or "on," **Figure 11C**.

Surface EMG Spectral Features (Frequency Domain)

Examining sEMG signals in the frequency domain can provide information on changes in the frequency content of the signal, manifesting as alterations in the shape of the EMG amplitude/power spectrum, **Figure 12C**. Changes in the mean frequency or median frequency of EMG power spectral density are often used to track peripheral muscle fatigue, see Example (xvii) in Tutorial Code. During fatiguing muscle contractions there are a number of ionic and metabolic changes within the muscle that slow muscle fiber conduction velocity. As muscle fiber conduction velocity decreases (i.e., as the speed at which action potentials travel along the muscle fibers reduces), the action potentials recorded by the electrode will appear longer in duration and the action potential will have a lower frequency content, **Figure 1D**. This results in a compression of the sEMG power spectrum toward lower frequencies with

[28] EMG signal normalization re-scales the EMG signal amplitude by dividing the signal by a reference EMG amplitude.

[29] A reference value should be obtained under standardized and reproducible conditions and have good test-retest repeatability.

[30] An M-wave is the summated electrical response of motor units within a muscle, evoked by electrically stimulating the muscle's motor nerve.

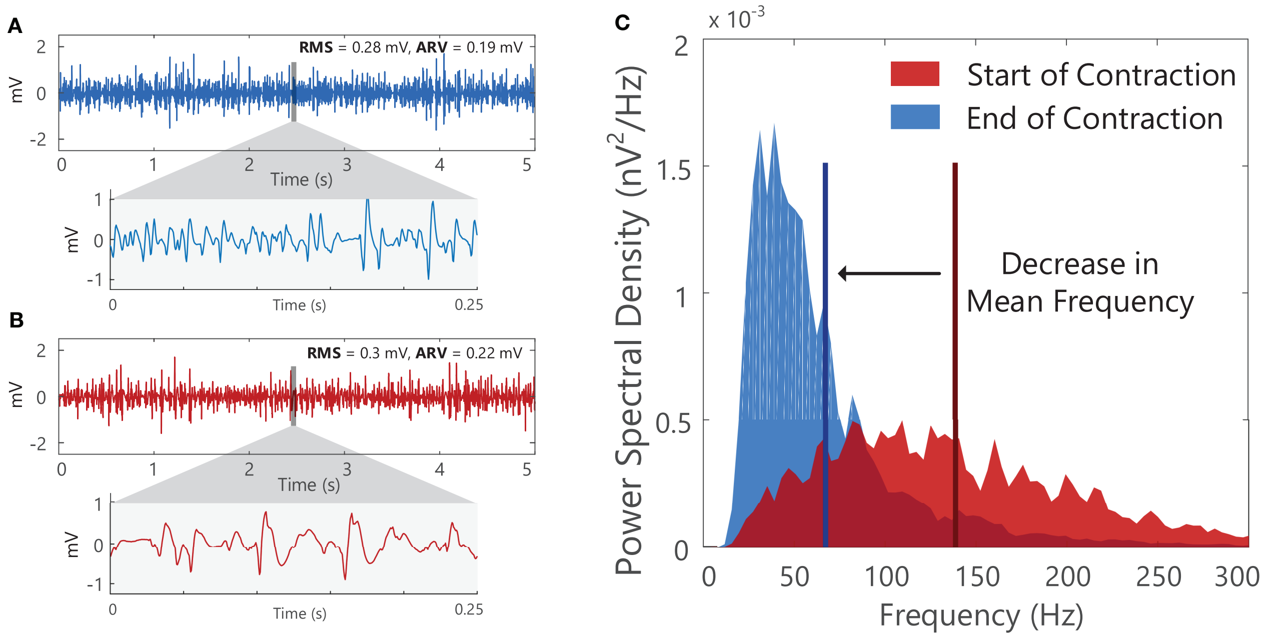

FIGURE 12 | A 5-s segment of surface EMG signal from at **(A)** the start and **(B)** the end of a fatiguing isometric contraction in the first dorsal interosseous muscle. With fatigue the duration of the motor unit action potential lengthens, and there is a shift in the surface EMG signal to lower frequencies. **(C)** The shape of the power spectral density of the surface EMG segments shown in **(A)** and **(B)**. A decrease in the mean frequency (vertical line) of the surface EMG signal is observed, accompanied by an increase in the surface EMG amplitude, see increase in RMS and ARV of the surface EMG amplitude in **(B)**. See Example (xvii) in Tutorial Code.

a consequential reduction in the mean/median frequency of the sEMG signal, **Figure 12**. During fatiguing isometric muscle contractions, the decrease in mean/median frequency is typically accompanied by an increase in the sEMG amplitude (see increase in RMS and ARV of the sEMG amplitude in **Figure 12B**). The changes in the amplitude and spectral parameters of the sEMG during sustained muscle contractions are often referred to as "myoelectric manifestations of fatigue." The mean and median frequency of the sEMG power spectral density are also sensitive to motor unit synchronization[31], which increases during fatiguing contractions (90). Changes in skin and muscle temperature also influence the EMG power spectrum and median frequency as muscle fiber conduction velocity decreases with temperature reduction (84, 91). More advanced time-frequency transforms, such as the wavelet transform[32], can be applied to investigate non-stationary sEMG signals that exhibit rapid temporal variations in frequency content (i.e., during dynamic muscle contractions).

SURFACE EMG LIMITATIONS

The primary advantage of sEMG over intramuscular EMG, along with its non-invasive nature, is that the signals are relatively straightforward to record and analyze (with some basic signal processing knowledge). It also provides an estimate of the overall activity of a muscle or group of muscles in contrast to the more selective nature of intramuscular recordings. Surface EMG, however, is only suitable for recording from superficial muscles and is not appropriate for recording deep muscle activity. Recording from small muscles without contamination from surrounding muscles can be difficult and signals can be prone to cross-talk, particularly over regions where there is substantial subcutaneous fat (66, 92). Furthermore, it should be emphasized that the sEMG signal is not a direct measure of the behavior or properties of the underlying motor unit population. The properties of the sEMG signal are determined by the number of action potentials generated by active motor units within the detection volume of the sEMG electrodes in addition to the shape of these action potential waveforms. It is an interference signal, comprised of the superposition of many action potentials leading to constructive and destructive interference, and is sensitive to many other factors (e.g., the recording instrumentation, crosstalk from other muscles, external noise/interference, see section Surface EMG Amplitude Features (Time Domain) for further details). Unlike signals recorded using surface EMG grids (section Practical Applications of Surface EMG in the Clinic), conventional bipolar sEMG cannot provide direct information on individual motor units. The amplitude and frequency characteristics of the sEMG signal can thus only be used to infer changes in motor unit activity and muscle fiber conduction velocity, respectively. It should also be emphasized that due to the variability of sEMG measurements, sEMG signals recorded under different conditions (different

[31] An increased tendency for two or more motor units to discharge together or within a few milliseconds of one another.
[32] A transform that deconstructs a time domain signal into a sum of "wavelets" or short waveforms of different scales and time shifts, to produce a time-frequency representation of a time domain signal.

subjects/muscles/measurement sessions/electrode positions) can only be reliably compared after applying correct normalization procedure [see Besomi et al. (22) for details].

DISCUSSION

Sensor technology has developed rapidly over the past 30 years, but physiotherapy education has lagged behind in training new therapists to use the newest sEMG innovations in clinical practice. For sEMG to be widely adopted as a quantitative assessment tool, therapists need to see how this technology can directly benefit everyday practice, with guidance from a trusted source such as an educator or clinical mentor. Therapists also need to be empowered with the technical knowledge to enable them to record and analyze their own data. Through education this can be provided in a succinct and accessible manner that removes the perceived complexity of the technology. Modern curricula for physiotherapists may provide a basic introduction to recording and analyzing sEMG signals. However, without practical experience working with sEMG signals, and a comprehensive overview of the technical aspects involved in recording and analyzing the signal, it is difficult to bridge the gap between knowledge of the theory and the ability to apply this in practice. This paper provides a concise guide that simplifies and condenses the relevant information for recording and processing sEMG. Although this material and accompanying tutorial may help to remove some of the educational barriers (i.e., the perceived difficulty and relevance of sEMG as a clinical tool), access to information alone is not enough to motivate therapists to adopt sEMG in their own practice. To effectively promote and encourage the use of sEMG in clinic, practical experience working with sEMG needs to be embedded into education in the form of workshops, tutorials, or course placements. A deeper understanding of signal processing concepts, and the confidence to apply these methods to sEMG signals is hard to achieve without first-hand experience of working with sEMG signals in a guided setting. Placements in clinics or research labs that use sEMG can also expose students to the utility of sEMG and how it is used by experienced practitioners demonstrating the practical benefits. This can be facilitated by establishing links between local clinics and physiotherapy and biomedical engineering departments within universities. Tutorials that form part of the biomedical engineering course could be adapted for a clinical audience and offered to physiotherapy students. Prior experience either using sEMG themselves or observing first-hand how it can be successfully implemented in clinic is likely to be a deciding factor in a practitioner's decision to adopt sEMG in their own practice.

A lack of prior exposure to sEMG signal analysis may thus present the greatest barrier to physiotherapists wishing to incorporate sEMG as a measurement tool in their clinical practice. However, therapists may also be discouraged by the fact that many resources and scientific papers currently available for sEMG analysis are targeted at a technical audience. These resources often assume the reader has prior coding experience and the resources to develop customized code for signal analysis. Clinicians and therapists may alternatively opt to use software packages to extract relevant features from the sEMG signal where the underlying calculations may not be evident. Even in these cases, a basic understanding of signal processing is still important so that the user can select appropriate analysis parameters for different conditions and justify this choice when interpreting and reporting their results. To encourage the uptake of sEMG in clinic, this paper presents an overview of key topics that could be used to guide the content of lectures/tutorials on sEMG in the curricula for physiotherapists or used to form the base of an elective module on EMG applications. It is important to note that some of the simplest applications of sEMG (that require minimal knowledge of sEMG concepts and are relatively easy to implement and interpret) may be the most useful in practice (e.g., visual feedback on muscle activation). The basics of sEMG could be relayed in a single workshop/practical ($\sim$ 3 h), which could be incorporated into the undergraduate curriculum for physiotherapists. More advanced signal analysis could be then be covered in postgraduate or elective modules. Combining sEMG theory with practical classes in basic computer programming (in addition to providing code and lectures online to support the material covered) is an effective way to teach sEMG concepts to physiotherapists, break down its perceived complexity, and encourage them to incorporate sEMG as a measurement tool in their practice (93).

Sample sEMG signals are provided in the **Supplementary Material** (and at https://doi.org/10.5281/zenodo.4001609) accompanying this paper that could be used in sEMG tutorials in cases where it is not feasible to record sEMG signals. Sample codes for signal analysis are also provided, illustrating how to extract commonly used features such as the RMS or ARV amplitude and the mean or median frequency of sEMG (see Key Functions Code). The background material and the signal analysis code are intended to be used in parallel, often practical examples can help to simplify more difficult concepts. The examples also illustrate the importance of understanding these signal processing concepts, by illustrating how they can influence outcome measures. The parameters used to analyze the sEMG signals in these examples can also be altered in the code to directly examine the effect on signal output, which can provide a greater insight into the function and relevance of each signal parameter. Though the material is designed to be accessible, it will require a time investment to read, run the accompanying code and understand the output. However, for those interested in incorporating sEMG into their practice, time dedicated to developing a deeper understanding of the technical aspects of sEMG will be rewarded as it will enable them to optimize and tailor their recording and analysis to address the problems they are most interested in. While some may wish to leave sEMG recording and processing to clinical engineers or technicians, with an understanding of the topics outlined in this paper and some investment of time, there is no reason that recording and processing cannot be performed within the clinic by physiotherapists themselves. Therapists themselves are the ones best placed to know where sEMG could be most useful and practical in clinic, and what is practical to implement during the time allotted for a patient appointment. Even where rehabilitation engineering support and resources are available, a common language and understanding enhances the collaboration between engineers and therapists to ensure the most appropriate application of sEMG to address each research question.

More widespread use of sEMG in clinical practice should contribute to increasing the reliability and reproducibility of studies evaluating the efficacy of healthcare interventions in physical and rehabilitative medicine, however, the full potential of sEMG in clinical assessment and neurorehabilitation has yet to be realized. Through the material presented here we aim to facilitate this by addressing some of the educational and technical barriers that limit the clinical translation of sEMG.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in https://doi.org/10.5281/zenodo.4001609.

AUTHOR CONTRIBUTIONS

LM and ML conceived and designed research and drafted manuscript. LM prepared figures. LM, GD, and ML edited and revised manuscript and approved final version of manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fneur.2020.576729/full#supplementary-material

Supplementary Data Sheet 1 | Further reading.

Supplementary Data Sheet 2 | Appendix: Advanced topics.

Supplementary Data Sheet 3 | Tutorial codes.

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Winter School on sEMG Signal Processing: An Initiative to Reduce Educational Gaps and to Promote the Engagement of Physiotherapists and Movement Scientists With Science

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The application of surface electromyography (sEMG) in neurology is sometimes limited by a scientific background in the use of sEMG. Students frequently use sEMG only when developing their graduate studies. To reduce these barriers, we promoted a free Winter School on sEMG to Latin American students. The school was a 3-day event with theoretical classes and computer programming in Matlab. Lectures were delivered in Portuguese and Spanish to 50 participants. All lectures were recorded and made available on YouTube®. After the School, participants completed a written exam to receive a certificate. The written exam revealed the average effectiveness of 71 ± 20% in the comprehension of topics addressed during the school. Participants rated the School as "excellent" and considered the event as having changed their thoughts about the use of sEMG. Limited mathematical skills or background were the main barriers identified to follow the lectures and to make use of sEMG. We conclude that the Winter School had a positive impact on participant's formation, especially by showing them the importance of continuous involvement with the concepts related to sEMG to become proficient in its use. From the participant's point of view, the activity was excellent and the follow up of the school on YouTube® suggests that combining face-to-face activities followed by the online availability of lectures is a valid strategy to reinforce the learning process and to reduce barriers in the use of sEMG. Whether similar results would be achieved for a paid registration event in an economically developing region, still requires further investigation.

Keywords: surface electromyography, education, knowledge transfer, teaching, neurorehabilitation engineering

INTRODUCTION

Latin America is one of the most unequal regions in the world based on the Gini Index (1). Therefore, low cost educational and science opportunities are a milestone in providing access to knowledge and social mobility, providing educational innovation with the opportunity to be prepared for the burgeoning of information technologies, globalization, and changes in the knowledge (2). This inequality in knowledge also concerns students and professionals whose professional actuation is often limited by the lack of a scientific background on the theoretical and technical aspects of techniques which can contribute in a relevant way to therapy and assessment in rehabilitation e.g., sEMG (3–5). These barriers to the wide use of techniques like sEMG have different sources. We consider that restriction in universal access to higher education, as observed in economically developing countries, plays a major role in these barriers. Furthermore, in these regions, once a student joins the university, not all institutions will be able to offer research laboratories to complement lectures or to support research groups, limiting the experiences that the student will have during the professional formation. In Brazil, most of the exposition to science happens for students attending free public universities, which are also the institutions producing most of the scientific research in that country and Latin America. However, public universities promoting free education are not available in all countries and sometimes have a bad geographical distribution.

For example, in Chile, which is considered an emergent economy, social inequality remains high, like in other Latin American countries, and education is considered a consumer good. It means that even public education has a high cost, which can be higher than the cost of studying at private institutions. It results in science being transformed to privilege people with better economic conditions and credit capacity, which ends up segregating the society (6). In Brazil, public universities are free for students and in the past 15 years there was a strong effort to promote a better geographical distribution of public universities to benefit a larger number of people, including social programs to help families send young family members to universities. It may help to explain some of the differences between Brazil and other countries in Latin America, regarding scientific research, and development in some fields.

In addition to the economic barriers, there are other barriers requiring attention. These include weak, or absence of a proper educational background to move forward in concepts related to higher education. One important topic of education and research widely used in the fields of physical education, physiotherapy, and engineering is surface electromyography (sEMG). However, many barriers are observed in the use of this tool, as we will further discuss in this article.

sEMG encompasses the measurement of electrical signals involved in the muscle contraction and is quantified using surface electrodes, with applications in humans (7) and other animals (8). Over the past decades, studies on nerve conduction (9) and other applications of sEMG have increased both in number and quality, and a few textbooks have been written on sEMG (10–15). Furthermore, recent technological advances permit the collection of signals in the field using wireless sensors, and hardware has become more accessible at a lower cost because many companies are providing different solutions for data acquisition. However, the same technological development that enabled tablets and smartphones to process and analyze biological signals used in clinical practice and research, making the access to sEMG easier, has created a scenario where programming and analytical thinking sometimes is no longer necessary (16). While facilitating the spread of sEMG use, this reduces the immediate need to understand the calculations involved in data acquisition, processing, and analysis, causing a gap/barrier between theory and practice in students and professionals from the health and life sciences. In this regard, if these topics are not adequately covered during university studies, there is a high chance of increased misuse in professionals with a weak technical background who start to use tools like sEMG.

For example, to promote better use of the sEMG in clinics, hospitals, and gymnasiums, knowledge of several basic concepts from anatomy, neurophysiology, and physics, among others, will be required. The user needs to properly locate the electrodes and be aware of particularities depending for example on the muscle evaluated (17, 18). Similarly, sEMG users must understand the mathematical aspects of signal acquisition and processing, the risks of making mistakes, and the risks of subjective interpretations. For a deeper understanding of these topics, we recommend visiting http:www.robertomerletti.it and www.seniam.org, where a wide number of sources for historical and updated academic material are available to help elementary and advanced sEMG studies.

The real condition is that most health professionals from Latin America do not receive a background in mathematics sufficient enough to understand and use sEMG in their professions. Many students seek training in health courses just to get away from mathematical work. National scientific journals related to human movement sciences are available, and most of the papers published in these journals, addressing sEMG, are the result of laboratory research developed during master's and doctoral programs. These papers are accessible to students, but the use of scientific papers during the study of these topics needs to be strongly promoted. This establishes an important barrier to sEMG applications that have been considered when promoting regular congresses in the field, like the Brazilian Congress of Biomechanics, and the Congress of the Chilean Association for Human Movement Sciences. But this limitation is not observed only in economically developing countries (EDC).

The evaluation of the knowledge from participants working in developed countries also suggested that neurology residents show a knowledge gap regarding the use of sEMG, resulting in up to a quarter of residents expressing a lack of confidence when using techniques like sEMG (19). Furthermore, life sciences students report difficulties in carrying out laboratory calculations (20). In this study, the promotion of educational activities like workshops improved the level of competence in a laboratory environment (20). This lack of confidence, the knowledge gap, and difficulties with laboratory calculations can influence the use of sEMG. As a result, sEMG results provided by automated routines and which does not require a higher level of technical knowledge, could both help and be a trap for users. Software and graphical interfaces using custom made codes are very useful (21), but they do not exclude the importance of the user's knowledge when acquiring and processing the biological signals. We could exemplify this by considering an sEMG examiner making use of a graphical interface that requires a choice of parameters like the criteria for activation on/offset identification (21). Such a tool, like others available for free on the internet, can be a powerful and a valuable instrument in the clinical field, research, and also from an educational perspective, but the user needs basic knowledge to make the correct configurations and to avoid bias in the sEMG analysis (22). The current movement toward open science increases the sharing of codes for example, and sometimes the sEMG user can get a code from a colleague to use on their own data, but the basic knowledge on how to use it remains obligatory so as to avoid misleading results or to generate new incorrect data. Having a code and the skill to run it will, therefore, not be enough to overcome the barriers to proper use of the technique.

The knowledge about sEMG may also impact on aspects related to patient management. When considering the use of sEMG in a clinic or hospital, a patient's education about sEMG is also important. We consider that in some cases, not informing the patient or participant about what the examination is, and how it works, may increase stress and possibly change participants' behavior when realizing that many electrodes are going to be attached to their own body, and this misunderstanding may lead to limited clinical results. Among middle-aged patients undergoing sEMG examination, 52.1% of the patients either received no information about what sEMG is, or, the information provided was very poor or incorrect (23). On the other hand, these data may reflect the lack of knowledge of the sEMG user in charge of the examination who is unable to properly explain what is going to happen. Different groups of scientists try to provide solutions to reduce these effects and companies also try to improve the software for each new version launched.

Considering all these aspects, we promote educational activities that reduce the knowledge gap and barriers faced when using sEMG, observed among health professionals who want to or already do use of sEMG without proper training in basic concepts related to its use. In 2018 we organized the first Winter School on sEMG Digital Signal Processing for Latin American students. Here we describe this educational activity, and the impact it had as perceived by the participants. We also share our experience in the selection of the topics for lectures and the methodology for the development of the course. The barriers faced when using sEMG are also discussed.

ACTIVITY DESCRIPTION

The Winter School lasted for 3 days during September 2018 and was held at the Universidade Federal do Pampa, a Brazilian public university established in a remote region of the Rio Grande do Sul state in Brazil. Registration was free of charge and we received 50 applications for registration. The event was advertised on social media and through email lists of different institutions. There was no limitation in the background level required or the purpose of the participants registering to the school, and the program was available to all participants before completing the free registration. We did not control registration according to the level of knowledge of the participants because it has been suggested that merging students with different levels of expertise may bring education advantages especially for those who are less experienced (24). Upon registration, participants received a customized handout including brief explanations of the main concepts that would be addressed in the school. They also received a reference list of papers, books, and book chapters that should be read before the Winter School started.

The 50 participants had different backgrounds (29 from physiotherapy, 18 from physical education, 2 from engineering, 1 from high school) and came from cities from the south of Brazil (border with Argentina and Uruguay) to participate in the school that was conducted based on a group-learning methodology and thinking-based learning activities. The school was advertised to other countries from Latin America and we consider that the main limitation for attendance of participants from other countries was the high cost to travel and stay abroad. All the participants had a connection with academia being either undergraduate ($n = 24$, 49%) or graduate students ($n = 13$, 26%, were master or Ph.D. students in human movement sciences or physiology), and the other 25% were young investigators with a master's or Ph.D. degree in human movement sciences or physiology, one post-doctoral fellow, and one high school student. We did not collect data regarding personal information like the age of the participants, but informally we can report that most of the participants were young with age ranging between 17 and 30 years. A higher number of female participants was noted, which may in part relate to the fact that most of the participants were from the physiotherapy field, which in Brazil usually has a higher percentage of female graduates.

Upon registration, considering a scale from zero (meaning no knowledge on signal processing) to 10 (proficient in signal analysis), only 10.2% of the registered participants indicated a score higher than 5. The school's program was designed to include theoretical and practical activities in a friendly environment. We organized a single room meeting, with coffee and finger food; lectures were delivered using media projectors, whiteboards, and questions were allowed at any time. The organizers worked to have the entire class actively participate, and when the participants showed signals of tiredness or if they missed the concepts (for example, sleepy faces, side conversations), a short break was proposed.

The main goal of the school was to promote a solid basic background, and therefore, concepts related to muscle contraction, joint angles, and ground reaction forces were briefly addressed to ensure that all participants were familiarized with the origins of biological signals that were used for the examples. In this regard, differences between kinetic, kinematic, and sEMG signals were discussed, and sEMG generation and interpretation were often mentioned, commented on, and explained during the course. Topics were organized to promote a progressive level of complexity. The entire program was covered in 3 days within a total of approximately 20 h of activities. Topics were organized in three blocks:

- 10%: the importance of the proper knowledge related to signal processing, its application in sEMG analysis, and where to find relevant material to study;
- 10%: important aspects of data acquisition, mostly related to hardware characteristics;
- 5%: examples of signal processing methods that are common among different techniques (like kinematics and kinetics) in human movements sciences;

- 75%: data processing concepts: limits, derivation, integration, sums, complex numbers, functions, Euler identity, definitions and classification of signals, discrete acquisition, Nyquist theorem, aliasing, time domain and time-series, frequency domain, Newton Prism experiment and frequency decomposition, Fourier series, harmonics, Fourier transform, spectrum, inverse Fourier, and signal filtering. We also focused on the interpretation of sEMG alterations and distortions, cross-talks, amplitude analysis, windowing functions, cancelation of signals, onset-offset analysis, frequency analysis, co-activation, synergy, and linear decomposition into basis functions. We also included some concepts of the Teager energy operator and prosthesis control, but these last topics were only briefly mentioned.

The approach to these topics was always based on evidence from the literature. Basic topics related to the mathematics involved in sEMG processing and analyses were discussed based on scientific papers, and the explanation of concepts for signal processing and analysis was always followed up by a discussion of topics related to data processing and the interpretation of results from scientific papers, i.e., topics for non-engineers began with basic math and sinusoidal wave analysis. When a practical situation was needed to illustrate concepts, as well as to discuss how a decision on data analysis or processing affects the results of sEMG analysis, scientific articles were used, i.e., filter coefficients, signal decomposition, or alias signal (aliasing). Papers considered for the examples were always related to the general study area of the participants such as those addressing gait biomechanics, jump landing, and for some cases, papers reporting the use of EMG associated with prosthesis control and biofeedback, especially to give a contextualized health scenario for non-engineers.

The voluntary tutors to the school were one professor with a Ph.D. in human movement sciences, two Ph.D. students in biological sciences, and one MSc. in engineering, and a MSc. in kinesiology and clinical biomechanics. In addition to the handout and the introductory references already mentioned, the teaching activities were mostly based on the textbooks "Digital Signal Treatment" (25), "Discrete-time Signals Processing" (26), "Electromyography: Physiology, Engineering and Non-invasive Applications" (10), "Biomechanics and Motor Control of Human Movement" (27), and the SENIAM guidelines (28, 29). The tutors worked together in the months preceding the school to prepare the material considering similar terminology, to connect the examples used, and considering common references. In the different activities of the school, signal-processing concepts were represented using Matlab 2016a (MathWorks, Massachusetts, USA) and a custom-made code shared with the Winter School participants (see **Supplemental file**). This environment was used to facilitate the tutors' enrollment since they all had experience with this tool, but during the school, other tools, including open-source and free options like R studio (RStudio, Inc., Boston, United States) and Python (Python Software Foundation, Wilmington, United States) were frequently commented on.

An important concern when planning the school was the need for a follow up on the educational activities, and the importance of revisiting the concepts discussed during the lectures. This is why all the lectures were video recorded and uploaded with free access on YouTube®. Lectures are available for free in the non-monetized official channel of the Applied Neuromechanics Group, the NeuromechTV (http://youtube.com/neuromechTV). Slides used to explain the mathematical concepts and examples of data analyses were also uploaded to Researchgate as "*Escola de Inverno: Fundamentos de processamento de sinais discretos em biomecânica.*"

To provide us with an idea of how the school helped the participants to better understand sEMG, at the end of the Winter School, all participants underwent one written exam and filled in a survey. The exam included 15 questions on topics addressed during the lectures. The participants had 10 days to send the answers by email after the school was completed. We also requested that participants answer a short survey to provide us with a general assessment of the school. The school was funded by the Universidade Federal do Pampa, the Brazilian Society of Biomechanics, and the Brazilian Physiology Society, without registration fees for participation.

MAIN OUTCOMES AND DISCUSSION

The general evaluation of the school involved rating the activities from 0 (zero, meaning low quality) to 10 (ten, high quality). Participants graded the advertisement given to the school when registration was open as 9.83. The handout and reference list provided upon registration were considered pertinent, and about 50% of the participants said they read the material before the school started. The strategies employed to discuss the concepts on signal processing were graded as 9.33, and the performance of the tutors was graded as 8.83. The overall grade for the activities was 9.85, and the free registration was considered to be of 60% importance on a scale from 0 to 100, in which we asked whether participant registration was conditioned by the free registration.

The written exam completed by participants after the school showed average effectiveness of 71 ± 20% (ranging from 40 to 100%) in properly answering the 15 questions related to the topics studied. We observed that better answers were found for questions addressing those topics in which more time was spent on during the lectures and for topics we highlighted as important during the lectures (filtering and data visualization, for example).

The school had a significant number of undergraduate students from physical education and physiotherapy courses who participated, as we detailed in the previous section. As observed, when experiments and data processing and analysis using electrocorticography techniques were developed with undergraduate students, the enrollment in educational activities similar to that developed in our school may help increase their interest in following a postgraduate science program (30). Furthermore, students of different levels were developing activities together in the school. We consider that the merging of students from different levels can benefit those facing difficulties with the contents in laboratory calculations (24).

We do not believe that the different backgrounds of the participants limited the development of the activities in the school. Nevertheless, in schools aimed at more complex topics, or those prepared to solve particular problems, the heterogeneity of the participants may have different effects on the activity outcomes. We did not strictly control the methods of each activity, but in general, we conducted a team-based learning approach, which is also known to benefit learning in the laboratory environment (31). We also consider that the model of collaboration between students during the course has been beneficial for those students at a higher level of knowledge, as the teaching process increases memory acquisition and persistence in the context of medical sciences, a background from which most of the participants originated (32). We also consider that the interaction between the students from different levels can be a contributing factor to promote networks and mutual support, which in the end will help to reduce barriers in the use of sEMG. Informal conversations during the course also helped to bring students and speakers together.

Considering the topics addressed in the school, a good amount of time was spent on explaining filtering, especially because filtering is a fundamental step in the sEMG data analysis because of its susceptibility to low-frequency noise, baseline noise, and movement artifact noise (10, 27). Filtering was discussed considering pieces of evidence from the literature concerning the most adequate cut off frequencies, filter design, and the criteria for its determination (33). With this approach, we also wanted to reduce the barriers that students face when reading scientific papers and not properly understanding why and how the sEMG signals were processed. In addition to the temporal series analysis, which we considered as the most important when reading papers, we also discussed frequency analysis. Different examples were used to illustrate the applications of frequency analysis, including its potential to detect noise and to identify patterns of groups/clusters that may also help to identify movement deficiencies, for example (34).

The activities developed in the school also considered concepts related to data acquisition. We aimed to provide basic concepts and straightforward recommendations on how a sEMG examination should be conducted. When it comes to professor basic knowledge of sEMG procedures is required, improving teaching practices as well, and we consider that a specific school for teachers would be a valuable activity for the future. The results from sEMG examination can be a good platform to promote learning sessions and tutorials on how muscles are controlled, to discuss concepts of supraspinal control, reflexes, movement production, and regulation (35). Although it was not the main topic of the school, we provided basic concepts and discussions on muscle-computer interfaces and the use of sEMG for controlling external devices. This topic was addressed to stimulate the students to generate innovation by showing possibilities and enriching their experience (36). The program included a frequent revision of the basic concepts and more applied examples were discussed. We judge that this strategy was satisfactory in preventing some of the students from getting lost in the information flow. It became clear during the school that in addition to the basic physiological and mathematics concepts, there are technical aspects of sEMG that can also be considered a barrier to the correct methodological use of sEMG in daily clinical practice. These mixed limitations between math and physiology are frequently observed for health students and professionals. For example, in Chile, most students using sEMG never integrate math and physiology knowledge, and many professionals use the sEMG in clinical practice in a qualitative manner to justify rehabilitation decisions but with weak scientific support i.e., some private hospitals or universities have sEMG' devices but as the use of this devices in the analysis of treatment require time and knowledge, devices are not used well. Adequate data acquisition or analyses are frequently negatively affected by the economic pressure to treat the largest number of patients possible in minimal time. It also occurs with academic professors, who frequently have to lecture a higher number of hours in precarious conditions without time to properly address important technical aspects of sEMG. This is similar to many realities in Brazil and other countries in Latin America as well. As previously discussed, this condition affects different areas of education (6). Therefore, we consider that our approach helped to reduce this barrier as well.

We used a strategy of continuous online education by making all the lectures of the school permanently available online after the school was completed. Webinars and online classes are not a novelty these days, but most of the crash courses available are segmented for a very specialized audience, and sometimes assume that the viewers already have a good background. We believe that the recordings available online could promote additional learning when participants watch the classes again, also resulting in revalidation of the concepts, similar to what has been discussed when records of surgical procedures are integrated into patient care (37). Furthermore, the online lectures may serve as an introductory course to signal processing applied to human movement sciences, especially sEMG. The decision to make the lectures available online on YouTube® was because YouTube® was reported by 76% of physiology students as a primary source of learning (38). In the same study, 94% of students indicated that they would first search for answers online if they did not understand something in physiology, but only 31% check the sources (38). More importantly, online lectures may help other students and professionals who were not able to attend the school to learn from the lectures and to reduce barriers faced when using sEMG. While the population was struggling with the SARS-COV-2 pandemic in 2020, digital teaching and live meetings have confirmed the relevance and the utility of this strategy, benefiting learning in health and human movement sciences.

Finally, the main barriers identified by the tutors and participants were mathematical skills or background, i.e., algebra, calculus, and mathematical logical thinking. Furthermore, in many cases, fear of the numbers and programming a computer, and the insecurities and anxiety about colleagues from developed countries—who might be better prepared—were other barriers identified among the participants in Latin America. However, important social barriers also exist in regions where investment in research is not aligned with the economical aims of institutions, thus negatively impacting science education. We therefore recommend the organization of basic science schools for health careers in Latin-America, and to frequently develop critical lectures to fill educational gaps, using theoretical frameworks similar to those of engineering and other sciences, but adding innovative learning strategies from modern pedagogy in health sciences, that considers the biological profile of the students and professionals of health and life sciences.

CONCLUSION

The Winter School had a good impact on participant's formation and may have motivated other groups from Brazil to promote similar educational activities during 2019 as we observed schools in topics related to biomechanics and muscle function being promoted. From the participant's point of view, the activity was excellent, and the follow up of the school on the YouTube® channel, considering the social media engagement, suggests that combining face to face activities followed by online availability of lectures can be a valid strategy to sustain the interest of students on these topics.

We recommended frequent organizations of basic science Schools in health careers in Latin-America at all levels i.e., bachelor, Master, PhD, and post-doc, as an initiative to fill educational gaps using theoretical frameworks similar to those that engineering and other sciences adopt, as innovative learning strategies for modern pedagogy in health sciences is advisable. Furthermore, we believe that providing schools that are conducted 100% online could significantly benefit a larger number of students and professionals.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was provided by the participants.

AUTHOR CONTRIBUTIONS

CD, AM, and MK: conceived the project; delivered lectures; analyzed data; wrote and approved the final version of the manuscript. FC: conceived the project; approved funding; delivered lectures; analyzed data; wrote and approved the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fneur.2020.00509/full#supplementary-material

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sEMG: A Window Into Muscle Work, but Not Easy to Teach and Delicate to Practice—A Perspective on the Difficult Path to a Clinical Tool

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Surface electromyography (sEMG) may not be a simple 1,2,3 (muscle, electrodes, signal)-step operation. Lists of sEMG characteristics and applications have been extensively published. All point out the noise mimicking perniciousness of the sEMG signal. This has resulted in ever more complex manipulations to interpret muscle functioning and sometimes gobbledygook. Hence, as for all delicate but powerful tools, sEMG presents challenges in terms of precision, knowledge, and training. The theory is usually reviewed in courses concerning sensorimotor systems, motor control, biomechanics, ergonomics, etc., but application requires creativity, training, and practice. Software has been developed to navigate the essence extraction (step 4); however, each software requires some parametrization, which returns back to the theory of sEMG and signal processing. Students majoring in Ergonomics or Biomedical Engineering briefly learn about the sEMG method but may not necessarily receive extensive training in the laboratory. Ergonomics applications range from a simple estimation of the muscle load to understanding the sense of effort and sensorimotor asymmetries. In other words, it requires time and the basics of multiple disciplines to acquire the necessary knowledge and skills to perform these studies. As an example, sEMG measurements of left/right limb asymmetries in muscle responses to vibration-induced activity of proprioceptive receptors, which vary with gender, provide insight into the functioning of sensorimotor systems. Beyond its potential clinical benefits, this example also shows that lack of testing time and lack of practitioner's sufficient knowledge are barriers to the utilization of sEMG as a clinical tool.

Keywords: surface electromyography, education, clinical application, sensorimotor asymmetries, sensorimotor system gain, force control, hand dominance

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SEMG CHALLENGES AND ILLUSTRATIVE EXAMPLES

It is acknowledged that Neuroscience started with Ambroise Paré (1510–1590), who is credited for systematic "empirical observation…, and methodology for evidence-based medicine" (1, 2). Collecting observations and evidence became easier with the development of instrumentation, allowing the exploitation of physiological signals, as evidenced first by the invention of the stethoscope by Laënnec (3), for exploiting cardio-pulmonary sounds. According to a summary of

EMG history by Raez et al. (4), Luigi Galvani demonstrated in 1792 that muscle contraction could be initiated by electrical stimulation. However, it was not until four decades after the invention of the stethoscope that Emil Du Bois-Raymon (1849), founder of electrophysiology (5), showed it was possible to record the electrical activity generated by muscle contraction. This was termed "electromyography" by Marey in 1890 (6), now shortened to EMG, and in particular surface EMG (sEMG) when collected by a non-invasive technique. Since then, electrophysiological signals have been submitted to the torture of various mathematical tools to confess to "romantic lies and *novelistic* truth" [to borrow from Girard (7)]. In other words, the signals create the desire to seize upon expected cryptic information emanating from the object/system of interest. Nevertheless, mimetic evolutions of processing techniques have revealed a wealth of information. In the case of the sEMG, which is the focus here, useful information ranges from force exertion, or muscle load, to the recruitment/control of motor units and disorders effects and is extensively exploited in research (see this editorial project).

The muscle, source of EMG signals, is under the microscope of many fields of Neuroscience, and an allusion to all perspectives is beyond the scope of the present work, which is limited to EMG applications in Ergonomics and Occupational Biomechanics. These fields/disciplines are generally included in engineering, health and safety, and kinesiology schools/departments in the United States and Canada. Within these fields, there are three main categories of application. The first is to use EMG to describe the magnitude and pattern of muscle activity, also called *muscle load or muscle recruitment*. For example, during a task involving overhead reaches/manipulations there may be interest in knowing which of several shoulder muscles are involved, at what time, and with what intensity level [e.g., (8–10)]. The second application is using EMG to predict the forces generated by one or more muscles. Such predictions can be of use in detailed task analyses or for evaluating forces predicted using a biomechanical model (e.g., 3D SSPP™, University of Michigan). The third main application of EMG is to estimate the presence or extent of localized muscle fatigue [see for review (11–13)]. Return-to-work assessment is also receiving consideration; however, current utilization and information on this application are rather limited [(14); and papers in this editorial project].

The following comments express the perspective of lecturers and lab instructors, primarily in engineering but also in other fields. Their opinions are mostly derived from experience and exchanges between investigators as published data on the topic are not available, as far as we know. Two major types of hurdles, which are not specific to these fields, constrain the teaching of EMG as an ergonomic assessment and investigative tool. First, a number of methods designed to evaluate the risk factors associated with work-related musculoskeletal disorders [see for review (12, 15)] must be reviewed and presented, which requires several lectures within a course. The time-dependent risk factors to be identified and quantified include posture, force exertion, repetition, contact stress, vibration, and temperature. Hence, to complement or replace time-consuming observations, most methods rely on "sensors" (now mostly wireless wearable sensors), corresponding signals, and processing techniques designed to quantify the severity indicators for each risk factor. Thus, in addition to the EMG, a broad range of exposure assessment techniques (e.g., biomechanical modeling, upper limbs, and whole-body observation-based methods such as OWAS, OCRA, RULA, NQ, and NLG [see (12), force platforms, video and sensor-based motion analysis, vibration measurement, etc.]) has to be covered with greater or lesser emphasis as a function of each factor's prevalence in occupational activities. The three categories of EMG applications mentioned above (pattern, force/muscle load, fatigue) confer a high significance to the EMG as it relates to the engine powering all "activities." However, in engineering school graduate programs, in which ergonomics and biomechanics are taught, the whole time dedicated in one course to the EMG is on average 1.5 lectures or about 2 h. The second constraint includes the characterization of the EMG itself and its associated interpretation, as today sensor technology is no longer an issue with "cleaner" signals (thanks to miniaturization, wireless signal transmission, material science, and electronics).

Like many electrophysiological signals, such as the EEG, the EMG displays a noise-like complexion, which blurs the lines between truth and fiction. For example, the profile of a forest mirrored in a dark lake can morph into an EMG by discoloration (**Figures 1A,B**) and resemble a real EMG (**Figure 1C**). Hence, extracting meaningful information from that signal becomes a delicate exercise, including also detection and usage of the electromyography (EMG) discipline (16). Among these three components and their multiple issues starting from the anatomy of the muscle to the isolation of motor unit activity and the locus of muscle contraction [e.g., (13)], a number of topics cannot be presented in an easy-to-follow user manual. Although adequate recommendations concerning the placement of electrodes by SENIAM [see (17)] and the reporting of EMG data and measurement systems (www.isek.org) (13, 18) have been published, hands-on experience cannot be replaced by textbooks, lectures, or class demonstrations but must be based on previous theoretical knowledge. The following points summarize the main areas of difficulty for the novice.

- Electrode Usage. The vast majority of currently used electrodes are bipolar. However, the utilization of recently developed electrodes arrays contributes to some complexity that needs to be mastered, leading to significant benefits [(13); and this editrorial project].
- Electrode Placement. This operation, dependent on anatomy and muscle structure, and EMG susceptibility to many factors, is only mastered by hands-on experience. It takes experience to observe cross talk, impedance, artifacts, innervation zone, and electrode migration with skin movements, to cite only a few phenomena. Hence, getting a reliable signal requires the trainer to teach attention to detail and insistence on visual inspection of the raw signal, which can be elusive considering the noise mimetic façade.
- Signal acquisition and processing. Resolution, sampling frequency, gain and saturation, signal-to-noise ratio, non-linearity, sampling window, and calibration are notions rarely familiar to students in our discipline. In addition, being

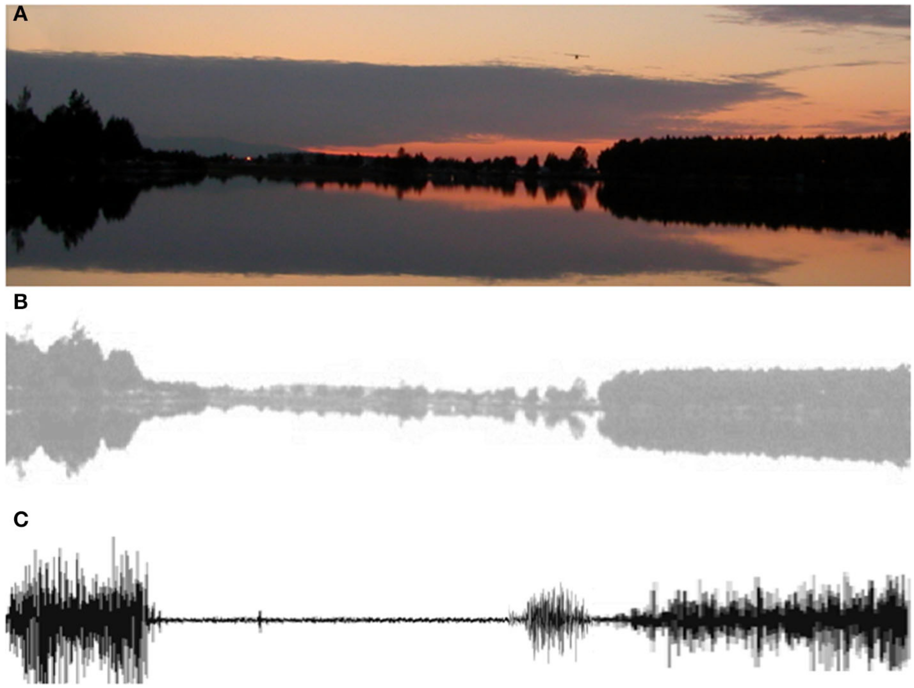

FIGURE 1 | The EMG forest or forest EMG. After adjusting the color **(B)**, the tree line, and its reflection over the dark water of the lake (unknown photographer) at sunset **(A)** produce an EMG-like signal **(C)**. Note that counting/identifying trees in the forest profile can be achieved by using filtering and different visual perspectives of the same scene—as done by the processing of photos obtained with multiple cameras in cutting-edge smart phones. Applied to the EMG signal for motor unit decomposition, a similar process is achieved using multiple comparisons of signals recorded by high-density electrode arrays (see text).

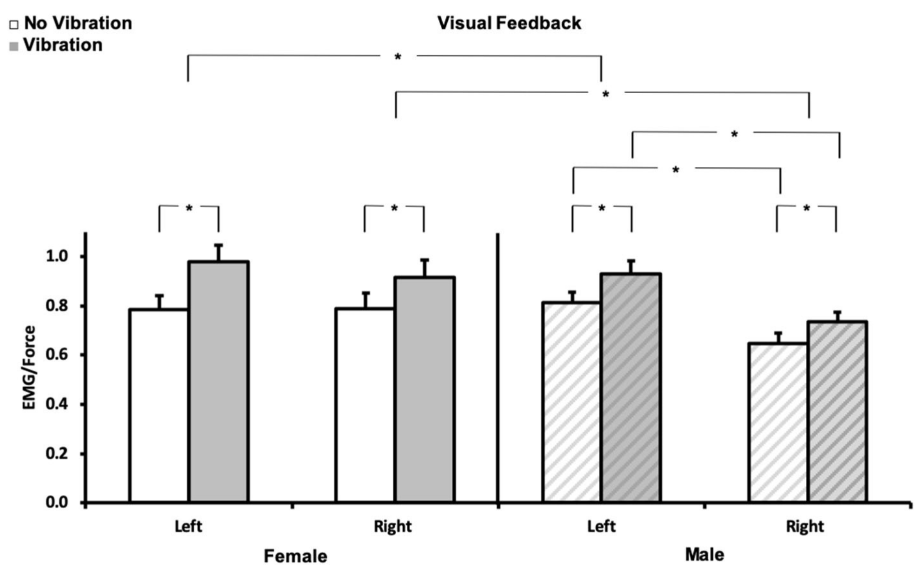

FIGURE 2 | Normalized EMG/force. Mean (± SE) for each hand (left and right) for no vibration (□) and vibration (■) for females (*N* = 10, left panel), and males (*N* = 10, right panel ▨). *$p < 0.05$. Each variable (EMG, force) was normalized to its corresponding 100% MVC. The required force exertion was 20% MVC.

a combination of muscle action potentials, decoding the temporal and spatial summations forming the sEMG is facilitated by the use of high-density electrode arrays and requires the utilization of simple to complex algorithms to characterize the muscle contraction status [e.g., see free tutorials by (19, 20)] and its eventual consequences, such as fatigue [e.g., (21–23)]. Hence, filtering and smoothing and frequency analysis are primary notions to assimilate. All these features require a course in signal processing to bridge the frequent "gap," difficult to fit in otherwise busy curricula.

Although a number of "packages" including electrodes, data acquisition, and signal processing software provide global solutions attempting to overcome most of the usual hurdles, they require training for correct usage and interpretation of the generated outcomes. "Noise-believed-EMGs" and aberrant spectra, which can be attributed to any of the aforementioned issues, are commonly observed in experimental results obtained by novices. These observations underline the necessity for a sufficient understanding of how to overcome the inherent limitations of EMG systems. They remain primarily designed for experts, may not cover all EMG applications, and, like all software, suffer from the usual weaknesses of interfaces and user guides.

In sum, times to teach and learn and training-based skills pose limitations to the utilization of EMG as a clinical tool aimed at the prevention and reduction of work-related musculoskeletal disorders. Furthermore, unlike other signals such as the EKG or EEG, which present similar limitations but are extensively used as clinical tools, the EMG does not provide information about life-threatening conditions, although it can provide useful information about health- or profit-threatening conditions. Hence, despite some utilization for the investigation of MSDs as a research tool, the absence of immediate life-saving status has probably relegated the EMG to a secondary role in the clinical arsenal and is not frequently used by occupational therapists (private conversations).

To illustrate some of the issues mentioned above and the work necessary to broadly support clinical applications, one component of a recent EMG-based study is presented as an original example. This investigation required the one-to-one training of a doctoral student in ergonomics from electrode placement to signal processing and interpretation due to the discovery of EMG practice. Major attention focused on precise electrode placement, signal validation, filtering techniques, and mechanisms underlying EMG variations in context. The hypothesis was that asymmetry in the functioning of the upper limb sensorimotor system (24–27) stems, to some extent, from the difference in sensitivity of the proprioceptive feedback loop between the dominant and non-dominant arm. This difference in sensitivity can be expressed by the difference in gain of the respective sensory-motor loops (28). It is posited that alteration of this imbalance by age, stroke, injuries, or diseases can be used to identify further sensory and motor deficits and then propose individualized rehabilitation procedures. To validate our hypothesis, EMG activity of the left and right flexor digitorum superficialis (FDS) was recorded in dextral young adults during a static, visually controlled, grasp force task [see (25, 27) for procedure] maintained before and during the application of a 60-Hz vibration to the distal tendons of the wrist flexor muscles. Vibration elicits a response of muscle and cutaneous receptors [e.g., (29, 30)], respectively mediated by Ia and cutaneous pathways. This sensory feedback drives primarily, but not necessarily, the motoneurons homonymous to the source activated (31, 32) and modifies perception (33). As a result, the interplay of the recruited muscles (agonist/antagonists) requires an adjustment of the motor command to maintain the grip force constant (33, 34). On this basis, changes in the EMG/force ratio was considered to reflect changes in the "gain of the sensorimotor system" tested. The aim was to quantify the extent to which the EMG reflects the expected differences between the dominant and non-dominant hand. All tests were performed in a standardized seated upright posture. Visual feedback of the grip force (20% MVC) was presented on a vertical scale displayed on a computer screen. Force and EMG signals were normalized to each hand 100% MVC obtained before the experiment. Two practice trials preceded the three test trials for each hand. The EMG/Force ratio was used as the dependent variable. While on average grip force level did not vary much due to visual control, for both genders, the EMG/Force ratio was greater with than without vibration for both hands ($p < 0.01$). *Post-hoc* comparisons indicated that the EMG/force was greater for females than males for the right and left hand ($p < 0.05$) and for the left than the right hand for males ($p < 0.002$). The EMG/force was not significantly different ($p > 0.05$) between hands for females. These results are illustrated in **Figure 2**. In brief, they illustrate the sensorimotor asymmetries between the right dominant and left non-dominant hand in males and confirm a gender difference with much less asymmetry in females despite their higher sensitivity (greater sensorimotor gain), which validates our previous hypothesis concerning a gender-dependent difference in the gains of the left and right sensorimotor systems (24–28, 35). Despite the value of such results, their exploitation time, as a diagnostic or rehabilitation assessment tool, is not negligible. Indeed, with a well-trained "tester" the duration of the test itself and following data processing is usually no <1.5 h.

CONCLUSION

A noise-like complexion makes the EMG, like other physiological signals, prone to confusion. Nevertheless, as evidenced by EMG quantification in the example provided above, the non-uniform gain of the sensorimotor proprioceptive systems of the upper limbs provides a number of insights concerning the functioning of sensory-motor loops and their contribution to force control. These include accessibility of homonymous motoneurons by Ia afferents, central control of sensory information, the gain of sensorimotor systems, and gender proprioceptive sensitivity. Each of these phenomena can be revealed by sEMGs and may be used to diagnose and monitor sensory and motor impairments resulting from aging, stroke, or other disease and injuries. To this end, the restoration of the disrupted "natural" balance/imbalance may be achieved via personalized rehabilitation procedures that consider the identified deficits. In Ergonomics, the methodology can be used to assess deficits resulting from work-related musculoskeletal disorders. Another application is the assessment of the muscle load induced by the operation of vibrating tools and thus tool selection. However, as indicated in section sEMG challenges and illustrative examples, the application of sEMG requires knowledge (e.g., EMG theory, signal processing, and neurophysiology), experience (e.g., electrode placement and signal morphology), and time (e.g., experiment design and procedure). These essential components may be deepened in doctoral studies but are not provided in clinical curricula such as physiotherapy and occupational therapy. Hence, broadening or amending the educational programs of physiotherapists, occupational therapists, movement scientists, and ergonomists (as future clinical users of sEMG) should prove useful. A lab course-specific training, including theory and hands-on practice, could be implemented. This could help resolve the recurrent comments from colleagues and professionals "We train them today, but they will work for the next 30 years and should be able to manage the huge technological changes that will take place… they should be able to read and understand papers and books in the field… we were not taught that in school, so it may not be too important… it was only an overview…" Although without a need to master the physics and mathematics of EMG, familiarization with basic concepts and technology should enable practitioners to translate scientific advances into clinical practice. However, if specialization is possible in some schools, getting a sufficient number of students in a specific subject remains a major issue in engineering and even biomedical engineering. Recruiting students from different schools or disciplines is already attempted but not very successful due to program requirements in terms of hours and content distribution and specific needs for research studies at the master or doctoral level. Hence, a new program focusing on clinical applications (including more extensively EMG as one of the tools) could be thought of in the realm of "health care" as is the case at the Delft University of Technology (DTU) in the Netherlands (see website). However, differences in the missions of Technical Universities in Europe (application oriented) and universities or Technology Institutes (generally labeled "school Name tech/IT") in the USA (research oriented), which are beyond the scope of this paper, may add difficulties to the adaptation of such a model. For example, the "Health Care" program "CHEPS" at the University of Michigan is focused on engineering health care (management/operation/patient safety). Thus, implementation of the DTU model may be more easily achieved in schools dedicated to physio- or occupational-therapy and perhaps in Kinesiology, with adapted teaching of technical skills. Furthermore, it appears that robotics rehabilitation is a rapidly evolving trend in the USA and most likely other countries. Hence, the expansion of other clinical application tools such as the EMG may be currently constrained within universities. These comments reflect only observations related to colleagues' work.

Furthermore, health insurance systems usually assume that one short expedited measure fits all, which prevents refinement of our understanding of sensory or motor deficits and thus precludes utilization of the tool presented. For example, stroke-induced deficits are estimated by crude physical assessments, and clinical rehabilitation procedures are mostly the same for everybody despite a common failure to promote significant recovery (36–38). The sEMG would supply information for better assessment of deficits as well as rehabilitation progress and/or efficacy. Finally, the instrumentation necessary to conduct such an analysis is usually expensive due to limited demand and technically complex with scarce support.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Michigan Institutional Review Board. The participants provided their written informed consent to participate in this study.

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Critical Issues and Imminent Challenges in the Use of sEMG in Return-To-Work Rehabilitation of Patients Affected by Neurological Disorders in the Epoch of Human–Robot Collaborative Technologies

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Patients affected by neurological pathologies with motor disorders when they are of working age have to cope with problems related to employability, difficulties in working, and premature work interruption. It has been demonstrated that suitable job accommodation plans play a beneficial role in the overall quality of life of pathological subjects. A well-designed return-to-work program should consider several recent innovations in the clinical and ergonomic fields. One of the instrument-based methods used to monitor the effectiveness of ergonomic interventions is surface electromyography (sEMG), a multi-channel, non-invasive, wireless, wearable tool, which allows in-depth analysis of motor coordination mechanisms. Although the scientific literature in this field is extensive, its use remains significantly underexploited and the state-of-the-art technology lags expectations. This is mainly attributable to technical and methodological (electrode-skin impedance, noise, electrode location, size, configuration and distance, presence of crosstalk signals, comfort issues, selection of appropriate sensor setup, sEMG amplitude normalization, definition of correct sEMG-related outcomes and normative data) and cultural limitations. The technical *and methodological* problems are being resolved *or* minimized also thanks to the possibility of using reference books and tutorials. Cultural limitations are identified in the traditional use of qualitative approaches at the expense of quantitative measurement-based monitoring methods to design and assess ergonomic interventions and train operators. To bridge the gap between the return-to-work rehabilitation and other disciplines, several teaching courses, accompanied by further electrodes and instrumentations development, should be designed at all Bachelor, Master and PhD of Science levels to enhance the best skills available among physiotherapists, *occupational health and safety technicians* and ergonomists.

Keywords: return-to-work rehabilitation, surface electromyography, instrumental-based biomechanical risk assessment, exoskeletons control, manual material handling monitoring

INTRODUCTION

Bipolar and multi-channel (high-density) surface electromyography (sEMG and HDsEMG) represent non-invasive physiological approaches, which enable greater comprehension of the upper limb, lower limb, and trunk muscle behaviors during the execution of movement (1–4). Differential bipolar sEMG signals, currently acquired using miniaturized wireless sensors attached to the skin, represent the spatio-temporal summation of all the motor unit action potentials, which propagate from the innervation zones to the tendon regions along the muscle fibers closest to the skin. In view of the complexity of these interference signals, simple indices facilitate an appropriate and complete analysis of the electrical activity of muscles. Simple indices provide information on "when" and "how much" the muscles are electrically active during the execution of both isometric and dynamic activities, and include the following parameters:

- amplitude indices (5, 6)
  - maximum,
  - averaged rectified value,
  - root mean square, and
- muscle activation timings (7).

Furthermore, sEMG-based algorithms enable greater in-depth comprehension of the muscle coordination mechanisms adopted by the central nervous system (CNS) by estimating the following:

- simultaneous activation of several muscles or muscle groups (co-activation), a mechanism adopted by the CNS to stabilize joints, upper and lower limbs, and the spine (8–11),
- myoelectric manifestation of muscle fatigue, estimated by measuring the decrease in fiber conduction velocity (12, 13), which is reflected in an amplitude increase and spectral compression over time (14–16), and
- locomotor coordination (17–26), analyzed to comprehend how CNS lesions of neurological subjects with motor deficits influence plasticity and modular control of muscle patterns (27). It has been demonstrated that the CNS can linearly combine, with different weights, a limited number of basic functions called primitives or muscle synergies, to implement several motor tasks. During steady-state walking and running, five and four primitives, respectively, account for muscle activity (28–30).

High-density sEMG recordings are performed using high-density surface grids placed on the skin to evaluate the online spatial distribution of the sEMG activity and estimate the discharge times of several motor units by using decomposition algorithms (2, 31).

Despite the many advantages of sEMG and HDsEMG, these instrumental tools are largely underexploited and their application lags expectations in the fields of ergonomics and occupational medicine. These tools have begun to be applied in the prevention of work-related musculoskeletal disorders, a set of painful inflammatory and degenerative conditions affecting the joints, spinal dizcs, cartilage, muscles, tendons, ligaments and peripheral nerves, caused by manual lifting, pushing and pulling, repetitive movements, and patients handling activities (32–39). However, they remain underused in return-to-work rehabilitation plans for people with neurological pathologies with motor disorders.

People affected by neurological pathologies need to be integrated/reintegrated into their workplaces because their motor disease symptoms appeared when they were of working age, reducing their working capacity (40, 41) and employability (42). Recent studies have proven that avoiding early exit from employment plays a beneficial and key role in the overall quality of life of people affected by neurological disorders (41, 42). Clinicians manage their patients' premature work interruption (43, 44) by designing appropriate traditional and innovative pharmacological, surgical, and rehabilitation treatments, such as robotic rehabilitation, virtual reality, and neuromodulation (45–49). Furthermore, job accommodation plans are being enriched with new ergonomic options, such as work task rehabilitation and workplace interventions (50–52). In fact, the fourth industrial revolution has recently opened new occupational scenarios within which key human-robot collaborative (HRC) technologies, such as exoskeletons (**Figure 1**) and cobots, assist workers in their workplaces. Cobots can be defined as reconfigurable collaborative robots able to interact with workers within a shared space and to respond to the worker intentions and task variations in a timely manner while simultaneously offloading them from external loadings, and keep them in task-optimum and ergonomic working conditions. Small-medium enterprises can currently use collaborative technologies allowing flexible and ergonomic workplaces, which can adapt to the characteristics of workers with neurological disorders (53). Quite recently, the European Union's Horizon 2020 research and innovation program funded the SOPHIA (Socio-physical Interaction Skills for Cooperative Human-Robot Systems in Agile Production) project to establish and achieve, among others, the goal of validating the HRC technologies developed under the aegis of the project in the healthcare sector and in return-to-work rehabilitation of patients affected by neurological disorders. In particular, the European consortium is developing myoelectric HRC interfaces to study how new hybrid work environments can flexibly adapt to the human physical states and needs, thereby contributing to improvements in ergonomic interventions (53). Furthermore, the project has the aims, for prevention, to design training plans of professionals specialized in the workers motor performance measurement by using sEMG-based approaches, develop miniaturized wearable devices to monitor human-motor variables and render haptic stimuli to specific areas of the worker's body and develop new standards for adaptation of work environments and biomechanical risk assessment in collaborative manufacturing scenarios. Within this context, it is quite evident that sEMG can play a crucial role in complex vocational reintegration programs in classifying residual motor functions, assessing pre-post-rehabilitation and ergonomic interventions, and controlling wearable robotics. The professionals trained for the sEMG in return-to-work programs should be physiotherapists, *occupational health and safety technicians* and ergonomists which should operate in a multidisciplinary team also constituted by neurologists,

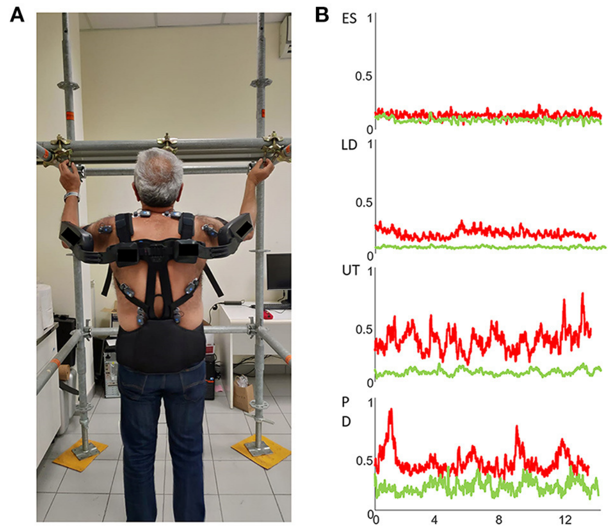

FIGURE 1 | (A) Wearable wireless sEMG sensors placed bilaterally over the erector spinae (ES), latissimus dorsi (LD), upper trapezius (UT) and posterior deltoids (PD) muscles to assess the efficacy of a passive exoskeleton during the execution of an overhead screwing activity. **(B)** sEMG envelopes of right ES, LD, UT and PD muscles of a representative subject without (red traces) and with (green traces) the use of a passive exoskeleton.

occupational physicians, physiatrists, biomedical engineers and movement scientists. We believe that no new professions should be created.

Occupational health and safety technicians have an academic degree offered at Bachelor of Science level in the same field of physiotherapists (health professions sciences). Instead, professionals from different disciplines, for example occupational physicians, who aspire to practice the profession of ergonomist, need a degree that is not conferred by universities. In Europe, the Center for the Registration of the European Ergonomists (CREE) is the professional certification supported by European ergonomics associations and recognized by the International Ergonomics Association (IEA) which provides the title of "Eur.Erg." and allows to practice the profession of ergonomist in 47 countries.

The above premise serves as a rationale for identifying and discussing the barriers to the coherent and widespread use of sEMG in work integration/reintegration.

This article represents the perspective, under the aegis of the SOPHIA project, of the Laboratory of Ergonomics and Physiology of the Italian Institute for Insurance against Accidents at Work (INAIL), a public non-profit entity aimed at facilitating the return-to-work of people with motor disorders.

AN OVERVIEW OF SEMG USE IN RETURN-TO-WORK OF PATIENTS WITH NEUROLOGICAL DISORDERS

Ethical review and approval and written informed consent were not required for the study because no human participants were recruited in the study and in accordance with the local legislation and institutional requirements.

Degenerative and acquired neurological diseases, including neuropathies, multiple sclerosis, stroke, spastic paraplegia, cerebellar ataxia, dystonia, traumatic spine and brain lesions, and encephalitis, are disorders, which can affect the motor function during working age and severely limit the autonomy and efficiency of workers (42, 54–58). The motor impairment of workers affected by neurological diseases may encompass several motor domains, including hand function, balance, and locomotion, resulting in considerable onus on the society in terms of reduced work productivity and cost. The main purpose of pharmacological, surgical, and rehabilitation treatments must be to improve the motor performance, autonomy, and daily lives of patients, thereby offering them the possibility of returning to work and optimizing their work capability.

Combined with kinematic and kinetic measurements, sEMG is currently widely used in research laboratories by movement scientists and still little in clinical routine by health operators to classify quantitatively the nature and degree of motor dysfunction, analyze the complex relationship between the primary deficit and the adaptive and compensatory mechanisms, categorize patients based on their specific neurological disease, and finally monitor pre-post-treatment. Importantly, as sEMG essentially investigates the final output of motor commands, it can quantify the residual motor function, which can theoretically be monitored continuously in workplace adaptation and integrated into HRC technologies.

Application of sEMG in Monitoring

When a worker affected by a neurological pathology with motor disorders is reintegrated at work, an exhaustive assessment of his/her residual motor function is of primary importance to design and/or adapt his/her workplace well. Additionally, it is necessary to verify and monitor the efficacy of these ergonomic interventions over time.

Although no consistent studies have specifically investigated the sEMG of patients with neurological disorders in the workplace context, there are several reports on the residual muscle function assessment of patients with neurological disorders [(10), for review see (59, 60)]. Many muscle activation measures and indices exploring several aspects of motor control have been proposed for patients with neurological diseases: co-contraction/co-activation of single-joint or multi-joint muscles [(9, 23, 61), for review see (62)], spatio-temporal modular muscle activation (19–22, 27), muscle activation asymmetry (63), time-frequency coherences between joint muscle signals during dynamic contractions to detect the spasticity in the upper limbs (64), and muscle fatigue (65, 66). Furthermore, it is possible to obtain from these studies a set of functional measures to consider for work reintegration while simultaneously taking into account the uniqueness of the motor deficit specific to each disease.

Some long-lasting degenerative neurological diseases, such as cerebellar ataxia and spastic paraplegia, often begin at a young age and can persist for the entire duration of a subject's working life. This is of interest in the context of work-related rehabilitation because the majority of patients consider themselves capable of working, and approximately 78% of non-working patients seek employment (42). Furthermore, workers with cerebellar ataxia show low or average-to-low job stress-related risk (42).

The use of sEMG analysis in patients with degenerative cerebellar ataxia (for instance, spinocerebellar ataxia) reveals a series of muscle activation abnormalities (67). Specifically, patients with spinocerebellar ataxia show increased amplitude and duration of sEMG bursts in both the upper and lower (21, 22) limbs, with significant differences in muscle activation timing (21, 22). Further evidence reveals increases in both single-joint antagonist muscle co-activation (61) and multi-joint multi-muscle co-activation (68). All these abnormalities are related to the severity of the disease and balance features, suggesting they could be exploited as potential biomarkers for the work-related biomechanical risk evaluation and workplace adaptation monitoring of these patients. One possible approach is the planning of assistive devices for workplace adaptation, such as the use of supportive elastic suits (69). These soft wearable devices can improve movement stability and reduce the need to co-activate muscles. Consequently, they can lower the associated energy costs and tissue-overuse injuries owing to excessive compression and shear forces at, for instance, the L5-S1 joint of the spine.

It has been reported that patients with degenerative spastic paraplegia (for instance, hereditary paraplegia) show increased global (23) and segmental lower limb muscle co-activation (9), which correlate positively with disease severity, degree of spasticity, and energetic costs (9). In addition, when mapping the simultaneous activities of a large number of muscles during walking onto the anatomical rostrocaudal location of the motor neuron pools (70), patients with spastic paraplegia show an abnormal spread of muscle activation during gait, initially involving the sacral segments and, at more severe stages, the lumbar segments (20).

Application of sEMG in Controlling HRC Technologies

Human-robot collaborative technologies, particularly exoskeletons, have proven significantly useful in the rehabilitation programs of patients affected by neurological diseases. Physiological parameters with sEMG play a key role in monitoring muscle activation amplitude and fatigue in the design of innovative active exoskeleton controller systems and assessment of their effectiveness on motor performance (71).

Recent improvements in the measurement and real-time classification of myoelectric signals have already facilitated the use of sEMG in man-machine interfaces for controlling prostheses and orthoses among other devices (72–76).

Very recently, human-exoskeleton interfaces were developed for the purpose of rehabilitation to support physically weak and disabled people in performing several motor activities of daily living, such as walking. These interfaces were developed based on new technical and mathematical approaches, including new sEMG signal-processing procedures (77–82).

The performance of these man-machine interfaces is quickly improving owing to neuro-musculoskeletal models driven by neural information obtained from the decomposition of HDsEMG (72).

BARRIERS TO SEMG USE IN RETURN-TO-WORK OF PATIENTS WITH NEUROLOGICAL DISEASES

The critical issues hindering the widespread adoption of sEMG in return-to-work programs are mainly attributable to technical, *methodological* and cultural limitations. The technical issues are attributable to both monitoring and control functions. With regard to monitoring, the most critical *technical* aspects are strongly associated with the sEMG technique:

- electrode-skin impedance, noise, and electrode contact stability;
- *while the methodological aspects are associated to:*
- problems linked to electrode location, size, configuration, and distance;
- presence of crosstalk signals (16).
- placement of sEMG electrodes for long hours;
- selection of the right sensor setup on the base of the neurological pathology and manual handling activity to be investigated;
- management the sEMG amplitude normalization;
- definition of appropriate sEMG-related outcomes and normative data.

Fortunately, the effect of these critical issues on the sEMG signal quality can be reduced with the aid of authoritative reference books and tutorials. In particular, the European Recommendations for Surface Electromyography (83), which needs to be updated, and the Atlas of Muscle Innervation Zones (84) are recommended as guides for the use of sEMG together with recent tutorials and consensus papers (85–87). A knowledge of the contents of these texts and tutorials makes users aware of the current limitations of the sEMG approach given its ability to monitor only a limited number of superficial muscles. Despite this, the technical *and methodological* limitations of the sEMG approach can be *minimized* and do not justify its non-usage in return-to-work rehabilitation plans. In addition, new wearable sensors and electronic smart devices such as smartphones and tablets allow simple monitoring of the worker at the workplace. Wearable sensors do not interfere with the typical movements performed by workers owing to their miniaturization and wireless communication protocols. In addition, multi-channel sEMG systems are available in wireless versions despite their high number of channels and high data rate. The combination of sensor networks and intelligent work environments provides real-time estimation of physiological parameters, enabling direct feedback to workers who are monitored directly and constantly at the workplace. Real-time monitoring is additionally useful for providing acoustic, visual, and vibro-tactile stimuli to workers (53, 88) executing manual handling tasks in awkward postures or requiring significant physical effort, or when muscle fatigue sets in.

As regard the sEMG use in work environment, each manual handling activity represent a risk of onset of well-classified diseases affecting the musculoskeletal system. For instance, lifting activities imply high compression and shear forces at L5-S1 joints (strongly correlated with muscle co-activation) with a significant involvement of erector spinae and rectus abdominus muscles, while handling low loads at high frequency imply neck and upper limbs muscles fatigue. For this reason the choice of channels and the rationale for selecting them should be task-guided.

The criticisms related to the use of sEMG to control collaborative wearable trunk and upper limb devices designed to assist people with neurological disabilities are attributable to the algorithms used in human-robot interfaces. These algorithms are used for pattern recognition and classification of patients' movement intentions. Only a few years ago, the performance of sEMG-based interfaces had not reached accuracies acceptable for widespread commercial use (74). Accuracy was limited by the high inter-subject variability, which required subjective calibrations and training. Fortunately, these interfaces, including machine-learning algorithms, have since been significantly improved, enabling the acceptable optimization of HRC control mostly for people with severe upper and lower limb disabilities (89).

Another technical limitation of sEMG-based interfaces for use in HRC technology control is the fact that most wearable assistive devices use traditional control tools, such as bipolar sEMG, to record antagonist muscle activities. This low spatial sampling implies that a maximum of one degree of freedom (DoF) can be controlled. Furthermore, managing up to two DoFs requires slow, sequential, and unintuitive control. The related limited functionality in conjunction with the extensive training required of neurological subjects led to the high rejection rates of these technologies (72). Currently, classification and regression approaches outperform traditional control tools in controlling complex motor activities in terms of speed and accuracy, providing a promising method for advanced myoelectric control (72).

Without doubt, in job integration/reintegration, the sEMG approach has yet to be adopted and the critical issues associated with it are managed with difficulty. In fact, while reasonable workplace accommodation and disability employment issues are being historically and widely addressed by the governments of the industrialized world, the adoption of instrument-based quantitative assessments of ergonomic interventions *has so far been disregarded*, owing to cultural barriers, which lead to a preference for qualitative approaches.

A clear testimony of the presence of this educational gap is the worldwide social policies for persons with disabilities (90, 91), such as the European Disability Strategy (2010–2020) and the directives 89/654/EEC, 2000/78/EC, and 2000/78/EC are the corresponding policies. Another example is that of the Job Accommodation Network, a facility of the United States Department of Labor's Office of Disability Employment Policy, which provides a valuable strategy for the inclusion of people with neurological disabilities (92). Nevertheless, only half of the population with disabilities has been accommodated well in terms of workplace design and there is evidence of poor knowledge about adaptation of workers with neurological pathologies.

The lack of quantitative approaches suggests that, except in rare cases, sEMG is not taught in the Ph.D. programs of universities and occupational medicine specialization schools. Furthermore, the domestic and international chapters of the Human Factors and Ergonomics Society do not actively promote meetings, conferences, and events to address the challenges of sEMG use. Finally, the reference society for sEMG, the International Society of Electrophysiology and Kinesiology, has thus far not dedicated specific training programs regarding job accommodation. All the above mentioned training activities would typically be successful to address methodological issues, as increased knowledge alone cannot overcome technical limitations.

The enormous potential of the sEMG and HDsEMG approaches and their very limited use in return-to-work programs represent a real paradox. It is difficult to determine why sEMG is underused. Perhaps, the most likely reason is that the training provided to professionals is based on more qualitative rather than quantitative approaches, and the transition from one approach to the other is evidently difficult. Professionals in the field have to be trained to understand the extremely variable abnormalities of workers suffering from neurological pathologies and to associate an appropriate return-to-work plan with them.

DISCUSSION

Although sEMG is considered the most informative instrument for muscle monitoring when wearable robots are used, its use poses a number of challenges.

One such challenge, which we believe is on the verge of being addressed, pertains to the use of exoskeletons for active rehabilitation therapies. It pertains to the optimization of appropriate smart algorithms to detect patients' intentions and allow exoskeletons to act in synergy with them (93, 94). The challenge is to enable symbiotic physical HRC by incorporating accurate subject-specific computer models of each individual's neuro-musculoskeletal system to enable appropriate anticipation mechanisms. This is crucial to estimate muscle and joint stiffness accurately to determine the onset of excessive rigidity, which may be related to fatigue or negative compensatory strategies (95).

Myocontrol should be increasingly based on HDsEMG to increase spatial resolution with respect to low-density sEMG and to improve the accuracy of motor workers' intentions recognition. Moreover, machine learning approaches such as artificial neural networks should be used to evaluate the capacity of workers with neurological diseases for myocontrol.

In a recent study (96), HDsEMG was used to test the ability of participants with Duchenne muscular dystrophy (DMD) to produce repeatable HDsEMG patterns, which were unexpectedly comparable with those of healthy participants, suggesting a clear potential for the myocontrol of wearable exoskeletons. High-density sEMG can be applied to analyze the altered motor control of people with DMD and potentially interface them with assistive wearable robots. In addition, non-invasive decoding of individual α-motor neuron activation may represent a new option for the design of real-time closed-loop control applications, such as transcutaneous and epidural electrical stimulations.

To bridge the gap between the return-to-work concept and other disciplines, several educational activities should be developed to enhance and apply the best skills available in rehabilitation engineering, physiotherapy, occupational therapy, and ergonomics. For a few years, INAIL has been promoting a Ph.D. program together with the Sapienza University of Roma titled "Kinematic, Kinetic, and Electromyographic Characterization of Motor Disabilities and Biomechanical Overload Risk Management for Job Reintegration," a Masters' course titled "New Methodologies for the Evaluation and Management of Biomechanical Risk and Criteria and Methods for the Adaptation of Workplaces," and several training courses regarding the role of sEMG in occupational medicine and ergonomics. The participation, although the events were not free and not recognized as continuing education, has always been conspicuous with a number of participants (*occupational health and safety technicians*, physiotherapists, ergonomists, occupational physicians, rehabilitation engineers and movement scientists) that has always reached the maximum allowed limit (30 in the case of training courses). The authors of this article begin to observe a first positive impact of these initiatives on the need that operators in the field have in using the sEMG approach.

These mandatory educational opportunities must capitalize on the skills of the leaders and innovators of sEMG to serve physiotherapists, health and safety technicians, and ergonomists by providing them with qualified training focused on the management of the monitoring and HRC technologies and instrumental recordings. In particular, these professionals should know the physiology of sEMG signals, electrodes placement, software and hardware for acquisition. Furthermore, they are expected to know basic and some more complex concepts of signal processing, do a general visual interpretation and be able to generate reports that can be interpreted by the other team members. The multidisciplinary team should plan, implement and evaluate the return-to-work program in both the clinical and occupational environment. It should be considered that when patients with neurological disorders are involved, the key professionals leading the team should be neurologists in the health sector and occupational physicians at workplace. INAIL is organized throughout the national territory in order to fully manage the job integration/reintegration process but this service is also offered by consultant companies. Rehabilitation engineers should be given greater options to work with patients and physiotherapists, health and safety technicians end ergonomists. We believe that no other hybrid professions should be created. The contents must be based first on elementary concepts [which are illustrated in free online materials, such as those available at [99]] and, second, on integrated approaches promoting the culture and acceptance of instrument-based quantitative methodologies. All these actions should be taken as early as possible by guiding workers with chronic neurological disorders to return to work and stay in work with well-managed occupational safety and health interventions. The abovementioned activities may additionally yield tangible savings for businesses and national health and welfare systems.

Obviously, the teaching activities directed to strategic professions alone cannot solve the problem of under-use of sEMG in return-to-work plans. In fact, they must be accompanied by further electrodes and instrumentations development especially from the perspective of emerging artificial intelligence that may be encapsulate sEMG knowledge. Such tools may provide the professional with information to act on, thereby reducing the current "art" aspect of using EMG to something more in everyone's hands to use and exploit.

In addition to the motor impairments, cognitive and speech impairments are major contributors that strongly impact on the returning to work. Important aspects to consider are to understand how patients with cognitive and speech problems can adapt to the sEMG monitoring and how they can be assisted by using specific sEMG technology (96).

There are other challenges that are specific to application of sEMG in return-to-work environment according to the specific motor impairment characterizing the different neurological diseases. For instance, muscle fatigue, which is a common feature of several neurological diseases (i.e., multiple sclerosis, stroke, muscle dystrophy) results in altered motor unit recruitment and decreased maximal voluntary motor unit firing rate that can be detected by sEMG monitoring. A specific scenario could be to adapt the workplace and to modify the work-task according to the subjects' abnormal fatiguing performance, by assisting the workers with devices and/or reducing the amount and the duration of the work-related activity. Furthermore, an individualized rehabilitative program could be planned to improve the impact of the work-task on the fatigability in a long-term period.

The abnormal muscle co-activation is another example of common problem identifiable by sEMG in several neurological disorders (e.g., cerebellar ataxia, Parkinson disease, multiple sclerosis, stroke) which can be detected by measuring the simultaneous time-varying sEMG signal in many muscles. It is known that patients with balance disorders increase the muscle co-activation to control their walking instability in the attempt to stiffen the body segments. Unfortunately, this compensatory mechanism has some negative effects, such as increased metabolic cost and risk of cartilage degeneration. A specific scenario for these workers is to plan an appropriate workplace rehabilitation to improve their balance, to stabilize the body segments and to reduce the need to increase the muscle co-activation.

In conclusion, sEMG should be used in job integration plans to:

- classify the nature and degree of residual motor function in order to design/adapt the workplace;
- assess the efficacy of work-task rehabilitation and ergonomic interventions;
- control new assistive technologies such as collaborative robots;
- evaluate the biomechanical risk during the execution of manual handling activities;
- plan a preventive rehabilitation program to prevent injury.

Including the sEMG approach in work integration/reintegration offers the possibility of designing programs based on the residual motor abilities of the worker and adapting his/her workplace. This allows to consider a wide range of workers with several neurological pathologies and different levels of severity but without a complete inability to perform activities of daily life.

To make this possible, Bachelor, Master and PhD programs should be promoted, or at least, supervised and monitored, by scientific societies in the fields of physiotherapy, ergonomics, occupational medicine, biomechanics, electrophysiology and kinesiology, and should include continuing education courses on the use of sEMG specifically oriented to teachers in these fields.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval and written informed consent were not required for the study as per local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

AR, MS, and FD planned the manuscript, performed the literature searches, wrote the text and revised the manuscript. All authors contributed to the article and approved the submitted version.

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MINI REVIEW
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Surface Electromyography: What Limits Its Use in Exercise and Sport Physiology?

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The aim of the present paper is to examine to what extent the application of surface electromyography (sEMG) in the field of exercise and, more in general, of human movement, is adopted by professionals on a regular basis. For this purpose, a brief history of the recent developments of modern sEMG techniques will be assessed and evaluated for a potential use in exercise physiology and clinical biomechanics. The idea is to understand what are the limitations that impede the translation of sEMG to applied fields such as exercise physiology. A cost/benefits evaluation will be drawn in order to understand possible causes that prevents sEMG from being routinely adopted. Among the possible causative factors, educational, economic and technical issues will be considered. Possible corrective interventions will be proposed. We will also give an overview of the parameters that can be extracted from the decomposition of the sHDEMG signals and how this can be related by professionals for assessing the health and disease of the neuromuscular system. We discuss how the decomposition of surface EMG signals might be adopted as a new non-invasive tool for assessing the status of the neuromuscular system. Recent evidences show that is possible to monitor the changes in neuromuscular function after training of longitudinally tracked populations of motoneurons, predict the maximal rate of force development by an individual via motoneuron interfacing, and identify possible causal relations between aging and the decrease in motor performance. These technologies will guide our understanding of motor control and provide a new window for the investigation of the underlying physiological processes determining force control, which is essential for the sport and exercise physiologist. We will also illustrate the challenges related to extraction of neuromuscular parameters from global EMG analysis (i.e., root-mean-square, and other global EMG metrics) and when the decomposition is needed. We posit that the main limitation in the application of sEMG techniques to the applied field is associated to problems in education and teaching, and that most of the novel technologies are not open source.

Keywords: HDsEMG, sport, exercise physiology, biomechanics, EMG, motor unit

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INTRODUCTION

Traditionally, the acquisition of EMG signals is prevalent to clinical contexts—neurology, orthopedics, physiatry—and, to the best of our knowledge, it almost always involves needle/fine wire EMG. The usage of surface EMG (sEMG) for the study of motor control is primarily applied to research environments. Only few clinical laboratories adopt sEMG measures to estimate the health and potential neuromuscular changes of the nervous system. The limited usage of sEMG only to research environments is mainly dictated by the fact that the global EMG signals is associated to the activity of many motor units and the properties of the tissue between the electrodes and the muscle fibers [i.e., the volume conductor, for (1–7)]. However, the parallel development of high-density EMG electrodes (grids of more than >32 electrodes with low interelectrode 5–10 mm spacing) with blind source separation algorithms allows. for the first time, the identification of individual motor unit spike trains (8, 9), which have been validated using both simulations and intramuscular EMG recordings (10, 11). The access to a representative population of motor neurons allows the identification of the responsible mechanisms for the development of muscle force (12).

Despite these advantages, there are major limitations for the access of sEMG analysis to exercise physiology. These limitations include the education of the exercise and sport physiologist, occupational therapists, and fitness and training experts. There is now sufficient evidence to show that it is possible to interface the output of the human spinal cord by applying high-density grids of electrodes on the surface of the muscles (8, 13–15). This type of technology allows to study the behavior of a representative populations of spinal motor units in an unprecedented way and in a fully non-invasive manner. This is obviously of utmost importance for the above listed professional, including those working in the field of preventive and adapted physical activity.

Nevertheless, as already pointed out by many authors (1, 2, 4, 12, 16, 17) global sEMG analysis shows important limitations that impede the access to the neural drive (ensemble of motor unit action potentials) to the muscle. The latter plays a significant restriction against the widespread use, acceptance, and relevance of sEMG data analysis from both researchers and professionals. Due to the fact that it is so deceptively easy to collect reasonable sEMG data, researchers tend to underestimate this technique, while movement professionals tend to overestimate it. There seems to be a failure to communicate among sEMG experts and potential users. In fact, if we look at citations our recent and less recent papers are receiving, it is immediately apparent that ∼90% comes from colleagues directly involved in the same field (Scopus source). The lack of citation from clinical and applied journals is, overall, associated to communications challenges between the clinical, professional and research fields. However, there are no doubts that the limitations in the accessibility and teaching of novel technologies (both at the software and hardware level) limits the diffusion of sEMG technique and data analysis outside the laboratories.

Figure 1 shows an illustration of the limitations and potentials of surface EMG analysis, from classic bipolar EMG recordings (global EMG estimates) and the information that can be extracted through the decomposition of the EMG signals.

The motor unit, which comprises an alpha motoneuron and the muscle fibers innervated by its axon, represents the output final common pathway of the central nervous system. Therefore, the behavior of these individual neural cells, provides important information on the status and health of the neuromuscular system. Indeed, motoneurons convey information from afferent and efferent fibers within the sensorimotor system and generate force by sending action potentials to group of muscle fibers (the muscle units). Any potential changes in the distribution and strength of common input sent to motoneurons can likely be assessed by decoding a representative population of motoneurons, as we showed in many studies (15, 18–21).

Our group has recently provided evidence that is possible to predict important behavioral parameters such as the maximal contractile speed of muscle (20, 22) and the neural changes following training (21) by identifying the discharge timings of the motoneurons using high density sEMG recordings (HDsEMG). Using this technique, we showed for the first time that the discharge characteristics of motor units in the tibialis anterior muscle tracked across the intervention change after 4 weeks of strength training consisting of isometric voluntary contractions. These adaptations included increase in motor unit discharge rate, decreases in the recruitment-threshold force of motor units and a similar input–output gain of the motor neurons during submaximal contractions at the same relative maximal force level (before and after training). The findings indicate that the adaptations in motor unit function may be attributable to changes in synaptic input to the motor neuron pool or to adaptations in intrinsic motor neuron properties. Most importantly, they point out that is possible to associate a large portion of the spinal cord output to function (e.g., the changes in force with training are due to neural mechanisms).

Another critical aspect that is fundamental for sport and preventions of injuries is the rate of force development of a muscle (23–26). With regard to this issue, we showed that the rate of force development is significantly correlated with the very early phase of the neural drive, which takes place even before the onset of movement and that can be characterized in terms of discharge rate and motor unit recruitment speed (20). This characteristic implies that the interfacing with the spinal cord allows accurate prediction of the contractile speed. Therefore, monitoring these physiological parameters is likely necessary in order to train and rehabilitate the neuromuscular apparatus. Moreover, the fluctuations in joint force during isometric steady state contractions can be predicted by low-pass filtering of the neural drive to the muscle (27), which implies functional associations between the common motoneuronal oscillations and force tracking accuracy. This is particularly important for the aging neuromuscular system, which shows poorer performances in force accuracies. Indeed, there are correlations between the variability in the output of the common motoneuronal fluctuations and force accuracy (28, 29).

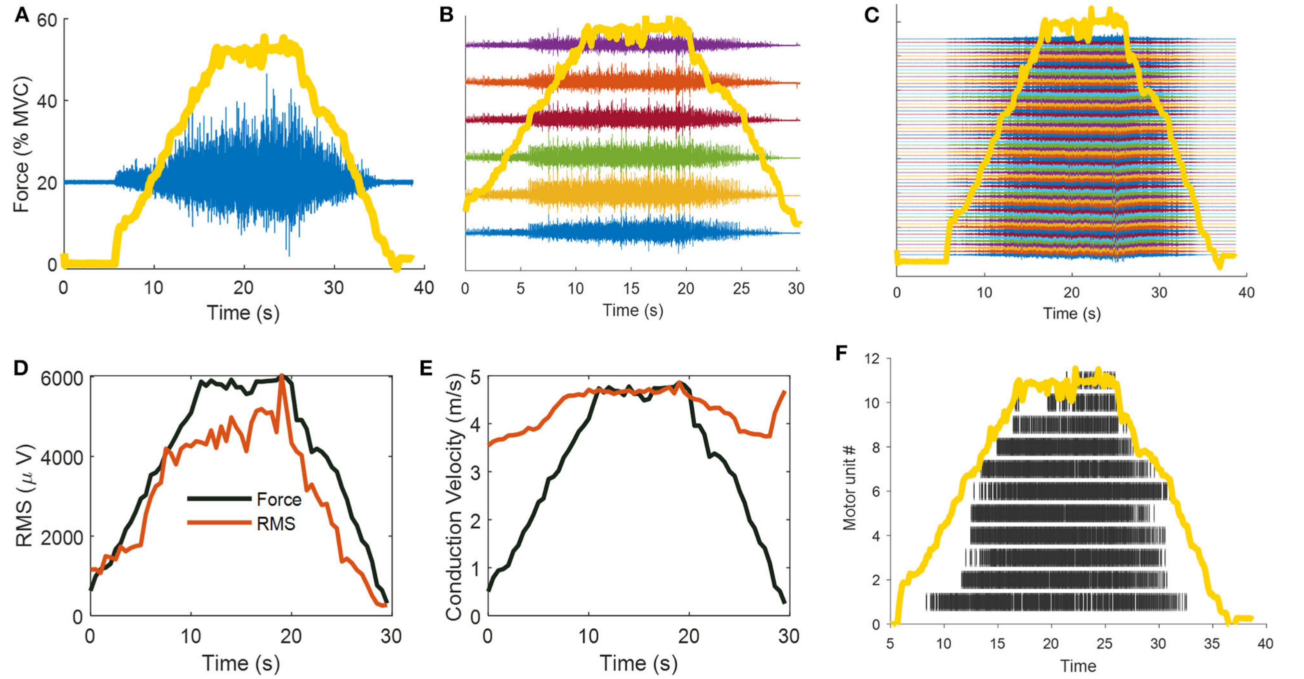

FIGURE 1 | Classic surface EMG recording frameworks: the evolution from bipolar, linear arrays, and high-density EMG configurations. In this example, a 26 year-old men performed isometric linearly increasing ramp contractions up to 50% of maximal voluntary force. **(A)** Bipolar (double differential, in blue) surface EMG recordings superimposed on ankle-dorsiflexion force (yellow line). **(B)** Six double-differential EMG recordings. **(C)** Sixty-four monopolar EMG signals. **(D)** The most common parameter that is extracted from a bipolar EMG signals is its amplitude. The surface EMG amplitude is weakly associated to the effective neural drive to the muscles due to the effect of volume conductor, amplitude cancellation, and random positions of motor units in the muscle tissue. The strong correlation with joint force, as shown in **(D)**, can be misinterpreted as the effective neural output that reach the muscle per unit time. This speculation is however wrong, since the amplitude of the surface EMG can only increase monotonically with force as it corresponds to an approximate sum of the number of motor unit action potential that reach the muscle per unit time (therefore both motor unit recruitment and motor unit discharge rate), and both of these measure increase with force (note that motor unit recruitment reaches a different plateau for different muscles, and is in the range 40–95% of maximal voluntary force). However, the influence of volume conductor, amplitude cancellation and divergent associations of EMG amplitude with motor unit action potential amplitude within different muscles, impedes the usage of EMG amplitude as a biomarker of neural function. Indeed, the shape of the action potential of the motor unit is only determined by the muscular properties. For some limited prosthetic applications, the amplitude of the EMG may be used as a proxy of the neural commands, as shown in **(D)** (the coefficient of correlations and Pearson *P*-value between force and RMS in **(D)** are, respectively, $R = 0.95$, and $P = 8.39e\text{-}31$). **(E)** Muscle fiber conduction velocity (MFCV) as estimated from 6 bipolar EMG signals. Muscle fiber conduction velocity is a basic physiological parameter related to the diameter of muscle fiber, pH level, and ion concentration. MFCV increases linearly with force with similar correlation to RMS, however, it can be only estimated if the muscle fiber are disposed in parallel with the recording electrodes. Note that the conduction velocity is sensitive to the activity of motor unit action potentials and is positively associated to motor unit conduction velocity and recruitment thresholds. The high-conduction velocity at the end of the ramp contractions in **(E)** is due to the non-propagating components (intrinsic noise of the EMG). Indeed, the coefficient of correlation between channels at this time point was very low $R = 0.23$, as opposed to the ramp contractions with high EMG activity (average correlation between channels $R = 0.84 \pm 0.018$). **(F)** The high-density EMG were decomposed with blind source separation approaches, identifying the unique spatiotemporal representation that constitute the original signal (i.e., the motor unit action potentials). The raster plot shows 11 motor units during that were identified during the contraction. Note the progressive recruitment of the motor units.

TRANSLATION OF SEMG FROM BASIC RESEARCH TO APPLIED ENVIRONMENTS

We investigated the role of education by looking at the first 100 bachelor and master courses, of the top 100 university (extracted via QS World Ranking and Shanghai Ranking) in the area of Human Movement, Biomechanics, Sport Science, Physiotherapy and Exercise Physiology, and we found that only a very limited number (5% of the total) teaches students the fundamental principles for studying the neural control of muscles at the direct motor unit level. Specifically, we aimed at finding direct evidence of theoretical or practical (lab-based) teaching of the fundamental principles of motor unit physiology and the potential methods available to the research/clinical environments. However, the full details of the course of neurophysiology for several university (∼24% of total) was not publicly available or not found.

One major limitation is the access to these technology to both research and non-research environments. There is critical need to open the access of these technologies and to instruct teachers across the disciplines of these fundamentals. Although the physiological principles and engineering developments strongly suggest that it is now the time to routinely monitor the spinal cord output by non-invasive high-density EMG recordings, we are failing to generalize and give access of these developments to the current generation of students, which would improve the applied translation in order to potentially predict and cure pathologies of the neuromuscular function. This has an impact, for example, on the student awareness level of some very simple points related to the correct collection of sEMG data. Issues such as electrodes location, innervation zone detection, skin preparation, movement artifacts and sweating are very often ignored.

Before coming to the most up to date sEMG technical developments, let us consider the simplest case, were one wants to describe the timing of muscle activations during the execution of a given motor task—as walking on a flat terrain—by means of bipolar sEMG recordings. Human locomotion, in its various forms, can be used as a paradigmatic example of application of sEMG to the study of dynamic exercise. Walking involves a series of coordinated movements of the body segments, implying an interplay of muscular forces and external forces (inertial, gravitational, and reaction forces) in order to achieve locomotion of the body (30). The importance of having a complete and precise description of human walking is evident: this knowledge provided significant contributions in various fields: from rehabilitation to exercise science. However, gait analysis data, to be used at their best, should be organized according to some standards.

As already pointed out by previous papers, to facilitate the systematic interpretation of sEMG gait data, stride-to-stride variability needs to be assessed before any particular stride is considered representative of subject's performance (31). Averaging multiple data will provide linear envelopes or ensemble averages of sEMG data that can then be used to identify gait deviation or changes intervening because of fatigue, a change in speed of progression or walking style [from race walking to stroke patients (32)]. It must be stressed once again that sEMG data alone are not enough, in the majority of cases, to obtain a complete and meaningful picture. Pertinent temporal parameters that should be included are walking velocity, cadence, stride time, step and stride length and duration, and double support and single support intervals.

Moreover, it would be important to associate gait parameters to the firing synchrony of multiple motoneuron pools. For example, the neural motor commands extracted from factorization analyses applied to multi-EMG recordings (33) may be analyzed at the direct motoneuronal level, by performing correlation and classification analyses to identify the unique spatiotemporal patterns (sequence of different population of motoneurons discharge timings) that are responsible for specific patterned behavior such as gait. Moreover, the identification of populations of motor neurons innervating different muscles would also allow to perform synchronization analyses revealing associations between specific motor nuclei and gait cycles. All this information cannot be extracted from global EMG estimates (i.e., EMG amplitude or conduction velocity).

It is immediately evident from the above example that an interdisciplinary approach is needed, commonly known with the term neuromechanics (34). The many interests involved produced a variety of competences and applications, but, at least in Italy, there are only scanty traces of any basic course of physics, mathematics, neurobiological data processing included in the curricula of physiatry, orthopedics, physiotherapists, and exercise/sport physiologists, which represents the potential professional users of this technique.

As described above, it is clear that to have an overview of our body in motion we must link direct cellular behavior to function. These tasks can now be achieved by the decomposition (with the use of blind source separation algorithms) of HDsEMG signals. Although the acquisition and analysis is relatively automatic, there is need of careful inspection of the signals (35). There is a large number of parameters that can be extracted from the discharge of populations of motor units and each of these parameters has a specific neurophysiological determinant. In a recent Tutorial article (35), we described the physiology and applications of these parameters. It is clear that these techniques are still relatively novel, therefore time is needed to train and grant access to everyone and assess its potential clinical utility. Specialized courses across the universities and clinical environments are needed in order to train and teach the future generation of sport and exercise physiologists, physiotherapy and clinical neurophysiology.

Another important main factor limiting the wide use of these technique is represented by the limited access to the software needed for separating the motor unit action potentials in the sEMG. Different research groups have proposed algorithms to decompose the sEMG interference signals, however, none of these approaches have been published open source. All of these problems impede the translation of HDEMG analysis to the applied field.

COSTS/BENEFITS

The aim of this short communication also includes to provide an opinion on the costs/benefits ratio regarding the use of novel sEMG techniques. First, what is meant, or better felt, by academics with respect to benefits. The probability of a work to be published is surely one of the perceived benefits. More important than this, though, is the probability to be cited a significant number of times. This, in turn, has an impact on the probability of a successful grant application. In the case of sEMG based papers this probability is limited due to the relatively small number of researchers in the field. Besides, also in sEMG parochial environment, the most cited papers are, or at least were until recently, those more technical in nature, while basic and applied physiology papers were less cited and appeared on medium level journals. As a consequence, in this specific application, basic and applied physiology have generated limited benefits to academics, both in terms of their personal achievement and in terms of financial support. It seems that this trend is now quickly (1, 20, 29) changing due to the uncontroversial advancement in sEMG technique of the last 10 years coupled to the increased power of the analytical tool specifically designed to decipher the sEMG signal (8). On the other hand, the lack of a widespread diffusion of a correct information on sEMG among professionals is still a serious drawback and this continues to prevent professionals from the routine adoption of sEMG in their evaluation protocols.

It is also to be considered that professionals need to have sEMG equipment that are feasible for the field usage. To this respect, wearable devices although promising are not fully mature, particularly on a high-density EMG scale (36).

What about benefits for companies? Selling devices to a large set of potential users is the obvious goal of a firm. In spite of this, the dissemination of information about their specific products is left mostly to standard internet channels. In our opinion, companies should increase their investments on peer to peer formation of end users provided these latter have been adequately formed by academics (see above).

Companies should also think in terms of application to sport, rehabilitation, clinical evaluation in order to increase the demand from the market. This will increase their earnings, allowing at the same time a reduction of the monetary costs for the clients, irrespective from being an academic or a professional. As a matter of fact, not only the most sophisticated and reliable equipment are somehow still very expensive (>15,000 euros for a plug-in hardware and software devices with ∼ 200 EMG channels), but so are the consumable associated with these instruments.

At the very end, it turns out that to overcome the present limitations of a large diffusion of sEMG in applied and allied sciences, a joint serious effort is needed from the many actors involved. There is not a single responsible for this situation and this, maybe, makes the problem complicated.

AUTHOR CONTRIBUTIONS

All authors contributed in equal part to conceptualization and writing of the manuscript.

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REVIEW
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Critical Appraisal of Surface Electromyography (sEMG) as a Taught Subject and Clinical Tool in Medicine and Kinesiology

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The characteristics and state of knowledge of bioelectric signals such as ECG, EEG, and EMG are initially discussed. This serves as the basis for exploration of the degree of scholastic coverage and understanding of the level of clinical acceptance of respective bioelectric signal subtypes during the last 60 or so years. The review further proceeds to discuss surface EMG (sEMG). The status of the field in terms of teaching and academic training related to sEMG is examined, and its clinical acceptance in several areas of medicine and kinesiology, including neurology, psychology, psychiatry, physiatry, physical medicine and rehabilitation, biomechanics and motor control, and gnathology, is evaluated. A realistic overview of the clinical utility of the measurement of sEMG signals and their interpretation and usage, as well as of perspectives on its development, are then provided. The main focus is on the state of the field in Croatia. EMG signals are viewed as "windows" into the function of the neuro-muscular system, a complex and hierarchically organized system that controls human body posture and gross body movement. New technical and technological means to enable the detection and measurement of these signals will contribute to increased clinical acceptance, provided current scientific, educational, and financial obstacles can be removed.

Keywords: bioelectric signals, surface electromyography, teaching, clinical medicine, kinesiology, physiotherapy, rehabilitation

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INTRODUCTION

Since its beginnings around the mid-twentieth century, the field of surface electromyography (sEMG) (1) has evolved and became established as a measurement, analysis, diagnostics, and (motor) control tool. sEMG forms part of a standard palette of methods and technologies at the disposal of scientists and professionals in a number of disciplines such as neurology, psychology, psychiatry, physiatry, physical medicine and rehabilitation, kinesiology, biomechanics and motor control, and gnathology; each discipline exploits specific features of this technique. sEMG is a component of the broader EMG field that includes subcutaneous techniques. It also is a part of the biomechanics of movement and represents a unique vehicle for monitoring the function of the neuromuscular system. sEMG offers considerable robustness, non-invasiveness, and a global view of skeletal muscle function.

Here, our aim is to critically reflect on the position of this measurement technique in both educational curricula (of primarily medical doctors, physiotherapists, and kinesiologists) and the clinical environment. The starting point of this endeavor is a discussion of the relationship of sEMG with tools that rely on the acquisition and interpretation of other types of common bioelectrical signals. In particular, the status of the field in Croatia is considered.

ON THE NATURE OF BIOELECTRIC SIGNALS AND THEIR INTERPRETATION

Changes in bioelectric potential originate in particular organs and organ systems. Because bodily tissues serve as an electrical conductor, potential changes generated spread through the body and reach the body surface, where they are amenable to detection by suitable technical means. In the following sections, the types of bioelectric signals most commonly recorded are succinctly depicted: an electrocardiogram (ECG) originates in cardiac muscle; an electroencephalogram (EEG) originates in the brain; and an electromyogram (EMG) originates in skeletal muscle(s).

The concept of membrane potential is central to bioelectric signal generation and conduction. The process of generation of change of equilibrium potential takes place at the cell membrane, which in a resting state maintains an electrical potential in the range of −40−90 mV (internal relative to external medium), the state of equilibrium being described by the Nernst equation (2, 3). When stimulated, under certain conditions, a change in potential across a membrane that reaches positive amplitude values, known as action potential, spreads along the membrane. Neural cells are electrically excitable and capable of conducting this electrical change (4). Further biophysical processes participate in transmission of electromagnetic fields, produced by bioelectric sources, through biological media (5).

Electrocardiography (ECG)

The contracting heart muscle generates electrical potentials. Numerous studies have modeled the mechanical action of heart muscle and performed bioelectric imaging (6). Clark provided a condensed, but comprehensive, explanation of the bioelectric activity of the heart muscle based on its anatomy, the types of excitable cells that comprise its functional components, and the electrocardiogram, i.e., signal waveform of electrical potential changes detected at the outer surface of the body (3). The standard 12-lead electrocardiogram recording is generally used in clinical practice.

Because cardiac contractions are a repetitive and continuous process, the ECG exhibits a characteristic quasi-periodic waveform. Since the beginnings of the analysis of the bioelectric characteristics of the heart muscle, the ECG technique has become established as a reliable, important, and practical diagnostic tool. Clinical standards have since been developed for the diagnosis of arrhythmias, ischemias, and numerous other pathological conditions.

Beginning in the 1960s, computer-aided analysis of ECG was introduced (7), and, over time, large databases of signals were established, such as the MIT-BIH Arrhythmia Database[1]. The field of computerized ECG processing (8) has developed since; as a result, ECG has acquired prominence as a clinically indispensable tool in cardiology. The ECG produces patterns that can be empirically correlated, through visual inspection by an expert, with important aspects of health.

Electroencephalography (EEG)

Since Hans Berger, a German psychiatrist, systematically analyzed the electrical activity of the brain for the first time, the EEG technique has gained prominence in neurology, contributing significantly to neurological diagnostics, and additionally proving useful in the fields of neuropsychiatry and psychology (3). The fluctuating potentials recorded represent a superposition of the field potentials produced by a variety of active neuronal current generators within the volume-conductor medium (3, 9). Extracellular potentials recorded from the cerebral cortex are to be interpreted.

Typical clinical EEG waveforms recorded using scalp electrodes (International Federation of EEG Societies 10-20 system) can be identified. Correlations exist with specific brain states (e.g., wakefulness, sleep) and specific pathologies associated with abnormal EEG waveforms. EEG frequency ranges are as follows: delta [below 3.5 Hz (usually 0.1–3.5 Hz)], theta (4–7.5 Hz), alpha (8–13 Hz), and beta (usually 14–22 Hz) (9).

Computer-aided EEG analysis has mainly been used for monitoring sleep and certain pathologic states, leaving the more difficult problem of diagnosis to the expert neurologist (7). Another potential field of application of EEG is, for example, as a brain-computer interface where EEG signals represent control signals for prostheses of extremities, as well as in a number of other areas such as the study of hypnosis.

Electromyography (EMG)

The field of electromyography encompasses both surface and intramuscular EMG: here, however we focus exclusively on sEMG. Although sEMG provides a global view of skeletal muscle function, in principle, the analysis of multielectrode recordings enables assessment of the activity of individual motor units (MU) as well (10). In addition, multichannel sEMG offers the ability to study features of multiple muscle systems. The term multielectrode sEMG is used to identify EMG detection with multiple electrodes on the same muscle, while the term multichannel sEMG comprises several bipolar recordings in several muscles.

Muscular contraction is a mechanical event involving the transformation of metabolic energy into mechanical force and power. Leaving the mechanical aspects of muscular contraction aside (11), here we focus on the electrical features of the transmission of the signal (5). Muscle action potentials may be associated with chemical processes through which mechanical energy is released. To quote Katz (2): "In muscle, the action potential, traveling at a speed of a few meters per second, serves to produce sufficiently quick 'mobilization' of the contractile apparatus in the interior of the cell."

The total bioelectric signal of a muscle is the result of spatiotemporal summation of the activity of a large number of MUs, producing what is referred to as an interference pattern. Basmajian and De Luca presented a mathematical model of

[1] https://physionet.org/content/mitdb/1.0.0/

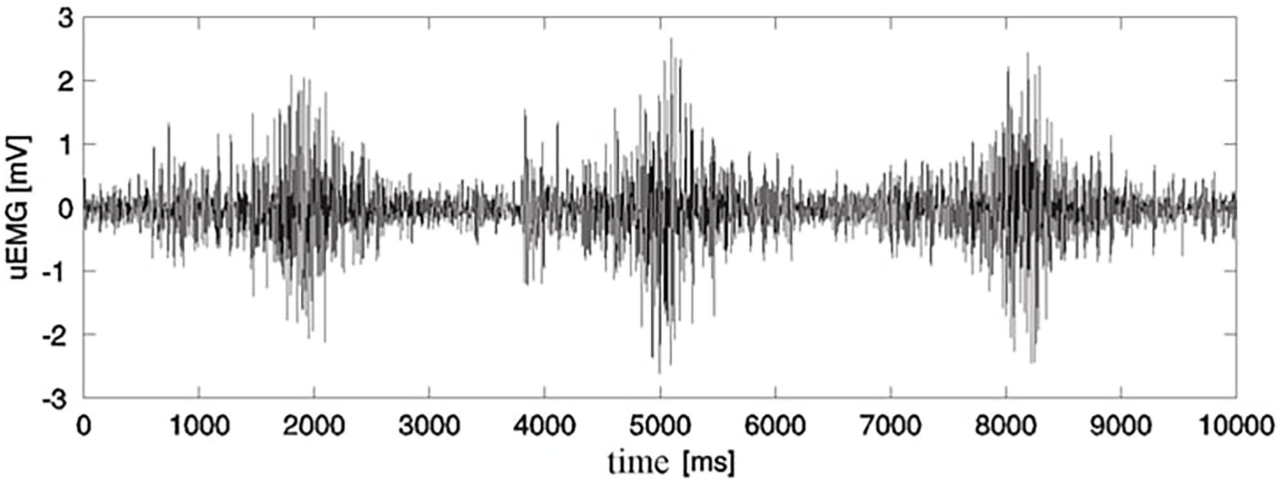

FIGURE 1 | Raw surface EMG recording for three successive contractions of m. vastus medialis during extension-flexion exercise of the lower leg (18) (Permission was received from the Faculty of Electrical Engineering and Computing for the use of this image).

the myoelectric signal (1, 12, 13). Starting from the basic physiological processes that give rise to nerve and muscle action potentials, all higher anatomical levels of integration were considered, which finally yielded a total EMG signal. This anatomically complex situation can be considered, in fact, to be a sort of mapping of a spatial (3D) process into a 1D signal (14).

Individual fiber potentials—recording of which would presuppose needle detection—sum up to represent a motor unit action potential (MUAP). A wide range of neuromuscular disorders alter the MUAP waveform in different but characteristic combinations, the interpretation of which is the domain of neurological diagnostics (14, 15). A train of motor unit action potentials is referred to as a (MUAPT). Modeling of EMG signals is a rich and well-developed research area (16, 17).

A typical sEMG signal is shown in **Figure 1** [from (18)].

Standard bipolar detection technique is assumed. Fundamental concepts pertaining to EMG signal acquisition are comprehensively summarized in (19). sEMG signals are amenable to several methods of signal processing, both in time and in the frequency domain (20). A practical overview of the technical aspects of sEMG for clinicians is given in (21).

COMMENT ON DIAGNOSTIC UTILITY OF TECHNIQUES BASED ON BIOELECTRIC SIGNALS AND THEIR CLINICAL ACCEPTANCE

The diagnostic value of ECG and EEG has been established firmly in the respective medical fields of cardiology and neurology; in addition, these techniques may be conveniently used in less clinical realms such as health kinesiology (ECG) or in brain research (EEG). It is understood, of course, that these bioelectric indicators most often form part of more comprehensive measurement and evaluation schemes in addition to other clinical diagnostics data such as CT or NMR records and relevant laboratory diagnostic results. Therefore, ECG and EEG methods may certainly be considered to represent a reliable and standard component of the so-called evidence-based medicine approach.

Compared with ECG and EEG, the field of clinical use of sEMG might seem less developed and standardized. sEMG was first considered and accepted as a relevant quantitative indicator in physical and rehabilitation medicine. In this field of application, sEMG forms a standard component of an assortment of biomechanical measures relevant for monitoring, evaluation, and (motor) learning in the rehabilitation context (22). The goal was to make this field a part of evidence-based medicine, and effective in the management of physical disabilities. In kinesiology, sEMG is accepted as a standard component of the biomechanical evaluation inventory where gross body movements are concerned (23–27). In clinical gait analysis, for example, building on the pioneering work by the Berkeley group, sEMG has been used from the very beginning (23). It preceded the later inclusion of 3D kinematic measurement methods, which have progressed rapidly to offer high levels of precision and automatization in recent times, and are successfully combined with multichannel sEMG. The same holds true also for research applications of the analysis of human motion in kinesiology and sport science.

Essentially, and assuming a quantitative relationship between sEMG and muscle force [(20, 28–33)—consideration in a broader context], it can be asserted that sEMG has become a reliable non-invasive correlate of muscle force in addition to the more basic, but less "muscle selective," means of assessing muscle force such as dynamometry, as well as to complementary methods such as mechanomyography. Recommendations for EMG measurements, processing (34–36) and interpretation (37) have been provided. As a result of advances in multielectrode sEMG [high-density sEMG (HD-sEMG)] recording techniques, further possibilities have emerged, both for research and for clinical applications (38–41).

SCHOLASTIC COVERAGE OF BIOELECTRIC SIGNALS

Measurement and interpretation of bioelectric signals, and of sEMG in particular, is a technical issue whereby a measurement method is applied to human subjects. Besides carrying diagnostic information, sEMG also may serve as a control variable (biofeedback, prostheses). It can therefore be explained and understood most thoroughly—both theoretically and practically—assuming a biomedical engineering (BME) perspective. We begin this section with a short comment on BME education, both worldwide and in Croatia, focusing later on education of medical doctors, physiotherapists and kinesiologists.

An inter- and multi-disciplinary approach to education is integral to the field of biomedical engineering. In Germany, between the two World Wars, and in the USA, especially after the World War II, independent university programs in the field of biomedical engineering were established. As a part of these efforts, DeClaris and Newcomb stated in the 1980s the need for biomedical engineering students to adapt traditional engineering knowledge of circuit theory toward systems theory in order to link them to physiological concepts more easily. Engineering analysis and design methods had to be adapted to the solution of problems related to biological systems (42). Biomedical engineering (bioengineering and clinical engineering, including medical physics) is today an established profession with a significant labor market. There are over 300 accredited biomedical engineering schools and university departments in the USA today, offering biomedical engineering programs at several levels up to a Ph.D.[2]. The field has undergone significant and rapid development worldwide.

At the beginning of the 1980s, at the Department of Biomedical Engineering, Johns Hopkins University School of Medicine, Baltimore, Maryland, USA, for example, the undergraduate curriculum for medical doctors already featured some basic concepts in the technical (engineering) sciences such as signal and systems theory and feedback control systems theory (43). These concepts were useful to medical students by enabling a better understanding of complex physiological systems, as has been recognized previously when explaining the necessity for teamwork in neurological diagnostics (44). We note that we are aware of the differences in university education in the USA and Europe for prospective medical doctors, wherein students in the USA, owing to the "pre-med" B.Sc. level study, have more opportunities to acquire broad-based knowledge.

In the current academic curricula, primarily for biomedical engineers, but also, to a lesser degree, for non-engineers (medical doctors, physiotherapists, kinesiologists), the issues of measurement and signal processing methods for all types of bioelectric signals (ECG, EEG, EMG, and others) are successfully covered. In addition to classical mathematical signal processing methods, which are commonly taught in engineering schools, numerous advanced methods, such as data mining, neural networks, artificial intelligence, and advanced statistics, are included. Further, there is no discrimination between applicability to ECG, EEG, and sEMG in this respect. It is understood that each of these signal subtypes is treated in accordance with the specificities of its domain of application. Numerous textbooks that cover these fields are available, e.g., Sornmo and Laguna (45), Begg and Palaniswarmi (46), Shiavi (47), Glaser (48), (an update of a classic Glaser and Ruchkin book by Academic: New York, from 1976), Akay (49); other books on sEMG and biomechanics specifically have already been pointed out in the previous section.

In Croatia, unlike in neighboring countries, no formal biomedical engineering educational programs are available to date; in contrast, in Italy and Slovenia, the BME field, including BME education, is highly developed. In Slovenia, the example of the Vodovnik group tradition from the late 1960s onward (50, 51) in the area of cybernetics in medicine may be considered, witnessed today by the organization of the forthcoming EMBEC 2020 symposium in Portorož, Slovenia[3], with the Slovenian Society for Medical and Biological Engineering acting as a co-organizer. However, an initiative was launched at the University of Zagreb in 2012, namely the Coordination Committee for Development of Biomedical Engineering, which is formed of representatives from various departments and institutes. Only in 2019 was an adequate program designed with the goal to develop the first university program in BME, satisfying the standards for professional training and qualification (52). The pre-requisites for this kind of program have been designed through extensive activity at various university departments and institutes across Croatia, which have been loosely coordinated by the Croatian Biomedical Engineering and Medical Physics Society (CroBEMPS) based in Zagreb. The Society encompasses divisions of clinical engineering, medical physics, and biomechanics.

At present, teaching activity in the area of biomedical engineering and physics in Croatia is accomplished mainly through a number of graduate and post-graduate mandatory and elective courses, at several university departments. In the respective courses, in addition to teachers with an engineering background (and a science background where appropriate, e.g., in the case of physicists and chemists), teaching staff with a biomedical background participates, including those with clinical expertise.

The subject of sEMG is included in the curriculum of human locomotion study, with biomechanical approaches being pursued. At the University of Zagreb, the subject of locomotion is covered rather well, and includes courses at both the under- and the post-graduate level at several departments: the Faculty of Kinesiology, the School of Medicine, and the Faculty of Electrical Engineering and Computing, as well as at a couple of

[2]https://www.educationnews.org/career-index/biomedical-engineering-schools/

[3]www.embec2020.org

other institutions (53). Relevant programs are pre-dominantly internet accessible[4,5,6,7,8].

Adequate laboratory facilities exist in Zagreb and in Pula, and, to a lesser degree, also in Split and Rijeka. Examples of undergraduate elective courses at the University of Zagreb are: Multisensor systems and locomotion[9] and Measurement and analysis of human locomotion[10]. The teachers combine expertise from research and university teaching; furthermore, in the second mentioned course, expertise is additionally derived from clinical fields such as neurology, orthopedics, physical medicine and rehabilitation.

During undergraduate study at all medical faculties (Zagreb, Osijek, Rijeka, and Split) future physicians are introduced to EMG as an electrophysiological diagnostic method and its significance in treatment and rehabilitation in the fields of taught neurology, physical medicine, and general rehabilitation, as well as pediatrics[5,11,12,13]. Both surface and intramuscular EMG are covered. Academic specialization for future specialists of physical medicine and rehabilitation follows the rulebook on specialist training of doctors of medicine, with a specialization in physical medicine and rehabilitation, which is compatible with the program of the European Union of Medical Specialists (UEMS) and the European Board of Physical and Rehabilitation Medicine (54). During residency as well as post-graduate study in physical medicine and rehabilitation and in neurology, medical doctors become familiar with electromyoneurography (EMNG) as a diagnostic method, its method of implementation, interpretation of findings, and its implementation in a therapeutic program (drug therapy, physical therapy, or rehabilitation). In addition to lectures, clinical practice in the EMNG laboratory is a mandatory part of training. Medical doctors (neurologists, physiatrists, and pediatricians) who wish to practice EMNG attend training with experienced electromyography trainers at referral centers for the treatment of neuromuscular diseases, usually for a period of 3 months, after which they take an examination to become certified for independent work. University neurological clinics in Zagreb and Split offer an ongoing training possibility of this type. Further, in the curriculum of specialist post-graduate studies for physical medicine and rehabilitation, residents learn about the latest advances in and indications for the therapeutic use of EMG and biofeedback (54).

[4]https://www.kif.unizg.hr/en/study
[5]https://mef.unizg.hr/studiji/diplomski/integrirani-preddiplomski-i-diplomski-studij-medicine/nastavni-plan-i-program
[6]https://mse.mef.unizg.hr/medical-studies-in-english/curriculum
[7]https://mef.unizg.hr/studiji/poslijediplomski/doktorski/phd-programme-in-english
[8]https://www.fer.unizg.hr/en/study_programs
[9]https://www.fer.unizg.hr/en/course/msal
[10]https://mse.mef.unizg.hr/medical-studies-in-english/curriculum/courses?studij=Medicina%20(na%20engleskom%20jeziku)&kol=3416&kolegij=Measurement%20and%20Analysis%20of%20Human%20Locomotion&pid=156
[11]https://www.medri.uniri.hr/hr/nastava.html
[12]http://www.mefos.unios.hr/index.php/hr/studij/sveucilisni-integrirani-preddiplomski-i-diplomski-studij-medicine
[13]http://www.mefst.unist.hr/studiji/integrirani-studiji/50

Physiotherapists in Croatia complete the physiotherapy studies at the University of Applied Health Sciences in Zagreb (Zdravstveno veleučilište; although named in English "University" this is a polytechnic level school in Zagreb, it is not a university level institution) after which they receive the title "Professional Bachelor of Physiotherapy (baccalaureus)," abbreviated as bacc. physioth. Additional education through the Specialist Professional Study for a period of 2 years confers the title of Bachelor of Physiotherapy or Master of Physiotherapy[14]. In course of their studies they acquire knowledge on sEMG and the skill of its application in biofeedback therapy as a part of rehabilitation. Also, they get elementary information on EMNG as a diagnostic method, as well as on application of sEMG as a subject in locomotion biomechanics course. They cannot automatically become assistants in EMNG laboratory, but may get additional education with a mentor, lasting 2 months, which they usually master easily due to good knowledge of functional anatomy of the neuro-muscular system.

At the Ph.D. level of studies, the subject of sEMG is taught primarily at the University of Zagreb (kinesiology, medicine, electrical engineering and computing), but is also included in a number of courses at other universities. Doctoral studies in kinesiology at the University of Zagreb may be taken as an example (55) where the subject of sEMG is covered in detail in a couple of courses on biomechanical aspects of human movement and exercise. Another particular example is the course Biomechanical and neurophysiological mechanisms offered by the Faculty of Electrical Engineering and Computing[15]. There is no Ph.D.-level study for physical therapists in Croatia to date; therefore, these professionals usually engage in Ph.D. programs in the fields of medicine or kinesiology. (Latest news tell about a so-called bridge program enabling them to pursue doctoral studies at the Faculty of Medicine, University of Rijeka and Faculty of Kinesiology, University of Zagreb, assuming several difference examinations.) In the absence of data on the actual numbers, it is not clear how many physiotherapists hold a doctorate in kinesiology or medicine, anyhow, they are amenable to pursue an academic career. It is worth mentioning that the University of Applied Health Sciences in Zagreb strives toward attaining a university level.

Employees of the Department for Rehabilitation and Orthopedic Devices University Clinical Hospital Zagreb participate in both undergraduate and post-graduate teaching of students of the School of Medicine, deliver classes for physiotherapists, occupational therapists, and nurses of the University of Applied Health Sciences, and collaborate in teaching delivered to students of the Faculty of Kinesiology, Faculty of Education and Rehabilitation Sciences, and Polytechnic (Tehničko veleučilište) in Zagreb. The Department further provides education for specialists in orthopedics, traumatology, and physical medicine and rehabilitation, as well as compulsory internships for B.Sc. degree students in physiotherapy, occupational therapy, and nursing. In offering education in the fields of prosthetics and orthotics, the

[14]as documented in: https://www.zvu.hr/?lang=en
[15]https://www.fer.unizg.hr/en/course/banm_a

Department collaborates with ISPO-Croatia (International Society for Prosthetics and Orthotics) and Human Study e.v., and with the Polytechnic in Zagreb.

A short overview of biomechanical research in Croatia, encompassing activities at the Faculty of Kinesiology and the Faculty of Electrical Engineering and Computing, University of Zagreb, and at the Peharec Polyclinic in Pula, appeared in the International Society of Biomechanics (ISB) Newsletter (56). The situation has since improved owing to the availability of partially equipped facilities for human motion measurement and analysis at the universities of Split and Rijeka.

There is, evidently, a striking difference between the training physiotherapists get compared to the other two categories; engineers and medical doctors. What would be needed in the first place is to have laboratory facilities better equipped (if equipped at all). Their curriculum includes courses on anatomy, physiology and biomechanics but in general there is a lack of well-equipped laboratory facilities. So, often, practical laboratory subjects such as sEMG measurement and analysis are organized through visits to a well-equipped laboratory of a collaborating institution (from which also visiting professors usually participate). So, although formally being a part of teaching program, various signal processing methods in time domain and in frequency domain can only be demonstrated and not practiced and thus acquired by students themselves. Laboratories, that are situated in other institutions (clinics, faculties) normally have a qualified professional staff including clinical engineers. Basic biomechanics and sEMG in physiotherapy schools is typically thought by a couple of teachers: a physiotherapist and an electrical or computer engineer.

Our experiences, and of some of our colleagues indicate that the acceptance of physiotherapy students of modern technology is good and that with better teaching conditions they would accept these, sometimes rather requiring technical protocols, and profit from it. There is no doubt that this kind of improvement in working conditions would have positive long-term consequences on the work of future physiotherapists, and that their clinical competences would also improve. In general, at present, adequate courses and upgrades for professors of physical therapy, on the subject of sEMG and other relevant medical technology, would be useful.

OVERVIEW OF THE CLINICAL ACCEPTANCE OF sEMG

There is no doubt that sEMG is a valuable research vehicle. In this section we address typical applications of sEMG suitable for clinical use. Although each of these applications possesses a capacity for a clinical method, the same is being realized in various degrees, depending on methodological, financial and/or other issues. There are rather stringent requirements for a clinical method: it should possess reliability, validity, sensitivity and specificity, all features being subject to verification by appropriate clinical testing and confirmation by relevant statistics. The clinical acceptance of sEMG is a key issue addressed in this paper. We explore the contribution of sEMG data to diagnostic, evaluation, treatment, (motor) control, and/or (motor) learning procedures taking place, primarily, in hospital wards where sEMG measurement equipment is available, because these factors determine its clinical acceptance. In addition, the equipment must have a satisfactory level of user-friendliness to be accepted by the staff.

In general, the neuromusculoskeletal system is amenable to a number of measurement techniques, including "muscle-centered" ones such as dynamometry, mechanomyography, ultrasound, and thermography. In the broader context, standard neurophysiological, physiological (physiology of activity, i.e., exercise physiology and sports medicine), and biomechanical methods are available. Electromyography is one of the well-established "muscle-centered" techniques. Although needle EMG (NEMG) has undisputed value in the neurological diagnostics of muscular diseases, it will not be discussed here, and we continue with the overview of sEMG applications.

In 2000, The American Academy of Neurology stated that more than 2,500 original articles, reviews, and books investigating the utility, techniques used, and clinical application of sEMG had been published (57). As a diagnostic measure, sEMG has been reported to be inferior to NEMG for evaluation of patients with neuromuscular disorders because of its limited spatial resolution, susceptibility to mechanical artifacts, and tendency for cross-talk between adjacent muscles. The authors considered sEMG an acceptable tool for kinesiologic analysis of movement disorders, and also found it useful in differentiating many types of tremors, myoclonus, and dystonia, for evaluating gait and posture, and performing psychophysical measurements of reaction and movement time (57). Because several technological advancements have been made since, we discuss typical methods and procedures in operation today where sEMG is used as a suitable quantitative tool for evaluation, diagnosis, and/or treatment of a particular human health condition or assessment of motor performance level. The clinical prominence of methods is of interest. We also refer, in particular, to the situation in Croatia.

Polysomnography (PSG)

A laboratory-based nocturnal polysomnography (PSG) method involves simultaneous recording of multiple physiologic variables related to sleep and wakefulness. PSG is the most commonly used test in the diagnosis of abnormalities of sleep and/or wakefulness, and can directly monitor and quantify the number of respiratory events (obstructive, central, or complex) and the resultant hypoxemia. In addition, it is useful in treating sleep disorders from a psychiatric or neurologic (sleep-related epilepsy) viewpoint. Assessment of sleep stages requires EEG, electrooculography (EOG), ECG, pulse oximetry, respiratory effort measurement (thoracic and abdominal), end tidal or transcutaneous CO_2, sound recordings to measure snoring, continuous video monitoring, and sEMG. One sEMG channel, usually chin or mentalis and/or submentalis, is used to record atonia during REM sleep or lack of atonia in patients with REM-related parasomnia. To assess bruxism, sEMG electrodes can be placed over the masseter. sEMG analysis of intercostal and abdominal muscles may be conducted to determine effort during respiratory events. sEMG recording for monitoring of limb muscles (tibialis anterior) is used for assessing periodic limb movements and restless legs syndrome (58, 59).

In Croatia, the PSG method is routinely used in both adults and children, in neurology clinics and pediatric clinics of clinical hospital centers in Zagreb, Rijeka, Split, and Osijek. Furthermore, it is used in the clinic in which pulmonary diseases are treated of the University Hospital Center Zagreb (Jordanovac) (60), a pediatric clinic in Zagreb, a pediatric hospital for pulmonary diseases in Zagreb (Srebrnjak), psychiatric hospitals (Rab, Vrapče), and a number of private polyclinics in Zagreb, Split, and Rijeka. As far as we are informed, there are no problems (technical, methodological) with implementing sEMG within polysomnography and using the available information in clinical context.

sEMG in Biofeedback

Biofeedback is a self-regulatory procedure through which patients are given feedback that enables them to develop control over their physiological functions through the provision of real-time data (61). Scientists and clinicians have used sEMG feedback as a tool when treating various medical disorders. Early studies on neurological disorders, such as torticollis, and in neurologically damaged patients have been reported (62–64). Psychosomatic diseases and functional disorders have also been targeted as a potential area for therapeutic interventions based on sEMG.

The first therapeutic applications of sEMG in biofeedback (sEMG-B) in psychiatry were carried out in the late 1960s. The goal of the treatment was to achieve relaxation, as a principal or adjunct mean of therapy (65). One study in 1991 evaluated the relationship between task performance and extrapyramidal effects of medication among psychiatric patients in a short-term stay psychiatric hospital, using sEMG-B. (66). Patients performed worse than healthy subjects in the psychophysical judgment task, showing impaired ability to make accurate psychophysical judgment, i.e., difficulty learning a biofeedback task that requires this skill.

sEMG signal is the most common physiological variable monitored using biofeedback, and is used in a variety of disorders such as tension headache, chronic pain, spasmodic torticollis, and temporomandibular joint dysfunction. EEG feedback, which is also called neurofeedback, is used in attention deficit hyperactivity disorder (ADHD) and epilepsy, and is increasingly the focus of research and other applications. Other commonly monitored variables are used when the aim of biofeedback is to reduce sympathetic arousal (heart rate, respiration rate, skin surface temperature, skin conductance, and heart rate variability).

Efficacy ratings for biofeedback training for various medical conditions have been reported in a previous study (67). Based on the Task Force of the Association for Applied Psychophysiology and Biofeedback and the Society for Neuronal Regulations' criteria, five levels of evidence-based clinical efficacy are defined: not empirically supported, possibly efficacious, probably efficacious, efficacious, efficacious and specific. sEMG has shown to be both efficacious and specific for female urinary incontinence; further, sEMG has been shown to be efficacious for anxiety, ADHD, chronic pain, constipation in adults, epilepsy, headache in adults, hypertension, motor sickness, Raynaud's syndrome, and temporomandibular disorders (TMDs). In alcoholism or substance abuse, arthritis, diabetes mellitus, fecal incontinence, headaches in children, insomnia, traumatic brain disorder, urinary incontinence in males, and vulvar vestibulitis, sEMG has been shown to be probably efficacious (67). Furthermore, the efficacy of biofeedback in psychiatric disorders specifically was confirmed for treatment of chronic anxiety, generalized anxiety disorder, panic disorders and post-traumatic stress disorder (PTSD) (68).

sEMG-B finds important applications in the field of rehabilitation: the signals are fed back to the patient, allowing patients to self-identify their muscle activity (69, 70). This is the most widely used and well-understood method of biofeedback, and has been shown to be useful in both musculoskeletal and neurological rehabilitation. The majority of biofeedback therapy is applied in the treatment of upper limb and lower limb motor deficits in neurological disorders. It can be used to either increase activity in weak or paretic muscle, or to facilitate a reduction in tone in a spastic one. It has been used since the early 1970s to improve gait, treat swallowing disorders, and enhance upper extremity function (71, 72). In daily clinical practice, sEMG is most frequently used in the treatment of weak or paretic muscles due to peripheral nerves injuries, as part of physical therapy, in order to increase their activity and strength. sEMG has additionally been used in the post-operative rehabilitation of surgically treated nerve injuries, as well in non-operated ones. Before visual or even palpable contractions occur, sEMG-B can provide valuable feedback to the patient and guide rehabilitation focused on sensorimotor re-education. However, complete therapeutic effectiveness can be achieved when the patient's voluntary muscular contractions occur (even in trace). By using sEMG-B therapy, both the therapist and the patient are provided with precise information about desirable and undesirable strategies for motor task execution aimed at improving muscle force and fine motor skills (73).

sEMG-B has demonstrated its usefulness in improving muscular torque and muscle recovery, as an addition to a conventional exercise program (74) such as that targeting the quadriceps femoris muscle after knee surgery or anterior cruciate ligament reconstruction (75), meniscectomy (76), arthroscopic partial meniscectomy (77), and in the treatment of pain due to excessive muscular tension (73). In order to reduce muscle tonus, sEMG-B has been used in spastic patients, both for the rehabilitation of hemiplegic adults after stroke, and in children with cerebral palsy (CP). Several studies have evaluated the effectiveness of biofeedback treatment on gait function in children with CP, e.g., sEMG-B of triceps surae muscle activity during gait, which may be used for improving gait symmetry in these patients (78, 79). Another group of authors has demonstrated the potential benefits of sEMG-B in conjunction with exercise in maximizing hand function in hemiplegic patients (80–82) or suggested that treadmill gait retraining augmented with sEMG-B facilitates improvements in gait function in post-cerebrovascular accident patients (83). These studies therefore indicate that sEMG-B is effective for post-stroke rehabilitation.

There is indeed a large number of medical conditions for which sEMG-B can be applied. In addition to those already mentioned, spinal cord injuries and low back and neck pain can also be addressed using this tool (84). The essence of the technique is illustrated well by the following statement: "A biofeedback device can be thought of as a sixth sense which allows the subject to 'see' or 'hear' physiological functions. Biofeedback can also be described as a 'psycho-physiological mirror' providing subjects with a way to monitor the physiological signals produced by the body and learn from them to self-regulate a targeted pattern of physiologic functioning" (85).

Gallina et al. (84) introduced multi electrode recording techniques into the field of sEMG-B, making this technique potentially more intuitive and specifically adapted to the patient. Research in the field is oriented toward clinical application (86).

sEMG-B is applied in clinical praxis in Croatia, in all adequately equipped physical therapy units across the country. As far as we are informed, this is maybe the most traditional use of sEMG in medicine and is successfully being applied across the country to aid in various disturbances and diseases.

sEMG in the Evaluation of Muscle Coordination

Although still pending clinical application, the evaluation of muscle coordination by means of sEMG signals deserves to be mentioned. This kind of application is pre-dominantly research-based in nature, and involves the measurement, processing, and correlation of myoelectric signals of several muscles that are co-active in performing a certain movement. A possible use is in sports research, where smoothed (full-wave rectified and low-pass filtered) sEMG signals that represent correlates of muscle forces may be used to quantify the degree of muscular coordination when performing a motor task, as has been performed in artistic gymnastics for example (27, 87). This approach has been used for quantification of the skill and performance level of a specific movement pattern, and has demonstrated the possibility for use of multichannel sEMG signals as indicators of the co-ordination patterns of multiple muscle forces associated with particular movements. Further, it offers possibilities for monitoring the progress in motorics during the course of particular diagnostics and/or treatment procedures in rehabilitation medicine.

Another possible application of muscle coordination evaluation is in the control of prostheses (section Myoelectric Prostheses).

Taborri et al. (88) performed a systematic review of the feasibility of muscle synergy outcomes in clinics, robotics, and sports. The muscle synergy concept underlies the ability of the central nervous system to control a large variety of muscles, via their simultaneous activation rather than individually, thus reducing the dimensionality of muscle control. It represents the continuation and further development of motor control concepts, which were originally conceived by Bernstein (the Moscow School of Biometrics) who developed a hierarchical multilevel model of organization of the system controlling voluntary movement and proposed the topic of many degrees of freedom in motor control (89). A number of studies have demonstrated that muscle synergies are robust across different tested conditions, within a period of a day as well as between days; within a single subject, and between subjects that have similar demographic characteristics. Taborri et al. (88) provide information for diagnosis or pathology assessment in clinics. A review of the available papers published between 2006 and 2017 was performed, taking into consideration only publications that provided results that were potentially useful for improving neuromuscular diagnosis and rehabilitation assessment for locomotion, balance, and upper limb functions. The pathologies addressed were locomotion and balance disturbances, CP, spinal cord injury, Parkinson's disease, stroke (quantifying abnormalities in modular muscle coordination; quantifying effects of therapy on muscle synergies; elucidating neural mechanisms of post-stroke muscle coordination), upper limb function, and pain. This indicates great, yet insufficiently explored possibilities that multiple EMG signals serve as "windows" into the function of the neuro-muscular system.

To the best of our knowledge, in Croatia, the above-mentioned issues are not currently being investigated, nor have they achieved clinical application at present. Our own experience includes the series of research projects investigating biomechanical and neuro-muscular aspects of complex movements, including sEMG correlates of (loco)motor skill. We have explored the issue on sportive movement patterns as a model of entrainment and skill acquisition (27, 87). Although having arrived at suitable quantitative measures of skill for a particular movement pattern, we did not standardize it to be usable as a clinical measure. Potential fields of application are neurorehabilitation and control of neuroprostheses.

sEMG-Based Evaluation of Local Muscle Fatigue

A distinct area of application of sEMG signals is in evaluating local muscle fatigue. This feature is based on the inherent property of a myoelectric signal to reflect the physiological status of fatigue in a muscle during muscular work. The phenomenon was first noticed as early as 1912 (90), and has subsequently been investigated and quantified extensively (18, 91, 92). Appropriate signal processing procedures, pre-dominantly in the spectral domain, have been defined, and shown to be able to quantify fatigue during static as well as dynamic contractions, as well as during electrically stimulated muscle activity (1, 13, 33, 71, 92, 93).We also additionally investigated the phenomenon during isometric and dynamic contractions primarily in the course of physical exercise and sports performance, and developed signal processing algorithms (27, 94–98) (**Figures 2**, **3**).

Further development of the signal processing methodology (99) is aimed toward clinical applications, in particular, in the pathology of low back pain (100–102). Another example of our research in the field of muscle fatigue is in the sport of table tennis, to be applied in the optimization of sports training (96).

In Croatia, despite being rather practical for application, the sEMG technique, to our knowledge, is not yet routinely applied

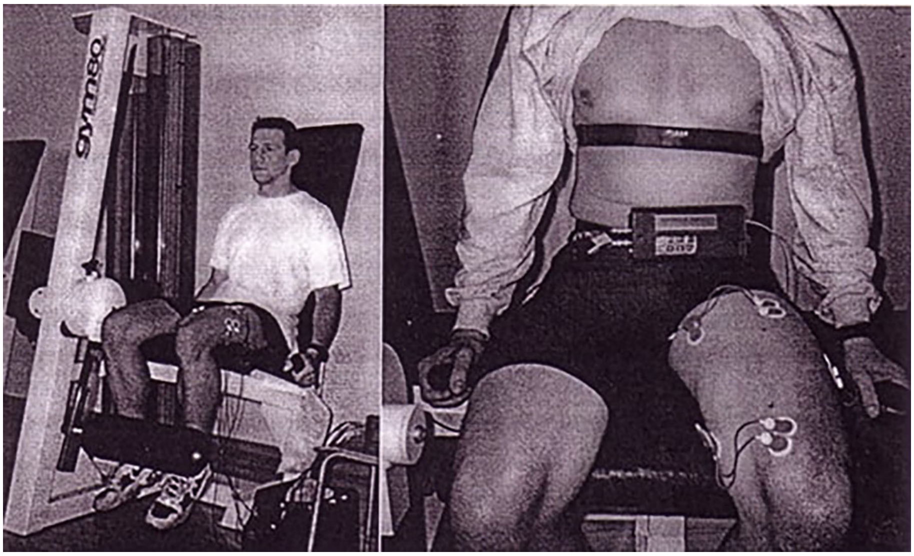

FIGURE 2 | Investigation of local muscle fatigue during lower extremity extension-flexion exercise under loading (18). Subject ready to perform repetitive extension-flexion exercise of lower extremity under loading to induce fatigue (Permission was received from the Faculty of Electrical Engineering and Computing for the use of reproduced image. Written informed consent was obtained from the experimental subject for the publication of identifiable image).

in clinical settings for evaluation of muscle fatigue, whether in a rehabilitation or a sports training context. We believe this is partly attributable to difficulties related to the standardization of mathematical signal processing methods to evaluate fatigue under conditions of dynamic contractions. Our own experiences include using the method in various movement patterns related to physical exercise and sports activities, as referred to before. Croatian BME group did have plans to design a practical and versatile method, supported by smart phone and suited for outdoor applications. So one may conclude that this method fails shortly to satisfy requirements of a clinical muscle fatigue evaluation method. But, we are of the opinion that perspectives are rather good.

sEMG in Clinical Gait Analysis

The general fields of kinesiology, biomechanics, and motor control have witnessed the widespread use of sEMG as an important indicator in the quantitative characterization of movement patterns, both healthy and pathological. In combination with kinematic and kinetic measurement data, multichannel sEMG forms a standard component of instrumental setups in motion analysis laboratories aimed at measuring human posture and movement, including gait. It can typically be found in hospitals, orthopedic wards, pediatric clinics, physical medicine and rehabilitation settings, sports medicine clinics, as well as in research institutes and university departments (23, 103–106).

In the referred literature, books, as well as in hundreds of papers, the clinical value of gait analysis is undisputedly documented, although uncertainties and limitations do exist that are well-known to the biomechanics and motor control community; however, a review of these is beyond the scope of our paper. sEMG information, which is typically obtained in the form of an 8 or 16 channel telemetrically obtained record, certainly bears its value and represents a component of a valid comprehensive gait report (107) (**Figure 4**). In the applications like this one, sEMG enables elucidating muscle involvement and co-ordination in performing a task of walking. In pathological situations manifested with gait abnormalities multichannel sEMG adds valuable information.

Whether a particular gait analysis requires sEMG data is specific to the problem at hand; sometimes, only kinematic and kinetic information suffices.

Critical appraisal of the situation in Croatia, however, shows that clinical gait analysis is only provided by the Peharec Polyclinic in Pula. Although the necessary equipment and expertise exist at the Faculty of Kinesiology, University of Zagreb, and despite adequate experience in research applications: kinematics and kinetics in (108), kinematics, kinetics, and sEMG in (109), for example, gait analysis has not been implemented at the clinical level as of yet. One of the reasons are financial and organizational constraints, i.e., the lack of qualified staff required to operate such a facility. To meet international standards, the operation of this kind of unit requires appropriate staff, available at a full-time and/or a part-time basis, with multidisciplinary competencies. For a clinical gait analysis laboratory, such staff would ideally include a director, manager, gait analyst, biomechanist, technician, clinician, and clerical officer (105). But, due to the existence of a number of clinical centers, and with about one million of people gravitating to the Zagreb area, there is a high probability that soon clinical gait analysis might be realized and included into the pallete of diagnostic methods in health care and in sport science.

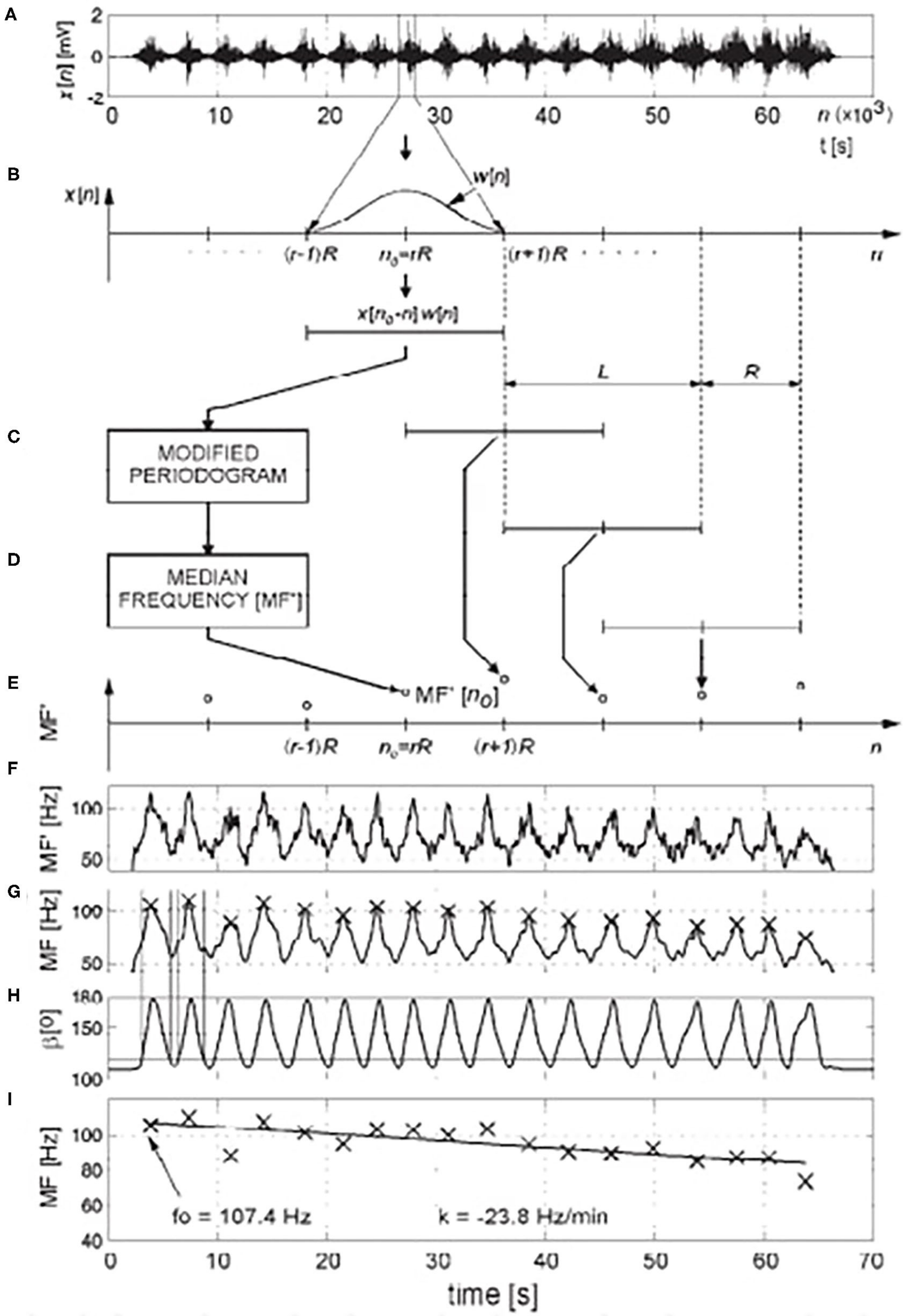

FIGURE 3 | Investigation of local muscle fatigue during lower extremity extension-flexion exercise under loading (18). Myoelectric signal spectral analysis for quantification of muscle fatigue during dynamic contractions: **(A)** sEMG signal x[*n*], raw data; **(B)** extracted data, using window sequence w[*n*] of length L, with shift of

(Continued)

FIGURE 3 | R samples **(C–E)** estimation of median frequency (MF') using modified periodogram of windowed sequence, **(F)** course of median frequency (MF'), **(G)** after low-pass filtering, maximum values of MF during each contraction were calculated, **(H)** limits of contractions were calculated using shaft angle data, **(I)** the slope of the regression line (*k*, expressed in Hz/min) that fit maximum values of MF in a least-square sense was used as a fatigue index. From the regression line, the frequency at the beginning of exercise (f_0) was calculated (Permission was received from the Faculty of Electrical Engineering and Computing for the use of reproduced image).

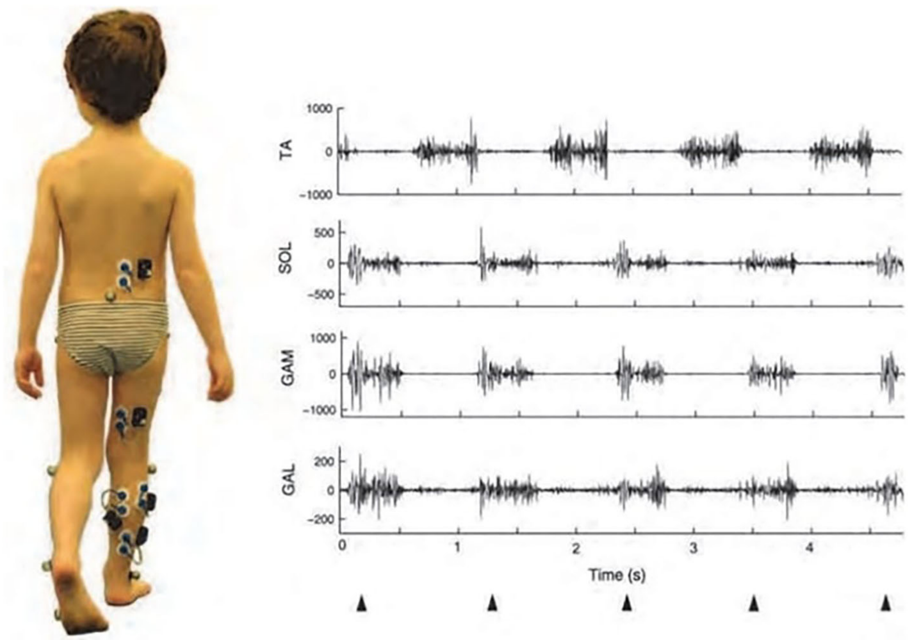

FIGURE 4 | sEMG recording in a 5-year-old child during gait, as a component of a comprehensive gait report. The picture on the left shows the electrodes and the self-powered cases, each of which was provided with a pre-amplifier and antenna for independent transmission of myoelectric signals. Traces on the right-side are illustrative examples of EMG activities recorded from the tibialis anterior (TA), soleus (SOL), gastrocnemius medialis (GAM), and gastrocnemius lateralis (GAL) during a tiptoe walking task (107). Triangles below the diagrams indicate first contacts of the foot with the ground (Permission obtained from Clinical Biomechanics for the use of the image).

Myoelectric Prostheses

The modern field of design, development, and application of prostheses of extremities is highly technologically complex. Here, we do not provide a comprehensive overview, but explore some important points. In the context of myoelectric prostheses, sEMG undoubtedly plays an important role: since cybernetics was first conceptualized by Norbert Wiener, sEMG forms a natural connection between a biological and technical sub-system of a "man-prosthesis" system. Childress (110) illustrates the historical aspects of development of powered limb prostheses up to the 1980s, while examples of modern approaches are presented in (111–115).

Motorized prostheses are typically controlled with sEMG data recorded on the residual muscles of amputated limbs. However, the residual muscles are usually limited, especially after above-elbow amputations; as a result, sufficient sEMG signals for the control of prostheses with multiple degrees of freedom cannot be obtained. Signal fusion is a possible approach that may be applied to resolve the problem of insufficient control commands, wherein some non-EMG signals are combined with sEMG signals to provide sufficient information for motion intensity decoding. One possible solution is to combine sEMG and EEG, in order to improve the control performance of the upper limb. Prosthetic hands differ in their complexity and components with some offering different grip patterns (adjustable by external means). Although myoelectric components of the prosthetic hand, wrist, and elbow are available, and various combinations of myoelectric-controlled components with body-powered components to control shoulder and/or elbow function can be created, optimal results are achieved for below-elbow amputation. For proper control of the prosthetic hand, the evaluation for possible muscle or nerve damage of the stump must be performed; then, the selection and calibration of the most effective electrode site on the clear silicone test socket fitting must be carried out using an adequate tester or sEMG analysis.

With regard to the status of the field in Croatia, other parts of the former State have, in the past, made greater creative contributions to the field; these include The Belgrade Hand by Tomović (110) and the previously mentioned Ljubljana Vodovnik group as examples. A series of meetings titled

"Advances in External Control of Human Extremities" were held in Opatija and Dubrovnik; in Opatija, Norbert Wiener himself once participated.

In Croatia, the field subsequently progressed through implementation of available technical solutions, and myoelectric prostheses have been used since the 1990s, during the rehabilitation of war amputees at the Department for Rehabilitation and Orthopedic Devices University Clinical Hospital Zagreb in Zagreb, using Otto Bock products (Otto Bock HealthCare GmbH[16]). Subsequently, these prostheses became available in other rehabilitation units as well (Osijek, Rijeka) (116).

We may critically value current status of the field of myoelectric control in Croatia as a branch providing standard routine service in realms of health care, with—as far as we know—no efforts in pursuing novel solutions potentially possible based on modern technology. But, as in recent years collaboration between university institutes and small electronic and mechatronic firms rose, it is possible that some advancements to the field will come.

sEMG in Gnathology

Gnathology is the study of the masticatory system, including physiology, functional disturbances, and treatment. In this field, Klasser and Okeson (117) have provided a comprehensive review of the literature regarding the scientific support for the use of sEMG in diagnosing and treating TMDs. Articles on the clinical utility of sEMG based on reliability, validity, sensitivity, and specificity of the results were included. The gold standard used to identify the presence or absence of TMD, or one of its subcategories, involves a comprehensive evaluation of the patient's history and clinical examination supplemented, when deemed appropriate, with imaging. After critically reviewing the relevant biological variables, the authors concluded that measurement of sEMG is inherently problematic, with many limitations, and thus has questionable value. The clinical use of sEMG in the diagnosis and treatment of TMDs has been found to be of limited value when one considers reliability, validity, sensitivity, and specificity of the measurement standards. sEMG does not appear to contribute any additional information beyond what can be obtained from the patient history, clinical examination, and, if needed, appropriate imaging. In conclusion, while sEMG has been found appropriate as a research tool, its clinical usefulness has been found restricted mainly to the area of biofeedback training.

In Merlo et al. (118), a sEMG-based method was devised wherein muscle contraction onset periods were computed by a wavelet-based method for muscle on-off detection, which proved suitable for clinical applications and is completely automated. It was applied in (119) in a clinical study of chewing problems in children and their correction. sEMG was recorded simultaneously with chewing kinematics, and, after processing, the data were used for evaluating coordination between the bilateral masseter muscles. Authors reported the correction of the malocclusion with a functional appliance, resulting in a favorable change in the neuromuscular control of chewing among patients, who recovered a normal-like coordination between the masseter muscles during chewing and a significant reduction of the reverse chewing patterns.

Although the issue of the clinical usefulness of sEMG in the aforementioned applications remains controversial, bioengineering and biomechanical approaches seem promising in offering viable solutions.

As already mentioned in section sEMG in Biofeedback, sEMG-B has been successfully used in TMDs (67).

Although we are aware of a long tradition of using sEMG within the School of Dental Medicine, University of Zagreb, to the best of our knowledge, it has not been applied in clinical praxis in Croatia to date; numerous private dental offices across Croatia do not use sEMG either. Based on personal observation of the first author, knowing both electronics and dental medicine experts in Zagreb University based institutions, a part of lack of success in developing valid clinical methods is in a rather conservative attitude that "engineers have to design the equipment and implement signal processing techniques, while medical doctors (doctors of dental medicine in this case) alone have to use these equipment." The field of BME attains a more inter-disciplinary attitude however.

Future Prospects

Important aspects of the development of sEMG technology are multielectrode (HD-sEMG) recording techniques. Although these techniques have been available for some time already (38–41), they are still rather avant-garde, and have not, to our knowledge, achieved widespread application as yet, however, they offer remarkable new possibilities. One direction is to explore, by mathematical analysis of measured signals, the functioning of particular MU in a muscle, thus providing a potential complement to the needle electrode detection technique and advancing neurological diagnostics. Although this sounds like an ambitious goal, it is supported by references [(10), as mentioned in section Electromyography (EMG), and (39)]. Drost et al. have already provided a systematic review of the clinical applications of HD-sEMG in 2006 (39). Clinical studies of muscle fatigue, motor neuron disease, neuropathies, myopathies (mainly in patients with channelopathies), spontaneous muscle activity, and MU firing rates have been reported. In principle, HD-sEMG allows the detection of pathological changes at the MU level, especially changes in neurogenic disorders and channelopathies. The authors described the status of the field at that time as being in the pre-clinical stage. **Figure 5**, which is taken from (39), elegantly illustrates the domains of application of different types of EMG detection. It is evident that HD-sEMG is applicable at the MU level.

Aside from the novel electrode technology mentioned here, one has to emphasize the technological development in the field of the acquisition systems. Small, wireless amplifiers have been developed that can be integrated with the detection system and interfaced with smart devices. This, although requiring certain versatility in operation and use (which, we believe, is easily surmounted with praxis) enables flexible applications of measurement equipment outdoors and in different milieus.

[16]https://www.ottobockus.com/prosthetics/upper-limb-prosthetics/

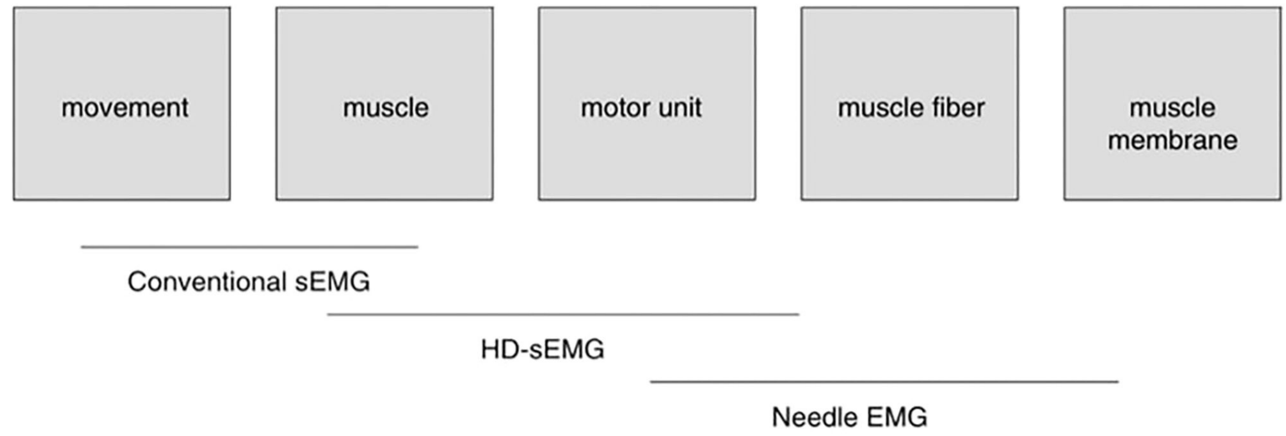

FIGURE 5 | The scope of the various EMG techniques. Conventional bipolar sEMG, with one bipolar electrode pair over each muscle, is mainly used in movement studies. It yields information for muscle activity in different muscles simultaneously. The development of HD-sEMG, a technique that utilizes multiple electrodes on each muscle, has additionally made it possible to extract information at the single motor unit (MU) level. With HD-sEMG, information on muscle–fiber conduction velocity (MFCV) can be used to supplement the information at the muscle–fiber level obtained by needle EMG [from (39)] (Permission obtained from J EMG Kinesiol for the use of the image).

An interesting further ramification of the methods of signal detection is presented by Inzelber and Hanein (120) who report on novel technologies using printed electronics-type electrodes. Being ultrathin, these electrodes are designed so that the contact area be maximized, the contact impedance lowered, and movement artifacts simultaneously reduced. High-density printed sEMG has emerged as a non-invasive method for acquiring precise information related to muscle activation by increasing the electrode number and enabling data analysis schemes. The authors describe various practical applications, such as in sleep research, electrooculography, and REM recording; among these, the most interesting may be the measurement of sEMG from the cheek and eyebrow regions to detect emotions. This latter application should enable the detection of facial expressions as, ultimately, a potential marker of neuropsychiatric conditions. Therefore, printed electrodes on soft substrates, together with advanced analysis schemes of the acquired data, provide a facile and inexpensive tool for, potentially, objective mapping of neurophysiological abnormalities. Additional sensors, such as those measuring temperature and skin conductivity, may further enhance the performance of printed films. In addition to improving both printed technology and data analysis methodology, contributions to improved diagnostics, evaluation of treatment efficacy, and enhanced research possibilities of neuropsychiatric disorders may be facilitated. Ideally, such systems would enable automatic feedback and screening of normal vs. pathological conditions.

Another promising application is shown in (115) where HD-sEMG is used in Duchenne muscular dystrophy, a degenerative disorder, to enable thorough spatiotemporal analysis and pattern recognition of HD-sEMG signals providing the efficient control of exoskeleton, an active orthosis, in efforts to assist individuals in hand/wrist motor control. The ultimate aim is to enable functional solutions for performing daily living activities. The authors refer to bipolar (low-density) sEMG as a clinical golden standard control of robotic devices.

Our concluding remark on the future of sEMG focuses on man-machine interfacing possibilities in rehabilitation technologies (111). There are representative examples of the use of sEMG signals for device control purposes in neurotechnology, in three main areas of neurorehabilitation: replacement, restoration, and neuromodulation. In these examples, either data-driven or model-driven approaches can be used for processing the sEMG and generating control signals to external devices, prostheses, using advanced prosthesis control schemes. The possibilities of combining sEMG with subject-specific musculoskeletal models, allowing the establishment of an improved interface with the subject compared with that offered by traditional sEMG processing and movement analysis techniques, are promising. This is an approach compatible with the methodology introduced by Scott Delp, in the 1990s, that is well-known to the biomechanics community. It resides on a theoretical and experimental basis made available at the time for creating faithful mathematical models of the muscle-tendon complex (121), leading to computer-supported quantitative and graphics-based solutions to simulate the action of the neuromusculoskeletal system of a particular individual (122). This approach, which adds to classical inverse dynamics, enables detailed and realistic biomechanical modeling and simulation possibilities of complex neuromuscular systems and has been broadly implemented until our days, in research and clinical applications (123).

CONCLUSION

The two main goals of our paper were as follows: first, to evaluate the scholastic coverage and second, to explore the degree of clinical acceptance of sEMG relative to ECG and EEG. We have summarized current knowledge in the field and provided an overview of the state of the art of technology and instrumentation. Our overview has been international in its approach, as well as specifically focused on the status of the field in Croatia.

The scholastic coverage, through teaching and training, of the areas discussed is only partially adequate, we believe, both worldwide as well as in Croatia. Academic training for all categories of students, i.e., physiotherapists, kinesiologists, medical doctors, engineers, consists of teaching basic knowledge on technical methods of recording, and processing the signals in question, with the goal of using these empirical data, along with other available variables and/or data, in intended research and clinical applications where it can be interpreted and used to solve a problem. Of course, when teaching engineering students, a more fundamental grasp of hardware/software knowledge is to be pursued as they as future professionals will be acting not only as users but also as designers and constructors of new equipment. The biomedical engineering approach is assumed, reflecting the inter- and multi-disciplinary nature of the field. This approach is prominent in existing curricula, as reported in section Scholastic Coverage of Bioelectric Signals, depending on the availability of appropriate laboratory facilities where signal recording equipment can be used and shown to students. The transfer of knowledge is possible, provided adequately trained staff are available. There is, of course, always room for improvement and inclusion of novel teaching tools. In addition to classical teaching methods, in a classroom and in a laboratory, online materials and courses, incorporating popular video clips for showing procedures and exercises, may be used.

Clinical acceptance of both ECG and EEG methods is superior and undisputed, as briefly stated in sections On the Nature of Bioelectric Signals and Their Interpretation and Comment on Diagnostic Utility of Techniques Based on Bioelectric Signals and Their Clinical Acceptance. The degrees of clinical acceptance of the sEMG method vary according to specific applications. There are many potential applications of this technique, as has been concisely discussed in section Overview of the Clinical Acceptance of sEMG. For these methodologies to be further implemented in Croatia and other countries, certain scientific as well as economic/organizational pre-requisites must be fulfilled. The scientific pre-requisites are 2-fold, comprising a research and a teaching component. The research component comprises the potential to conduct applied, clinical studies to validate and standardize applications of sEMG in the clinical environment. To achieve this, both equipment and manpower must be available, in the form of multidisciplinary research groups capable of securing research grants. The importance of proper staffing of clinical units and biomedical institutes is to be underlined at this point. This comprises having competent leadership in these institutions which requires interdisciplinary education to pursue clinical studies with the goal of developing and introducing new clinical methods. The importance of this "human" factor cannot be overemphasized.

Further, the applied component of research consists of the development of innovations (university-industry collaboration)—it is assumed that there should be a demand for such products—and presumes transfer of developed products to the market. At the University of Zagreb, Faculty of Electrical Engineering and Computing, an innovation center, namely the Inovacijski centar Nikola Tesla (ICENT)[17] is being conceptualized, with a number of laboratories where engineering Ph.D.-level staff are to be employed. The ICENT project encompasses several institutes, including the Institute for Biomedical Engineering, which includes five laboratories; among these, the most relevant to the sEMG field being the Laboratory for Biomechanics and Laboratory for Biomedical Instrumentation.

Economic and organizational issues are a matter of broader social and even political endeavors supported by the relevant State ministries of health, science and the economy.

In regard to the appropriate teaching and education of primarily clinical staff, we believe that the acceptance of sEMG by the staff (physical therapists and kinesiologists, typically) is generally good. We speculate that EMG information may be more easily and intuitively interpreted by non-engineers than data obtained using technically more complex apparatus like CT or NMR. New trends in the presentation of information using intuitive and visually attractive displays will increase user-friendliness and further contribute to knowledge acquisition. However, a basic limitation is a fact that sEMG instrumentation, despite not being very expensive in comparison with many other technical methods in medicine, is still not available in all working environments where it could be useful. Through our teaching experience, we have witnessed a genuine interest in the features and potential of sEMG when introduced and explained for the first time.

The limitation of our study is that the assessment of the status of the field in Croatia has not been based on objective documented data on the adoption of sEMG instrumentation across institutions. We cannot conclude whether, at the level of the State, evidence of biomedical instrumentation exists in institutions such as hospital wards, university laboratories, and research institutes. Although some initiatives have been made in this direction by the State ministries of science, education, and health, these have not been implemented, to our knowledge. The effective implementation of such endeavors would be indispensable in this context.

Furthermore, we did not organize and conduct a survey among users of the equipment to assess their perceptions of the instrumentation and methodology; such data would be very informative.

We have based our statements on our subjective knowledge and our academic professional contacts, and the concepts explored were defined by our fields of expertise, namely electronic and biomedical engineering and biomechanics research and teaching; research and clinical work in psychiatry; and research, teaching, and clinical work in physical medicine and rehabilitation.

[17]https://www.icent.hr/en/

AUTHOR CONTRIBUTIONS

VM, SM, and IK conceived the manuscript. VM coordinated the activities of preparing the manuscript and mainly contributed to the biomedical engineering and kinesiology aspects. SM contributed to medical and clinical aspects, primarily in psychology, psychiatry, and neurology. IK contributed to medical and clinical aspects, primarily in physical and rehabilitation medicine, neurology, and myoelectric control. All authors contributed to the scholastic aspects, and wrote and approved the final version of the manuscript.

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