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REVIEW
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Integrating Tactile Feedback Technologies Into Home-Based Telerehabilitation: Opportunities and Challenges in Light of COVID-19 Pandemic

Shirley Handelzalts[1,2]*, Giulia Ballardini[3,4], Chen Avraham[5,6], Mattia Pagano[3,4], Maura Casadio[3,4] and Ilana Nisky[2,5,6]

[1] Department of Physical Therapy, Ben-Gurion University of the Negev, Be'er Sheva, Israel, [2] The Translational Neurorehabilitation Lab at Adi Negev Nahalat Eran, Ofakim, Israel, [3] Department of Informatics, Bioengineering, Robotics and Systems Engineering, University of Genoa, Genoa, Italy, [4] S.C.I.L Joint Lab, Department of Informatics, Bioengineering, Robotics and System Engineering (DIBRIS), Santa Corona Hospital, Pietra Ligure, Italy, [5] Department of Biomedical Engineering, Ben-Gurion University of the Negev, Be'er Sheva, Israel, [6] Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev, Be'er Sheva, Israel

The COVID-19 pandemic has highlighted the need for advancing the development and implementation of novel means for home-based telerehabilitation in order to enable remote assessment and training for individuals with disabling conditions in need of therapy. While somatosensory input is essential for motor function, to date, most telerehabilitation therapies and technologies focus on assessing and training motor impairments, while the somatosensorial aspect is largely neglected. The integration of tactile devices into home-based rehabilitation practice has the potential to enhance the recovery of sensorimotor impairments and to promote functional gains through practice in an enriched environment with augmented tactile feedback and haptic interactions. In the current review, we outline the clinical approaches for stimulating somatosensation in home-based telerehabilitation and review the existing technologies for conveying mechanical tactile feedback (i.e., vibration, stretch, pressure, and mid-air stimulations). We focus on tactile feedback technologies that can be integrated into home-based practice due to their relatively low cost, compact size, and lightweight. The advantages and opportunities, as well as the long-term challenges and gaps with regards to implementing these technologies into home-based telerehabilitation, are discussed.

Keywords: haptic, training, stroke, neurorehabiliation, somatosensory, assessment

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***Correspondence:**
Shirley Handelzalts
handelza@post.bgu.ac.il

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INTRODUCTION

The COVID-19 pandemic highlights the need to accelerate the development and implementation of innovative approaches for home-based rehabilitation (Simpson and Robinson, 2020). While in normal, non-pandemic times many individuals in need of rehabilitation services do not receive sufficient therapy due to difficulties posed by the need to travel to the location where the therapy is provided, a shortage of regional rehabilitation care, and poor adherence to assignments (Cramer et al., 2019), the COVID-19 pandemic is presenting new challenges to rehabilitation services. The restrictions imposed to contain the spread of infection further limit access to rehabilitation services (Chaler et al., 2020) and challenge societal well-being. This may lead to long-term negative consequences by increasing functional impairments, and reducing participation and quality of life (Boldrini et al., 2020b). Telerehabilitation from home may partially mitigate these challenges, but state of the art telerehabilitation systems often only use visual or/and auditory feedback and lack somatosensory feedback (Navarro et al., 2018).

Somatosensory input is essential for accurate motor control and interactions with the external world (Pearson, 2000; Perez et al., 2003; Borich et al., 2015). The somatosensory impairment that is observed in many neurological disorders such as stroke, traumatic brain injury, and spinal cord injury can lead to impairments in adjusting the amount of force applied during grasping and fine manipulation of objects (Sullivan and Hedman, 2008; Doyle et al., 2010, 2014; Connell et al., 2014; Hill et al., 2014) and in performing tasks that require rapid dextrous movements (Goebl and Palmer, 2008), as well as in controlling more gross functions such as gait and posture (Maki and McIlroy, 1997; Horak, 2006).

In in-person rehabilitation intervention therapists frequently use touch to assist, and to provide and perceive information, as well as to comfort and encourage patients (Roger et al., 2002). In a survey regarding satisfaction with telerehabilitation during the COVID-19 pandemic, the absence of touch was reported by patients as a limitation (Tenforde et al., 2020). The current review focuses on tactile technologies that can be used as innovative solutions to support home-based telerehabilitation and addresses some challenges that have become more salient during the COVID-19 pandemic.

Previous reviews discussed telerehabilitation and wearable haptic devices; however, none has provided a comprehensive perspective on the variety of tactile stimulation technologies and the ways to exploit them for home-based telerehabilitation. An overview on tactile displays was conducted by Jones and Sarter (2008); however, since then significant developments in tactile technology have been presented. Culbertson et al. (2018b) reviewed the design, control, and general applications of haptic devices, but did not focus on rehabilitation applications. Several reviews focused on wearable technologies (not necessarily haptics) that can be used for remote monitoring of physiological and kinematic measurements, with a brief overview on the applications for home-based rehabilitation (Patel et al., 2012; Wang et al., 2017). Navarro et al. (2018) proposed features related to adaptive, multisensorial, physiological and social aspects that should be considered in the development process of the next generation of telerehabilitation systems. A systematic review of virtual reality technologies for rehabilitation examined the effect of haptic feedback on motor performance (Rose et al., 2018). Another review (Shull and Damian, 2015) examined wearable haptic applications for a variety of sensory impairments; however, the focus of that review was on stimulations to enhance motor performance. A previous narrative review focused on tactile technologies for hand rehabilitation in central nervous system disorders (Demain et al., 2013). In this work, we extend previous reviews by covering the development in tactile technologies over the last decade with an emphasis on wearable devices that potentially could be utilized at home. We also expand the scope to include the assessment of somatosensory deficits, in addition to various rehabilitative applications, and address the recent developments in mediation of social interaction. Specifically, we review: (1) clinical approaches for stimulating somatosensation in home-based rehabilitation, (2) tactile technologies that can be integrated into home-based rehabilitation, and (3) the challenges and gaps, as well as the opportunities, in this field.

CLINICAL APPROACHES FOR STIMULATING SOMATOSENSATION IN HOME-BASED NEUROREHABILITATION

Providing Tactile Augmented Feedback to Enhance Motor Control Performance and Learning

Somatosensory augmented feedback provides additional sensory cues that complement and/or replace native sensory input from the somatosensory, visual, and/or vestibular systems (Bach-y-Rita and Kercel, 2003). Tactile cues can guide patients on how to improve their movements (Bark et al., 2015) and may assist them in achieving their goals more quickly and/or more easily (Magill, 2004). A promising application of tactile feedback is to provide patients with guidance on how to improve their movements without the constant presence of a therapist (Bark et al., 2015; Bao et al., 2018), including when practicing on their own. The augmented feedback can be triggered by the participant's motor performance and can provide information continuously during the action or at specified times (Ferris and Sarter, 2011; Galambos, 2012; Kaul and Rohs, 2017). Compared with visual feedback, real time tactile feedback makes it possible for patients to receive information regarding movement errors without the need to shift visual attention, thus affording a more "natural" movement (Bark et al., 2015).

Tactile stimulation can also be beneficial even if it does not provide any information. For instance, subthreshold tactile stimulations (i.e., below the level at which a person can perceive the stimulation) add noise to proprioceptive signals and might help these signals to overcome the threshold of specific neural circuits. This phenomenon, also known as the stochastic resonance theory (Gammaitoni, 1995; Gammaitoni et al., 1998; Moss et al., 2004), facilitates more efficient detection of somatosensory information, and improves sensorimotor performance (Collins et al., 1996, 2003). As such, it could be used in the rehabilitation of individuals with sensorimotor deficits to improve motor functions (e.g., grasp, object manipulation, balance and gait) and tactile sensation (Enders et al., 2013; Seo et al., 2014, 2019).

Applying Tactile Stimulations to Improve/Restore Cutaneous Somatosensation

Somatosensory impairment is considered to have a negative prognostic impact on rehabilitation interventions and overall motor function recovery (Bowerman et al., 2012; Dietz and Fouad, 2014; Zandvliet et al., 2020). Although the current literature in this field is limited, a recent systematic review and meta-analysis indicated positive effects in improving somatosensory impairments (Serrada et al., 2019). Specifically, sensory discrimination training by repeated practice to distinguish textures and localize tactile stimuli can influence the sensory system and drive recovery (Carey et al., 1993; Yekutiel and Guttman, 1993; Turville et al., 2019).

Presenting Tactile Feedback in Virtual Reality Environments

Telerehabilitation is often based on virtual reality systems and interactive video games that aim to facilitate repetitions of movements and to make the repetitive exercises more engaging, enjoyable and motivating (Standen et al., 2015). The virtual experience can be further enhanced by using tactile devices that can convey haptic interactions between the user and the virtual objects (Galambos, 2012; Culbertson et al., 2018b).

Conveying Social Tactile Interaction

Haptic feedback plays a critical role in emotional and social communication (Strong and Gaver, 1996; Brave and Dahley, 1997). During in-person rehabilitation sessions therapists often use touch to comfort and encourage patients (Roger et al., 2002). Recent developments in wearable tactile devices demonstrate very promising results in conveying sensations such as comfort and affection (Culbertson et al., 2018a; Nunez et al., 2019, 2020), attention (Baumann et al., 2010), playfulness (Mullenbach et al., 2014), or social presence (Baldi et al., 2020). The integration of social tactile aspects into telerehabilitation systems would open new possibilities for remote therapist-patient communication and may facilitate wider adoption of telerehabilitation from home by patients.

Assessing Tactile Impairments

In addition to the above training strategies, the use of measures to quantify somatosensory deficits could help therapists to understand patients' impairments beyond motor and functional status and assist in targeting appropriate interventions. The assessment of somatosensory functions, including proprioception and sensitivity to light touch, pressure, and temperature, cannot be done remotely in the traditional way where the therapist applies the stimulation and evaluates the performance using scales. Portable, and often wearable devices that apply multimodal stimulations have the potential to provide reliable and quantitative information regarding somatosensory impairments in a home-based setting (Rinderknecht et al., 2015, 2019). Such portable devices have already been used in some virtual reality systems for baseline measurements of activity and kinematics and for tracking changes over time (Patel et al., 2012; Chen et al., 2015; Bortone et al., 2018).

TACTILE STIMULATION TECHNOLOGIES

Over the last few decades, technologies that can provide versatile tactile stimulations have become very popular and many new devices continue to be developed. These devices can be integrated into wearable technologies and utilized for telerehabilitation due to their low cost, compact size, and lightweight. From the technological point of view, there is a variety of ways to apply tactile stimulation. These can be categorized according to the mechanism evoking the tactile sensation: mechanical, electrotactile, and thermal. In order to provide an in depth review of the technology and its applications, in this review we focus on mechanical tactile stimulations. However, it should be noted that electrotactile stimulation is also used for various assistive technologies and rehabilitation applications such as for people with visual (Bliss et al., 1970; Kajimoto et al., 2001) and auditory impairments (Weisenberger et al., 1989), as well as in prostheses, orthoses (Schweisfurth et al., 2016; Svensson et al., 2017) and stroke rehabilitation (for a review see Laufer and Elboim-Gabyzon, 2011).

Mechanical tactile stimulations can be further divided into vibration, skin deformation, and mid-air stimulations. Recently the idea of wearable tactile devices that combine vibration, stretch, and pressure for conveying multimodal haptic information was introduced (Aggravi et al., 2018; Sullivan et al., 2019; Dunkelberger et al., 2020), highlighting the importance of understanding the unique properties of each stimulation type and harnessing the advantages of each to design devices that are more than the sum of their parts. In the remainder of this section, we review the state of the art in mechanical tactile stimulation devices. For each type of device we review the technology, its applications for healthy and patient populations, and its advantages and disadvantages. The different devices and studies are summarized in **Tables 1**, **2**. **Table 1** summarizes the devices by stimulation type, actuator type, technological maturity level, and application. We rank the technological maturity level based on how extensively testing of the device has been reported in the literature, with the following levels: prototype demonstration ($N < 10$); healthy user studies ($N = 10$–100); extensive healthy user studies ($N > 100$); patient user studies ($N = 10$–100); extensive patient user studies ($N > 100$). **Table 2** summarizes the studies that were reviewed here that were tested on patient populations for different rehabilitation applications.

Vibration

Vibration is the simplest and most common tactile stimulation technology that has become ubiquitous and is used in a wide variety of devices such as phones, watches, games, and home appliances (Culbertson et al., 2018b). Typically, the actuators used in wearable devices produce vibration at frequencies above 100 Hz, which activates the Pacinian corpuscles mechanoreceptors (Culbertson et al., 2018b). The most common locations for applying the vibrotactile stimulation are the arm (Bark et al., 2008; Huisman et al., 2013; Krueger et al., 2017; Shah et al., 2018; Risi et al., 2019) and the torso (Van Erp et al., 2005; Lee et al., 2012; Ballardini et al., 2020). Other locations for stimulation include the hand (Jiang et al., 2009; Wan et al., 2016) and different locations on the lower limb (Chen B. et al., 2016; Shi et al., 2019). The design of the device and the stimulation patterns (e.g., frequency and amplitude of the vibration) need to take into account the targeted dermatomes and the density and size of the mechanoreceptors' receptive fields which vary across the body (Jones and Sarter, 2008; Johansson and Flanagan, 2009; Shah et al., 2019) and across the skin type

TABLE 1 | Tactile stimulation devices by type, maturity level, and applications in healthy individuals.

Stimulation type	Device type	Device maturity level	Applications	Commercial availability
Vibration	Single actuator	Extensive healthy and patient user studies	Improve walking pattern (Janssen et al., 2009)	BalanceFreedom of SwayStar system https://www.b2i.info/web/index.htm
			Improve force control accuracy (Ahmaniemi, 2012)	
			Convey proprioceptive information (Bark et al., 2008)	
	Multiple actuators	Extensive healthy and patient user studies	Enhance motor learning and performance (Lieberman and Breazeal, 2007; Bark et al., 2015; Kaul and Rohs, 2017; Van Breda et al., 2017; Shah et al., 2018)	
			Guide movement direction (Van Erp et al., 2005; Krueger et al., 2017; Risi et al., 2019)	
			Improve standing balance (Lee et al., 2012; Ma and Lee, 2017; Ballardini et al., 2020)	Vertiguard RT https://zeisberg.net/posturographie.html
			Improve walking pattern (Chen B. et al., 2016; Wan et al., 2016; Muijzer-Witteveen et al., 2017; Xu et al., 2017)	
			Convey various types of information (Ferris and Sarter, 2011; Cobus et al., 2018)	
			Convey affective touch (Israr and Abnousi, 2018)	
			Assess somatosensory impairments (Tommerdahl et al., 2019)	Brain Gauge https://www.corticalmetrics.com/howitworks
	Multiple actuators on a glove	Healthy and patient user studies	Convey virtual objects information (Muramatsu et al., 2012)	CyberTouch http://www.cyberglovesystems.com/cybertouch2
			Convey force information (Galambos, 2012)	
			Assess somatosensory impairments (Rinderknecht et al., 2015, 2019)	
	Single actuator with multiple probes	Healthy user studies	Assess somatosensory impairments (Holden et al., 2012; Puts et al., 2013; Mikkelsen et al., 2020)	
Skin deformation—tangential and stretch	Tactor	Extensive healthy user studies and patient studies	Alter mechanical properties of virtual objects (Sylvester and Provancher, 2007; Quek et al., 2013, 2014b; Schorr et al., 2013; Farajian et al., 2020a,b)	
			Convey direction information (Bark et al., 2010; Guinan et al., 2012, 2013a,b; Norman et al., 2014; Chinello et al., 2018; Kanjanapas et al., 2019)	
			Convey information about curvature (Frisoli et al., 2008; Prattichizzo et al., 2013), weight (Kato et al., 2016; Choi et al., 2017), and virtual objects information (Yem and Kajimoto, 2017; Wang et al., 2020)	
			Improve object manipulation (Leonardis et al., 2017; Schorr and Okamura, 2017b; Bortone et al., 2018), tracking (Quek et al., 2014b), insertion (Quek et al., 2015b), palpation (Schorr et al., 2015) and grasping (Westebring van der Putten et al., 2010; Kim and Colgate, 2012; Quek et al., 2015a; Choi et al., 2017; Stephens-Fripp et al., 2018; Avraham and Nisky, 2020; Bitton et al., 2020; Farajian et al., 2020b)	
			Guide movement direction (Bark et al., 2010; Guinan et al., 2012, 2013a,b; Norman et al., 2014; Chinello et al., 2018)	
			Improve standing balance (Hur et al., 2019)	

(Continued)

TABLE 1 | Continued

Stimulation type	Device type	Device maturity level	Applications	Commercial availability
			Convey affective touch (Nunez et al., 2019)	
			Assess somatosensory impairments (Ballardini et al., 2018)	
	Adhesive rings	Healthy user studies	Convey affective touch (Haynes et al., 2019)	
	Belt/Vest	Healthy user studies	Substitute and augment force and torque feedback (Pacchierotti et al., 2016), convey sensation of mass (Minamizawa et al., 2007), and sensation of virtual objects (Minamizawa et al., 2008),	
			Convey direction information (Bianchi, 2016)	
			Provide feedback about grasping force (Casini et al., 2015)	
			Guide movement direction (Stanley and Kuchenbecker, 2012; Pezent et al., 2019; Smith et al., 2020) and convey path information (Kumar et al., 2017)	
			General tactile stimulation (Nakamura and Jones, 2003; Wu et al., 2010)	
	Rocker and roller	Healthy user studies	Enhance virtual object manipulation (Provancher et al., 2005)	
			Convey proprioceptive information (Battaglia et al., 2017 and 2019; Colella et al., 2019) (Clark et al., 2018)	
	Mechanical cranks	Healthy user studies	General tactile stimulation (Stephens-Fripp et al., 2018)	
Skin deformation—pressure	Indentator	Healthy and patient user studies	General tactile stimulations (Chinello et al., 2015)	
			Convey sensations of softness (Frediani and Carpi, 2020), and holding a virtual object (Merrett et al., 2011)	
			Convey direction information (Raitor et al., 2017; Agharese et al., 2018)	
			Render shape information of remote and virtual objects (Chinello et al., 2019)	
			Convey affective touch (Culbertson et al., 2018a)	
			Assess somatosensory impairments (Jacobs et al., 2000)	
	Belt	Prototype demonstration	Convey affective touch (Prattichizzo et al., 2010)	
	Pin array	Healthy and patient user studies	Create 2D and 3D graphic display (Shimizu et al., 1993; Leo et al., 2016; Brayda et al., 2018)	
			General tactile stimulations (Caldwell et al., 1999),	
			Convey sensations of roughness (Kim et al., 2009), and texture (Sarakoglou et al., 2005; Kyung and Park, 2007; Garcia-Hernandez et al., 2011)	
Skin deformation or vibration ultrasound	Mid-air technology using phased arrays	Extensive healthy user studies	Create 3D haptic shapes (Long et al., 2014; Vo and Brewster, 2015; Makino et al., 2016)	UltraLeap https://www.ultraleap.com/
			Convey affective touch (Shakeri et al., 2017, 2018)	

*Maturity level is ranked by the following levels: prototype demonstration (N < 10); healthy user studies (N = 10–100); extensive healthy user studies (N > 100); patient user studies (N = 10–100); extensive patient user studies (N > 100). Note that the applications column refers to studies in healthy individuals; for types of devices that were also tested on patients please refer to **Table 2** for more detailed information about the specific studies. Commercial availability of devices that were reviewed in the current paper and tested either on healthy or patient populations.*

TABLE 2 | Tactile device applications for rehabilitation.

Application	Population	Tested in a home setting (Yes/No)	Type of stimulation	Type of device	Wearable/ Non-wearable	References
Enhance upper extremity function	Multiple Sclerosis (*N* = 24)	No	Vibration	Multiple actuators	Wearable	Jiang et al., 2009
	Stroke (*N* = 12)	No	Subthreshold vibration	Single actuator, (TheraBracelet)	Wearable	Seo et al., 2019
Enhance gait and balance control	Stroke (*N* = 8)	No	Vibration	Multiple actuators	Wearable	Afzal et al., 2019
	Stroke (*N* = 17)	No	Vibration	Multiple actuators	Wearable	Yasuda et al., 2017
	Stroke (*N* = 3)	No	Vibration	Platform (The Rutgers Ankle Haptic Interface)	Non-wearable	Boian et al., 2003
	Stroke (*N* = 20)	No	Vibration	Multiple actuators	Wearable	Jaffe et al., 2004
	Parkinson's disease (*N* = 43)	No	Vibration	Single actuator (VibroGait)	Wearable	Fino and Mancini, 2020
	Parkinson's disease (*N* = 20)	No	Vibration	Multiple actuators (BalanceFreedom)	Wearable	Nanhoe-Mahabier et al., 2012
	Parkinson's disease (*N* = 16)	No	Pressure	Steel stick	Non-wearable	Barbic et al., 2014
	Parkinson's disease (*N* = 10)	No	Vibration	Multiple actuators (Vertiguard)	Wearable	Rossi-Izquierdo et al., 2013
	Parkinson's disease (*N* = 9) and older adults at high risk for falls (*N* = 8) and older adults (*N* = 10)	No	Vibration	Multiple actuators	Wearable	High et al., 2018
	Parkinson's disease (*N* = 9) and older adults (*N* = 9)	No	Vibration	Multiple actuators	Wearable	Lee et al., 2018
	Older adults (*N*= 12)	Yes	Vibration	Multiple actuators	Wearable	Bao et al., 2018
	Peripheral Neuropathy (*N* = 4)	No	Pressure	Ballon arrays	Wearable	McKinney et al., 2014
	Vestibular disorder (*N* = 6)	No	Vibration	Multiple actuators	Wearable	Sienko et al., 2012
	Vestibular disorder (*N* = 7)	No	Vibration	Multiple actuators	Wearable	Sienko et al., 2013
	Vestibular disorder (*N* = 13)	No	Vibration	Multiple actuators (Vertiguard)	Wearable	Brugnera et al., 2015
	Vestibular disorder (*N* = 8)	No	Vibration	Multiple actuators	Wearable	Bao et al., 2019
	Vestibular disorder (*N* = 105)	No	Vibration	Multiple actuators, (Vertiguard)	Wearable	Basta et al., 2011
Enhance tactile sensation	Stroke (*N* = 5), diabetic neuropathy (*N* = 8) and older adults (*N* = 12)	No	Subthreshold vibration	Single actuator	Non-wearable	Liu et al., 2002
	Stroke (*N* = 10)	No	Subthreshold vibration	Single actuator	Wearable	Enders et al., 2013
	Stroke (*N* = 16)	Yes	Vibration	Multiple actuators on a glove	Wearable	Seim et al., 2020b
	Digital nerve injuries (*N* = 49)	No	Pressure	Rotating disk and a card	Non-wearable	Cheng, 2000
	Chronic pain (*N* = 13)	No	Pressure	Probe	Non-wearable	Moseley et al., 2008
	Spinal cord injury (*N* = 7)	Yes	Vibration	Multiple actuators on a glove (Mobile Music Touch)	Wearable	Estes et al., 2015
Somatosensory assessment	Stroke (*N*= 2)	No	Vibration	Multiple actuators on a glove (ReHaptic Glove)	Wearable	Rinderknecht et al., 2019
	Stroke (*N* = 3)	No	Skin stretch	Tactor	Non-wearable	Ballardini et al., 2018
	Brain injury (*N* = 1)	No	Vibration	Multiple actuators (Brain Gauge)	Non-wearable	King et al., 2018
Enhance interaction realism in virtual reality environment	Children with neuromotor impairments (*N* = 20)	No	Skin stretch and pressure	Tactor	Wearable	Bortone et al., 2018
	Spinal cord injury (*N* = 9)	No	Vibration	Multiple actuators on a glove (CyberTouch)	Wearable	Dimbwadyo-Terrer et al., 2016

(e.g., hairy skin has a reduced number of Pacinian corpuscles compared to glabrous skin) (Colgate and Brown, 1994; Ackerley et al., 2014). Skin type can also influence the quality of stimulation via its mechanical properties and its physical propagation of the vibration (Dandu et al., 2019; Hachisu and Suzuki, 2019).

Technology

Vibrotactile feedback can be conveyed by a single actuator, or by an array of actuators that create an oscillating movement. The choice of the actuator affects the size, shape, cost, availability, robustness, speed of response, input requirements, and power consumption of the device (Choi and Kuchenbecker, 2013). An overview of the different actuators can be found in Choi and Kuchenbecker (2013) and Kern (2009).

The stimulation patterns can be divided into two fundamental categories: (1) binary on-off state, and (2) continuous vibration, created by changing parameters of the vibration signals such as amplitude, frequency, duration, rhythm, and waveform (Brewster and Brown, 2004; Jones and Sarter, 2008). Binary feedback is not continuously provided but is triggered by specific events such as an alarm or event-cue related information (Ferris and Sarter, 2011; Galambos, 2012; Kaul and Rohs, 2017). The vibration intensity can be constant or may vary according to the event (Cobus et al., 2018). Continuous vibrotactile stimulation is used to convey various types of information to the users, including: (1) state feedback, encoding position and/or velocity of limbs (Ferris and Sarter, 2011; Krueger et al., 2017; Shah et al., 2018; Risi et al., 2019), (2) force feedback, encoding the amount of force exerted (Ahmaniemi, 2012), and (3) error feedback, encoding information regarding the goal of the task and the state of the end-effector (Wall et al., 2001; Cuppone et al., 2016; Krueger et al., 2017).

By controlling the shape and timing of the signals from multiple static actuators, it is also possible to display illusions of movement that can enrich the design space of tactile stimulation. Prominent examples are: (1) phi (or beta) movement, where a smooth apparent motion of a single stimulus is created by the periodic activation of two spatially separated stimuli (Sherrick and Rogers, 1966; Lederman and Klatzky, 2009), (2) saltatory (or rabbit) illusion, i.e., illusory sweeping movement of discrete taps that occur by activating actuators in sequence (Geldard and Sherrick, 1972; Lederman and Klatzky, 2009), and (3) the tendons vibration illusion, which is an illusory perception of movement that can be evoked by triggering the muscle spindle afferents through vibrations applied to the tendon (Goodwin et al., 1972; Taylor et al., 2017).

Applications for Enhancing Sensorimotor Performance and Learning

In healthy individuals, vibrotactile feedback is used to enhance motor control and learning (Lieberman and Breazeal, 2007; Van Breda et al., 2017; Shah et al., 2018). It has been demonstrated that state feedback regarding the force exerted improved the accuracy of force repetition (Ahmaniemi, 2012). Other studies used state and/or error feedback to guide upper limb reaching movements in the absence of visual information (Krueger et al., 2017; Shah et al., 2018; Risi et al., 2019) and to reach accuracy levels beyond the limits of natural proprioception (Risi et al., 2019). Results from a meta-analysis indicated that vibrotactile feedback was effective in reducing task completion times, but neither forces nor errors were significantly reduced (Nitsch and Färber, 2012). In addition, vibration feedback encoding center of mass or center of pressure motion was used to improve standing balance (Lee et al., 2012; Ma and Lee, 2017; Ballardini et al., 2020) and walking patterns (Janssen et al., 2009; Muijzer-Witteveen et al., 2017; Xu et al., 2017). Vibrotactile feedback based on stochastic resonance was applied for improving visuomotor temporal integration in hand control (Nobusako et al., 2019) and balance control (Magalhães and Kohn, 2011). Vibrations that informed the users about collisions with virtual objects in a virtual reality context added realism and improved performance (Galambos, 2012; Kaul and Rohs, 2017). Also, a vibrotactile glove interface has been used to convey sensations of virtual objects (Muramatsu et al., 2012).

Applications in Rehabilitation

In persons with multiple sclerosis, vibrotactile feedback applied to the fingernails of the contralateral hand improved the performance of a grasping and lifting task of the more impaired hand (Jiang et al., 2009). In addition, real time state vibrotactile cues reduced postural sway during standing balance tasks and improved gait parameters after stroke (Yasuda et al., 2017; Afzal et al., 2019), in people with Parkinson's disease (Nanhoe-Mahabier et al., 2012; High et al., 2018; Lee et al., 2018; Fino and Mancini, 2020) and with vestibular disorders (Sienko et al., 2012, 2013). However, in all of these studies improvements were observed during trials, and long-term effects were not tested. Vibrotactile stimulations were also used to enhance interaction realism in a rehabilitation system based on virtual reality (Boian et al., 2003; Dimbwadyo-Terrer et al., 2016), and to avoid collisions during walking in stroke survivors (Jaffe et al., 2004).

Several randomized controlled trials (RCTs) with small cohorts tested the effect of balance training programs with vibrotactile stimulations. Following a 2-week training program using vibrotactile feedback, individuals with Parkinson's disease improved their balance control parameters and performance-based measures and retained improvements 3 months after training (Rossi-Izquierdo et al., 2013). Additionally, adults with vestibular disorders improved their balance performance and felt more confident regarding their balance while performing daily activities after a training protocol with vibrotactile stimulations compared with a control group that trained without stimulations (Brugnera et al., 2015; Bao et al., 2019). Furthermore, balance improvements were retained at 6-month follow-up assessments (Bao et al., 2019). Also, reduced body sway and improved clinical outcome measures [e.g., Sensory Organization Test (SOT) (Franchignoni et al., 2010) and Dizziness Handicap Inventory (Jacobson and Newman, 1990)] were observed in a study with a large cohort of participants with vestibular disorders ($n = 105$) who trained with vibrotactile stimulations over 2-weeks (i.e., ten-sessions) compared with a control group that trained with a sham device (Basta et al., 2011).

Subthreshold vibrotactile stimulation improved somatosensation and motor function in persons with sensorimotor impairments: stimulations applied at the wrist and dorsal hand improved the immediate fingertips light-touch sensation and grip ability of the paretic hand in stroke survivors (Enders et al., 2013). In addition, the vibrotactile detection threshold (i.e., the minimum level of vibration amplitude to be detected) at the tip of the middle finger in persons with diabetic neuropathy and stroke survivors was decreased (Liu et al., 2002). In persons with diabetic neuropathy the threshold was decreased at the foot as well (Liu et al., 2002; Khaodhiar et al., 2003). In a pilot randomized controlled trial, subthreshold vibratory stimulation was applied to the paretic wrist of stroke survivors during upper extremity task training (a total of 6 sessions provided in 2 weeks). The treatment group showed a significant improvement in hand motor function at the end of therapy, which was sustained 19 days after therapy, whereas the control group that practiced without stimulation did not improve from baseline performance (Seo et al., 2019).

While these studies were conducted in laboratory settings, few studies provided participants with vibrotactile devices to practice at home. Bao et al. (2018) tested the effect of long-term home-based balance training with vibrotactile sensory augmentation among community-dwelling healthy older adults. Participants were trained in static and dynamic standing and gait exercises for 8 weeks (3 sessions per week, 45-min each) using smartphone balance trainers that provided guidance while monitoring trunk sway. The experimental group received directional vibrotactile cues via actuators that were aligned around the torso in case the activation signal exceeded a pre-set threshold, while the control group practiced without supplemental feedback. Participants in the experimental group demonstrated significantly higher improvements in their SOT (Franchignoni et al., 2010) and Mini Balance Evaluation Systems Test scores (Clendaniel, 2000) compared with the control group at post training assessment. Seim et al. (2020a) designed a glove that provides subthreshold vibrotactile stimulation for stroke survivors to use at home and demonstrated the feasibility of wearing the glove for 3 h daily for 8 weeks. Also, in a double-blind RCT, chronic stroke survivors with impaired tactile sensation in the hand were given a glove to take home and asked to wear it during their normal daily routine (i.e., 3 h daily for 8 weeks) (Seim et al., 2020b). One group received a glove which provided vibrotactile stimulation to the hand and another group received a glove with the vibration disabled. Participants receiving tactile stimulations demonstrated significant improvement in tactile perception (assessed with monofilaments) in the affected hand. In another study, improvement in hand sensation was observed in participants with spinal cord injury after training with a glove providing vibration stimulations compared with participants who trained without stimulations (Estes et al., 2015). Vibration stimulations were applied during active practice sessions of playing piano in in-lab sessions (3 times a week for 30 min a session for 8 weeks) and during passive practice at home (2 h a day, 5 times a week). An illustration of a vibrotactile stimulation device is presented in **Figure 1**.

Applications for Conveying Social Tactile Cues

Gentle stroking touches resembling those of soft calming and caressing sensations are considered highly relevant in social interactions (Huisman et al., 2016). Using artificial means to convey such touches might enhance social presence in telecommunication or in virtual settings. Israr and Abnousi (2018), developed a vibrotactile device worn on the forearm that delivers stimuli which resemble caressing and calming sensations. Participants rated low frequency stimuli (<40 Hz) as pleasant sensations that feel like massaging and noted that they would be even more realistic with context. Huisman et al. (2013) developed a virtual agent setup that incorporates an augmented reality screen and a vibrotactile sleeve worn on the user's forearm. In this setup the forearm was placed under a tablet, thus allowing the user to see his/her forearm "through" the tablet. The vibrotactile stimulation combined with the visual

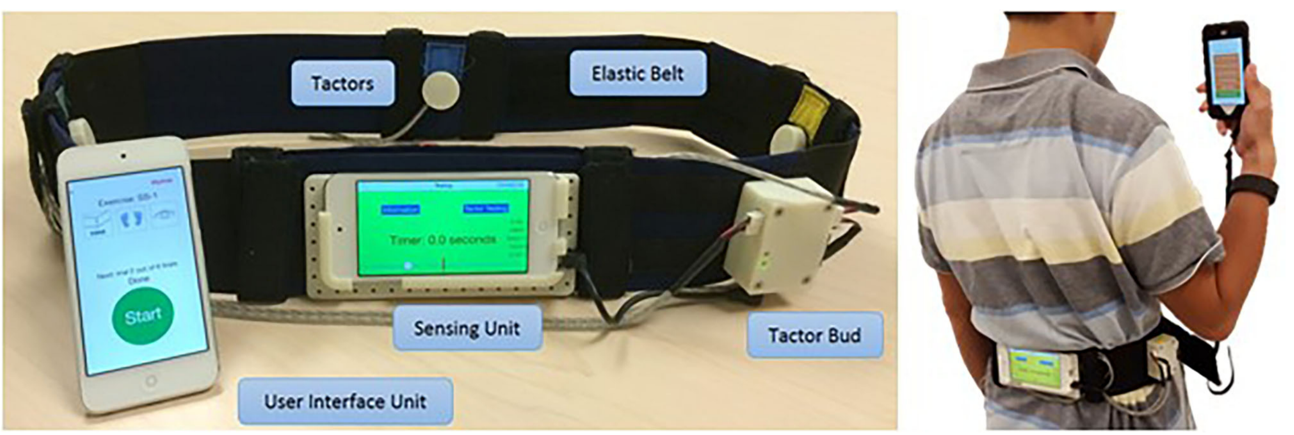

FIGURE 1 | Vibrotactile stimulation devices. The smartphone-based balance trainer used in Bao et al. (2018). The sensing unit is attached to an elastic belt worn around the torso to measure trunk sway. The four tactors are aligned over the anterior, posterior, and right and left sides of the torso to provide directional vibrotactile cues.

representation of a hand touching the user created a more realistic touching illusion.

Assessment of Tactile Impairments

Vibrotactile simulation can be used for assessment applications. In clinical settings the duration of vibration sensation and the perception threshold are commonly measured using a tuning fork (Perkins et al., 2001; Alanazy et al., 2018). However, results regarding its reliability are variable across studies (O'Neill et al., 2006; Lai et al., 2014; Lanting et al., 2020), and, most importantly, the assessment does not quantitatively provide the degree of dysfunction and depends on the level of clinical experience (Lanting et al., 2020).

To address limitations of clinical assessments, an automated approach to quantify topesthesia (i.e., the ability to recognize the location of a tactile stimulus) was developed (Rinderknecht et al., 2015). The system consists of two wearable gloves that can apply vibrations on the hand at 24 possible locations and a touchscreen to directly indicate with the non-tested hand the precise location of perception on the tested hand. The assessment provides a standardized, repeatable measurement as well as continuous outcome measures on ratio scales (Rinderknecht et al., 2015). It was tested on healthy individuals (Rinderknecht et al., 2015) and on stroke survivors (Rinderknecht et al., 2019).

In addition, a portable vibrotactile stimulator device was used to probe tactile function through a battery of tests assessing reaction time ("press the button when you feel the vibrotactile stimulation"), threshold detection (the weakest detectable stimulus), amplitude and frequency discrimination (discriminating between two stimuli that are simultaneously applied and discriminating between the frequency of two sequentially applied stimuli). The battery targets different mechanisms of somatosensory processing (Holden et al., 2012; Puts et al., 2013; King et al., 2018; Tommerdahl et al., 2019; Mikkelsen et al., 2020). These tests were used on healthy adults and children (Puts et al., 2013) for monitoring recovery from concussion (King et al., 2018) as well as a wide range of neurological disorders (Tommerdahl et al., 2019). There are also other specific tests that aim to independently evaluate only one of the aspects investigated by this paradigm; an overview of the tests assessing vibrotactile perception in healthy subjects can be found in Jones and Sarter (2008).

Advantages and Disadvantages

A major advantage of vibrotactile devices is that the actuators can be easily integrated into wearable devices because they are small, lightweight, low- power, and low-cost (Alahakone and Senanayake, 2009). On the other hand, disadvantages of vibrotactile feedback stem from the properties of the mechanoreceptors activated by vibration. First, it is difficult to accurately locate the source of the stimulations if they are placed close together, because of the propagation of the vibration (Sofia and Jones, 2013; Shah et al., 2019) and the large size of the mechanoreceptors' receptive fields (Johnson et al., 2000). Second, it is difficult to convey directional information, unless several actuators are used in a spatially and/or temporally coordinated mode (Rotella et al., 2012). Third, it has been suggested that the feedback coding of some vibrotactile devices may be less effective than of others in reducing applied forces i.e., if the vibration frequency or location varies, vibrotactile feedback may be less effective in conveying information on intensity or direction than a uniform signal that alerts the user of a required response (Nitsch and Färber, 2012). Fourth, prolonged exposure to continuous vibratory stimulation could result in an unpleasant sensation (Bark et al., 2008) and has been associated with long-term nerve and tissue damage (Takeuchi et al., 1986). Also, choosing the right type, number, and target location of the actuators for patients with possible degradation of perception due to aging or disease might be challenging (Jones and Sarter, 2008).

SKIN DEFORMATION

Tangential Force and Skin Stretch

Tangential skin deformation is evoked by pressure of the skin against a device, combined with a lateral movement of the entire device or a small part of it. Such deformation occurs naturally when touched by a therapist, when interacting with a real object, or when a device applies forces on a user, but it may also be elicited by technological solutions specifically designed to provide tactile stimulation (Bark et al., 2009; Quek et al., 2014b; Pan et al., 2017). The stimulation is detected by the Ruffini corpuscles which are slow adapting SA-II tactile afferents in the skin that are sensitive to tangential shear strain as well as the Meissner's corpuscles which are rapid adapting RA-I tactile afferents that are sensitive to dynamic skin deformation (Johansson and Flanagan, 2009). The detection resolution of the skin stretch at the fingertip is 0.1–0.2 mm, while the direction of the stretch can be accurately perceived with less than 1.0 mm of movement (Gould et al., 1979; Greenspan and Bolanowski, 1996).

Technology

There are different methods to render tangential and stretch forces, e.g., a roller (Provancher et al., 2005), a belt (Minamizawa et al., 2007), or a moving tactor (Quek et al., 2013). The most common location for applying the stimulation is the finger pad (Pasquero and Hayward, 2003; Drewing et al., 2005; Gleeson et al., 2010a; Solazzi et al., 2011; Tsetserukou et al., 2014), as it contains a very high density of mechanoreceptors (Abraira and Ginty, 2013). Other locations include the palm (Guzererler et al., 2016; Ballardini et al., 2018), the forearm (Bark et al., 2008; Kuniyasu et al., 2012; Chinello et al., 2016), the arm (Casini et al., 2015; Battaglia et al., 2017), and different locations on the lower limb (Chen D. K. Y. et al., 2016; Omori et al., 2019; Wang et al., 2020). The mechanism and actuation of the device can be tailored to the desired application (see Pacchierotti et al., 2017 for a review on wearable devices). By changing the magnitude and direction of the tactile stimulations it is possible to convey different types of information such as forces and directional guidance (Biggs and Srinivasan, 2002; Paré et al., 2002; Provancher et al., 2005; Guinan et al., 2014; Bianchi, 2016; Leonardis et al., 2017; Kanjanapas et al., 2019; Bitton et al., 2020).

Applications for Enhancing Sensorimotor Performance and Learning

Adding a skin stretch to force feedback has been shown to affect stiffness (Quek et al., 2013, 2014a,b; Schorr et al., 2013; Farajian et al., 2020a,b) and friction (Sylvester and Provancher, 2007; Provancher and Sylvester, 2009) perception. In addition, concurrent tangential and normal skin deformation can be used to substitute and/or augment upper extremity force and torque feedback in navigation, tracking, insertion and palpation tasks (Quek et al., 2014b, 2015b; Schorr et al., 2015; Pacchierotti et al., 2016; Clark et al., 2018), generating a high fidelity haptic feedback for the sensation of mass (Minamizawa et al., 2007; Kato et al., 2016) and virtual objects (Minamizawa et al., 2008). It can also be used to enhance perception and performance in object manipulation tasks (Leonardis et al., 2017; Schorr and Okamura, 2017b), and to deliver grasp force information (Casini et al., 2015).

Skin stretch feedback providing position information improved the movement accuracy of healthy participants who controlled the movement of a virtual arm (Bark et al., 2008). Compared with vibrotactile stimulation, skin stretch feedback provided superior results, particularly when the virtual arm was in a low-inertia configuration and at low velocity (Bark et al., 2008). Gleeson et al. demonstrated the ability of healthy participants to accurately identify the direction of tangential skin deformation at the fingertip, and highlighted the potential of using skin stretch cues to aid patients with balance control impairments (Gleeson et al., 2010b). Skin stretch stimulation was also found to be effective for improving performance in a curvature discrimination task (Frisoli et al., 2008; Prattichizzo et al., 2013).

Stretching the skin can affect not only perception, but also forces that are applied by the user for stabilization. Westebring van der Putten et al. (2010) explored the influence of skin stretch and tangential deformation feedback on grasp control and demonstrated a significant improvement in pinch force control for participants who received augmented tactile feedback. Bitton et al. (2020) showed that applying tactile stimulation of the fingertips increases grip force, even in a static force maintenance task. In addition, adding an artificial skin stretch to the finger pads in the same direction as force applied by a virtual object or a haptic device increased the applied grip force (Quek et al., 2015a; Avraham and Nisky, 2020; Farajian et al., 2020b), although this effect was not seen in Quek et al. (2015b), or in the case of skin-stretch that is in the opposite direction to the external force (Avraham and Nisky, 2020).

In addition, studies have shown the ability of participants to accurately produce motion according to haptic stimuli provided by a skin stretch device (Bark et al., 2010; Stanley and Kuchenbecker, 2012; Guinan et al., 2013b; Norman et al., 2014; Chinello et al., 2018; Pezent et al., 2019; Smith et al., 2020), including in gaming applications (Guinan et al., 2012, 2013a). Skin stretch feedback encoding the velocity of postural sway along the anterior-posterior direction enhanced standing balance with perturbed sensory systems (removed vision and unreliable vestibular systems) in healthy young adults compared with conditions without skin stretch feedback (Hur et al., 2019).

In virtual reality systems, skin stretch feedback has been applied at different body locations to simulate rich physical properties during the interaction with virtual environments and objects (Minamizawa et al., 2007, 2008; Choi et al., 2017; Yem and Kajimoto, 2017; Wang et al., 2020). For example, a leg-worn device that applies varied skin stretch profiles to induce an illusory force improved the realism and enjoyment of virtual reality applications (Wang et al., 2020).

Applications in Rehabilitation

To date, most applications of skin stretch stimulation were demonstrated in the context of prostheses or assistive devices. For example, a multimodal tactile stimulation device helped to improve the grip force control of an electromyographic-controlled virtual prosthetic hand that was operated by targeted reinnervation amputees (Kim and Colgate, 2012). Other examples conveyed proprioceptive (Battaglia et al., 2017, 2019; Colella et al., 2019), grasp force and position information to users of prosthetic hands (Casini et al., 2015; Stephens-Fripp et al., 2018), or path information to users of a powered-wheelchair (Kumar et al., 2017). Although it has not yet been tested directly in rehabilitation protocols for neurological populations, these technologies could potentially be used for tasks such as restoration of fine object manipulation. An example of such an application was demonstrated on children with neuromotor impairments who trained in performing upper limb movements, including reach to grasp, path tracking, and hand orientation, with a wearable haptic device rendering contact forces by deformation of the fingerpad (Bortone et al., 2018).

Applications for Conveying Social Tactile Cues

Recently, wearable devices that can generate pleasant tactile sensations have been developed (Haynes et al., 2019; Nunez et al., 2019). A skin slip technology was used to generate an illusory sensation of continuous lateral motion that could be used to convey social touch cues, such as comfort and affection, in which stroking motions are used (Nunez et al., 2019). The stimulation was perceived as pleasant when the speed was closer to 10 cm/s and applied on the volar side of the forearm.

Assessment of Tactile Impairments

The assessment of tactile directional sensitivity (i.e., the ability to identify the direction of an object's motion across the skin) is considered to be a sensitive screening test of sensory function after injuries in the central or peripheral nervous system (Wall and Noordenbos, 1977; Bender et al., 1982; Hankey and Edis, 1989; Norrsell and Olausson, 1992). However, to our knowledge, assessment properties (e.g., reliability) were not tested. Recently, a skin stretch device was developed to assess somatosensory impairments at different body areas (Ballardini et al., 2018). The system offers quantitative and reliable measures of tactile acuity (i.e., testing discrimination of the direction and amplitude of skin stretch stimuli) and was validated in healthy participants and in a small cohort of stroke survivors.

Advantages and Disadvantages

There are many advantages to skin stretch deformation. This stimulation provides a strong, quick, and accurate response to changes in skin strain (Edin, 2004). In addition, skin stretch at low frequencies is attractive for wearable devices as it does not require much power (Bark et al., 2008). It can also convey direction even with a single actuator, does not suffer from adaptation effects, and is effective even at low velocities and with small movements (Bark et al., 2008). Moreover, skin stretch feedback is effective in inducing the perception of virtual textures and illusory forces and can be used to convey intuitive proprioceptive feedback (Chossat et al., 2019). Nevertheless, skin stretch stimulation has some disadvantages. The amount of skin deformation depends on the mechanical properties of the skin and the strength of the normal forces against the actuator, and thus partial or full slippage may occur. These and other factors contribute to large inter-participant variability in the perceptual effects of skin stretch (Quek et al., 2014b; Farajian et al., 2020b), while some individuals are not at all sensitive to stretch effects (Quek et al., 2014b). Also, this type of stimulation is commonly applied at the finger pad where there is a limited area for applying the stretch. Finally, although skin stretch devices are usually safe, when developing the device, one should carefully consider unpleasant sensations and abrasion. Illustrations of tangential and stretch stimulation devices are presented in **Figure 2**.

Pressure

Pressure triggers a response in the low frequency range of the slow adapting afferents SA-I, innervating the Merkel cells (Johansson and Flanagan, 2009). Technologies that provide this type of feedback deliver forces that cause deformation, and the strength of the stimulus is determined based on sensitivity thresholds, which vary across the body.

Technology

Pressure stimulation is commonly provided by devices that contact the skin with a single end-effector that can: (1) change its properties, such as the shape in soft actuators (Koehler et al., 2020) or the viscosity in electrorheological or magnetorheological fluids (Taylor et al., 1997; Jungmann and Schlaak, 2002; Jansen et al., 2010; Yang et al., 2010; Kim et al., 2016), (2) tighten a band around a body location, like the fingertip (Merrett et al., 2011), wrist (Stanley and Kuchenbecker, 2012) or forearm (Meli et al., 2018), and (3) press on the skin with a servomotor (Quek et al., 2015b; Schorr and Okamura, 2017a) or a hydraulic, or pneumatic actuator (Franks et al., 2008; Yem et al., 2015; Talhan and Jeon, 2018). For the latter solution, it is also possible to enlarge the area of stimulation by increasing the number of end-effectors in contact with the skin using a pin array matrix, i.e., a matrix of actuators that can be activated separately. In order to provide efficient tactile stimulation it is also important to consider the size and density of the contact points, since these will affect the cost and weight of the device, as well as its perceptual effect.

Applications for Enhancing Sensorimotor Performance and Learning

Using force indentation at different orientations makes it possible to display contact forces for multiple applications. Already in 1993, the technology was used to produce 2D and 3D graphic display for haptic recognition of familiar objects and was tested in blind and sighted participants (Shimizu et al., 1993; Leo et al., 2016; Brayda et al., 2018). Since then, multiple tactile devices with lightweight and compact mechanisms have been developed to produce pressure stimulation, thereby providing a range of tactile sensations including natural touch (Caldwell et al., 1999; Chinello et al., 2015; Culbertson et al., 2018a), roughness (Kim et al., 2009), softness (Frediani and Carpi, 2020), and texture (Sarakoglou et al., 2005; Kyung and Park, 2007; Kim et al., 2009; Garcia-Hernandez et al., 2011). In addition, pressure stimulation was used for conveying directional cues (Raitor et al., 2017; Agharese et al., 2018), and for rendering shape in virtual and remote environments (Chinello et al., 2019).

Applications in Rehabilitation

In patients with digital nerve injury, stroking, and pressing a pocket tactile stimulator and contacting the rotating disc of a tactile stimulator improved functional sensitivity measured by the smallest perceivable force using Semmes-Weinstein monofilaments (Semmes et al., 1960), and the shortest perceivable distance using a standardized two-point discrimination test instrument (Dellon et al., 1987; Cheng, 2000). In patients with complex regional pain syndrome of one limb, tactile stimulation was shown to decrease pain and increase tactile acuity when patients were required to discriminate between the type and location of tactile stimuli (Moseley et al., 2008). Skin pressure stimulation at the hallux and first metatarsal joint of the feet applied to participants with Parkinson's disease increased step length and gait velocity and reduced cadence compared with baseline measurements (Barbic et al., 2014). A wearable tactile feedback system that was originally developed for sensory augmentation of prosthetic limbs has been adapted for individuals with bilateral peripheral neuropathy (McKinney et al., 2014). Using thigh cuffs (one per leg) with silicone balloons for conveying sensory information specific to each foot, participants could modify their gait in real time (i.e., increase walking speed, step cadence and step length). Although not tested in populations undergoing rehabilitation, tactile vests worn on the torso have been shown to create a variety of tactile stimuli that could potentially be useful in applications such as balance control training (Nakamura and Jones, 2003; Wu et al., 2010). Also, pressure applied simultaneously to the thumb and index fingers generated a perception of holding an object, exhibiting the potential to provide a realistic haptic sensation in virtual reality based rehabilitation (Merrett et al., 2011).

Applications for Conveying Social Tactile Cues

Culbertson et al. developed a device that creates a stroking sensation using a linear array of voice coil actuators embedded in a fabric sleeve worn around the arm. The voice coils were controlled to indent the skin in a linear pattern to create the sensation of a stroking motion even though only normal force was applied (Culbertson et al., 2018a). As indicated from participants' ratings, to create a continuous and pleasant sensation the device should be controlled with a short delay and long pulse width (800 ms, 12.5% delay). Another system, the RemoTouch (Prattichizzo et al., 2010), was designed to provide experiences of remote touch. The user perceives force

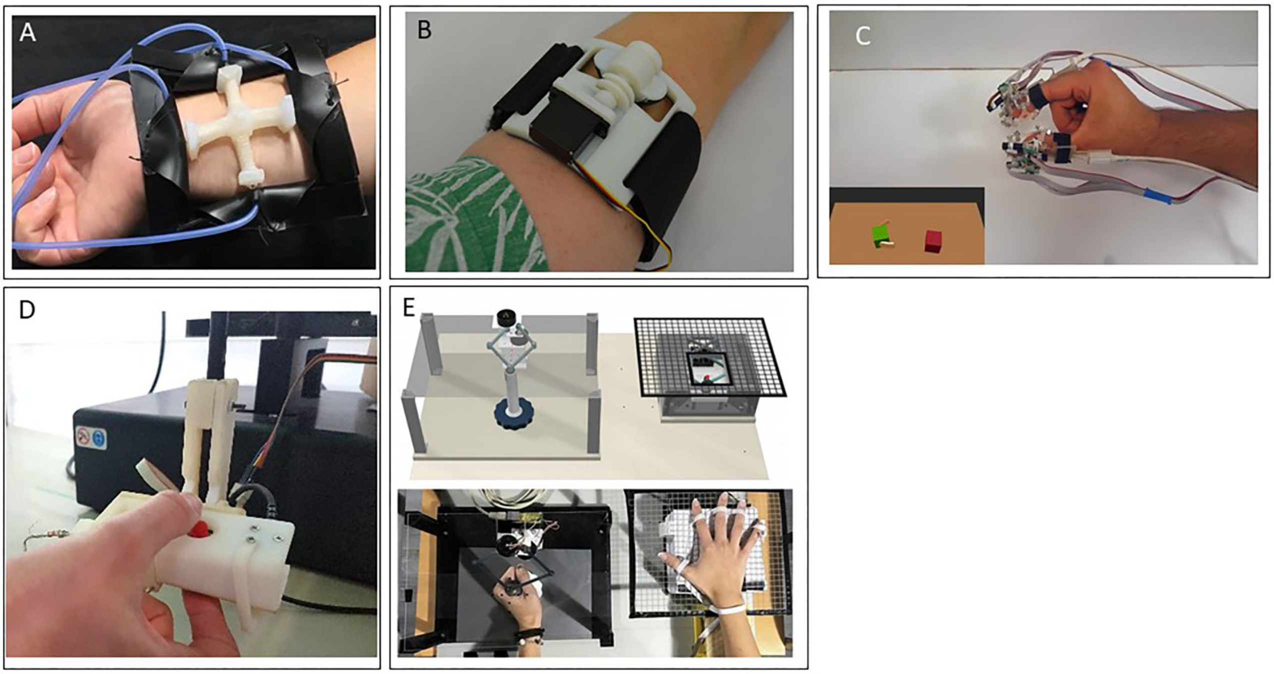

FIGURE 2 | Skin deformation—tangential and stretch stimulation devices. **(A)** A wearable device that is comprised of pneumatic actuators to guide motion direction (Kanjanapas et al., 2019). **(B)** The Rice Haptic Rocker that was designed to convey proprioceptive information to users of prostheses (Battaglia et al., 2019). **(C)** A wearable device that was used to render virtual environment forces (Schorr and Okamura, 2017b). **(D)** An aperture and tactor skin-stretch device that was used to study the contribution of tactile stimulation of the fingertips to motor adaptation (Avraham and Nisky, 2020). **(E)** The Tactile-STAR, a skin brushing stimulator (top right) and a recorder (top left) that were used to assess and train tactile perception acuity. The device was specifically designed to be appropriate for use with stroke survivors who may have difficulty in maintaining contact with an aperture and tactor type of a device (Ballardini et al., 2018).

feedback recorded by a human that wears a glove equipped with force sensors. The measured contact force at the remote interaction is fed back to the user through wearable tactile displays for each finger. Preliminary tests show that the realism of this remote experience largely improved with the tactile feedback.

Assessment of Tactile Impairments

Sensitivity to pressure is often used as a measure of absolute tactile sensitivity (for more details see Demain et al., 2013). The most commonly used method to assess pressure sensation is the Semmes–Weinstein monofilaments that are calibrated to apply predetermined forces to the skin (Semmes et al., 1960; Bell-Krotoski, 1984). Jacobs et al., suggested another approach for examining the psychophysical detection threshold of pressure stimulation of a prosthetic and a normal limb (Jacobs et al., 2000). Stimulations were applied using a computer connected to a probe and to a remote control that was operated by the patient. The patient could control the amplitude of the pushing force by pressing the remote control. To measure the detection threshold the up-down method was used (i.e., the amplitude of the pushing force was decreased until the patient did not feel the stimulation and stopped pressing the remote control). Then, the amplitude was increased until 16 reversals were obtained. This setup can be modified for home-based assessment, possibly by using a smaller controller instead of the computer.

Advantages and Disadvantages

Pressure stimulation enables rendering perceptual properties such as shape, curvature, orientation, and texture (Gabardi et al., 2016). However, sensitivity to pressure is largely dependent on the area of stimulation (Stevens, 1982). In addition, while multiple actuation approaches are available for applying pressure to the skin, each approach is suitable for a different application. Therefore, one should carefully consider the specifications of the design that would be appropriate for the desired application. Illustrations of pressure stimulation devices are presented in **Figure 3**.

Mid-air

All the technologies described above require physical contact between the device and the body to provide somatosensory feedback, and the energy produced by the actuators is transferred to the skin through a solid medium. This allows efficient energy transduction, creating natural haptic sensations with the aid of appropriate contactors to the skin. However, these solutions present some limitations: (1) they do not exploit arbitrary body locations, i.e., can deliver feedback only at a location close to the device's end effector, (2) they may cause undesired effects due to the continuous contact between the skin and the devices, and (3) if used by different individuals, they require cleaning and disinfecting, especially in light of the recent COVID-19 related recommendations (Thomas et al., 2020). Several recent

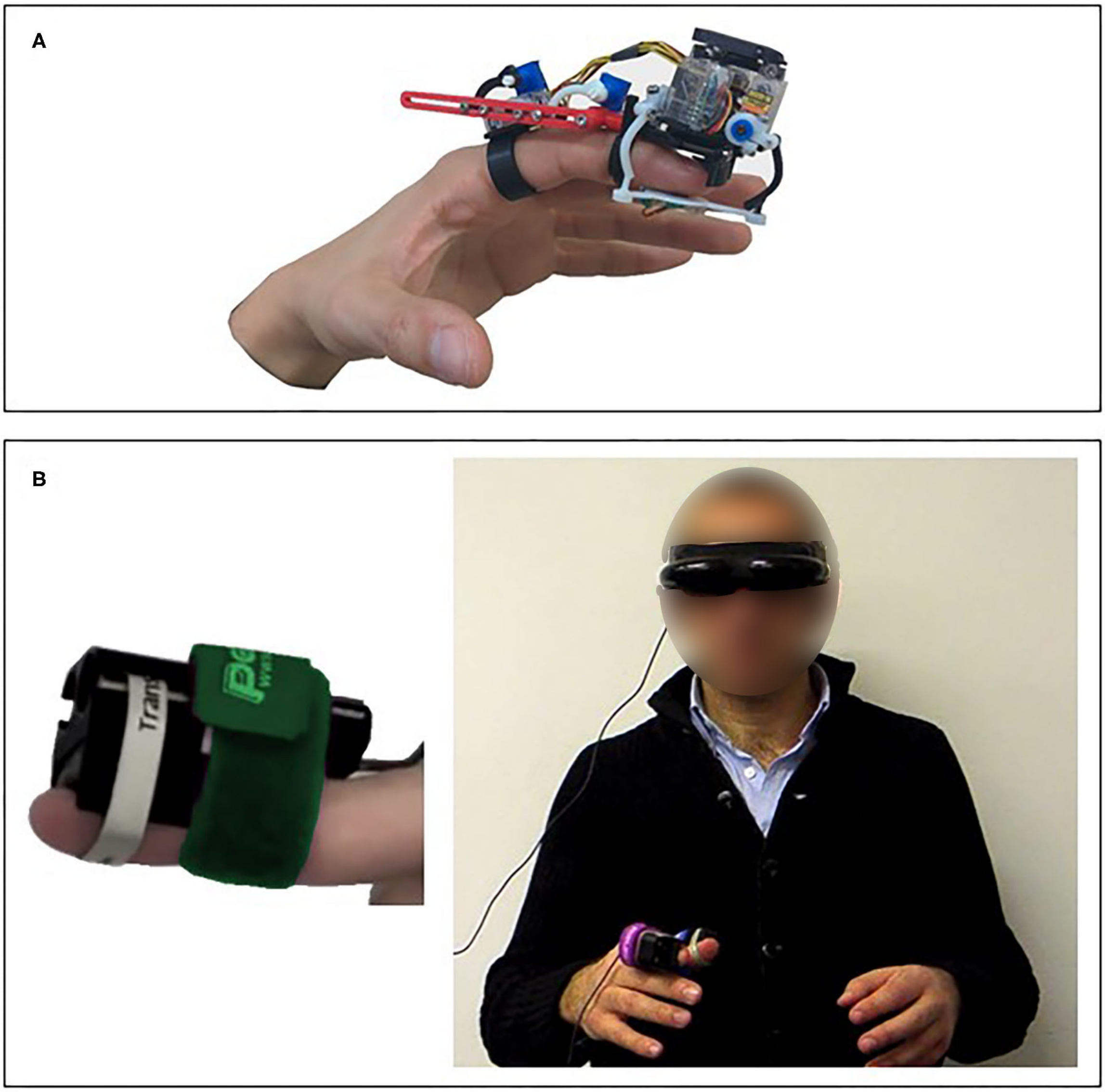

FIGURE 3 | Skin deformation—pressure stimulation devices. **(A)** A wearable finger device that was designed and tested in virtual reality applications (Chinello et al., 2019). **(B)** The RemoTouch system that provides experience of remote touch (Prattichizzo et al., 2010).

developments address these limitations by proposing mid-air technologies. They transmit the energy of the stimulus through air, avoiding the direct contact with the skin.

Technology

One of the main approaches to creating mid-air stimulation relies on ultrasonic waves, typically at 40 or 70 kHz frequencies (for survey see Rakkolainen et al., 2019). In this type of mid-air tactile stimulation the sensation is caused by a non-linear effect of focused ultrasound called acoustic radiation force, which induces a shear wave in the skin, creating a displacement, which triggers the mechanoreceptors within the skin and evoking mainly a pressure sensation (Gavrilov and Tsirulnikov, 2002). Most ultrasound haptic systems targeting the hand trigger the Lamellar corpuscles (Rakkolainen et al., 2019). In other body locations ultrasound can trigger other mechanoreceptors, such as Meissner corpuscles on the face (Gil et al., 2018), and Ruffini corpuscles or Merkel disks on the upper limb (Suzuki et al., 2018).

The most widely used technological solution to evoke tactile sensation with ultrasound is based on phased arrays of transducers, i.e., multiple transducers whose phase and intensity can be controlled individually, with a defined timing. In this way, the focused ultrasound waves can generate one or more localized regions of pressure in the 3D space, called focal points, without moving or turning the device. These focal points cannot be fully singular because of secondary peaks and wavelength limitations (Rakkolainen et al., 2019). However, several focal points can be controlled together to create shapes (Long et al., 2014) or textures

(Monnai et al., 2015; Freeman et al., 2017). If the radiation force is modulated at the 1–1 kHz range the ultrasound waves can also evoke a vibratory sensation in addition to the pressure sensation (Hasegawa and Shinoda, 2013; Howard et al., 2020; Rutten et al., 2020).

Applications for Enhancing Sensorimotor Performance and Learning

The use of focused ultrasound as a non-invasive method of stimulation has been studied since the early 1970s (Gavrilov et al., 1977). Recently, this technology was used for several proof-of-concept applications, including creating floating 2D icons (Gavrilov, 2008) and 3D haptic shapes (Long et al., 2014; Monnai et al., 2014; Vo and Brewster, 2015; Makino et al., 2016), interacting in a virtual reality environment (Romanus et al., 2019; Howard et al., 2020), and gesture interaction (Shakeri et al., 2017, 2018). To the best of our knowledge, mid-air haptic devices have not yet been used for rehabilitative purposes or for somatosensory assessment.

Applications for Conveying Social Tactile Cues

The communication of emotions through a haptic system that uses tactile stimulation in mid-air communication was explored by Obrist et al. and showed promising results of interpretability of emotions (Obrist et al., 2015). Despite these promising results the application of ultrasound devices for conveying emotions and social interaction has not yet been extensively investigated.

Advantages and Disadvantages

The major advantage of this emerging technology is its not requiring contact with the body, while easily and efficiently creating static or dynamic textures and volumetric shapes. Another important advantage is that commercial devices are available that use this technology, even at this early stage. In its current state, this technology has some inherent limitations that may have an impact on potential applications, including the size and the weight of the transducers (Rakkolainen et al., 2019) and the low intensity of the force conveyed to the user, which is at most 160 mN (Tsalamlal et al., 2013), and so does not allow the rendering of real-word interaction forces. Nevertheless, we anticipate that mid-air solutions will develop in the next few years, and we foresee that they will be designed for rehabilitation purposes and clinical assessments. Illustrations of mid-air stimulation devices are presented in **Figure 4**.

DISCUSSION

The COVID-19 pandemic is currently placing significant pressure on health services including rehabilitation services, worldwide. The reduced access to rehabilitation care due to restrictions as well as the reduction in rehabilitation services as a consequence of reassignment of rehabilitation professionals to acute care and the transformation of rehabilitation facilities into makeshift inpatient wards (Boldrini et al., 2020a; Chaler et al., 2020) are expected to lead to long-lasting negative consequences for individuals with disabilities (Boldrini et al., 2020b). In fact, these are only the tip of the iceberg when considering the long-standing and more severe problem of limited resources in hospital care together with the rising number of individuals with chronic diseases (Koh et al., 2015; Steihaug et al., 2016; Dodakian et al., 2017).

Remote communication technologies, as well as technologies developed for home-based telerehabilitation, have the potential to support neurorehabilitation care and make breakthroughs in treatment by facilitating continuous and intensive training. The emerging technological solutions reviewed in the current paper highlight the promise of wearable tactile stimulation devices to enhance home-based rehabilitation training gains by the provision of tactile feedback and haptic interactions. These technologies seem propitious and attractive for home-based rehabilitation: the devices are wearable, portable, and relatively low cost (estimated cost between tens and hundreds of dollars). Moreover, some of these technologies can easily be integrated into virtual/telerehabilitation environments (Feintuch et al., 2006; Bortone et al., 2018; Wang et al., 2020).

However, despite technological advantages and great potential for home-based practice, to date, tactile feedback devices have not yet evolved into common solutions for rehabilitation. There are still challenges that need to be met in a joint effort between sensorimotor neuroscientists, technology developers and clinicians in order to successfully integrate tactile technologies into neurorehabilitation programs. We review these challenges in the remainder of this section.

Testing Training Effects on Large Patient Populations

Most tactile device prototypes were tested on healthy individuals or on small cohorts of patients and their effects need to be further examined: (1) on larger patient populations, ideally in randomized controlled trials, (2) over longer training periods, and with long-term follow up assessments to evaluate whether improvements observed immediately post training have been retained after training is completed and (3) with respect to outcome measures relevant to the daily life function of the patients. Studies conducted on healthy individuals often focus on laboratory parameters, while in patients undergoing rehabilitation exploring whether training effects have transferred to daily life activities is of clinical significance. As was demonstrated above, few such examples exist in the literature; however, these are the exception and not the rule, and more studies are needed. Several factors contribute to the difficulty of overcoming this challenge. First, the lack of collaborations between technology developers, researchers, clinicians, and rehabilitation facilities. Second, it is difficult to secure funding for such large-scale studies. Third, the facts that most tactile devices are not commercially available and do not have medical device safety approval limits the ability to easily test them on patient populations.

Translation Into Clinical Practice

To integrate tactile stimulations into rehabilitation training it is critical to identify the optimal method to provide the feedback and the patients that would benefit from such training. The feedback provided by some common devices might be difficult to interpret and integrate. Also, the tactile stimuli patterns might not be intuitive or might be too complex for the user, due to

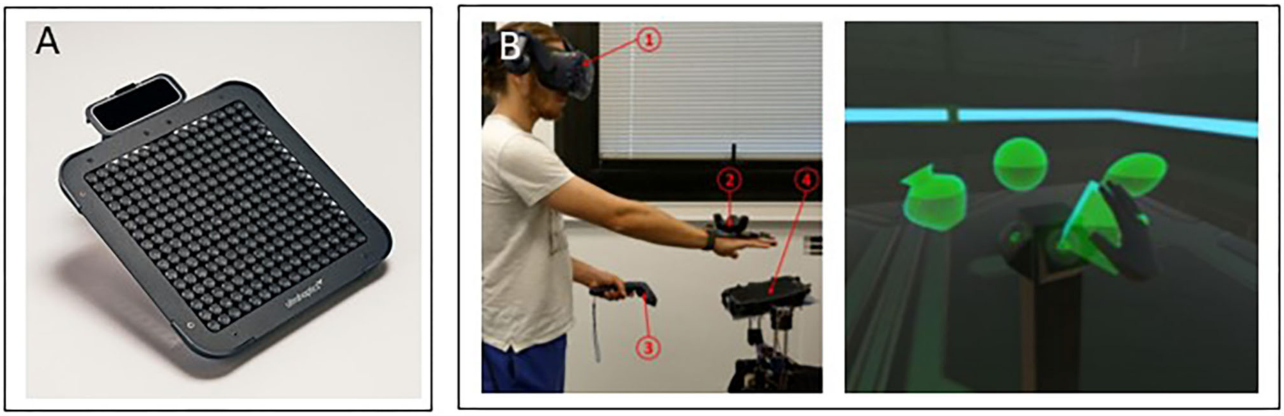

FIGURE 4 | Mid-air devices. **(A)** The Ultraleap device (https://www.ultraleap.com/). **(B)** Its application to interaction with a virtual reality environment (Howard et al., 2020).

either the number of tactile motors forcing the user to process a redundant set of signals, or to the encoding methods that may require specific attention (Brewster and Brown, 2004; Ballardini et al., 2020). This is especially important for patients undergoing rehabilitation training, who are often at the initial stages of learning that already require a relatively high degree of cognitive effort and attention (Fitts and Posner, 1967). Moreover, some neurological patients suffer from cognitive and attention deficits, and hence, to benefit from added information, the feedback must be simple (Van Vliet and Wulf, 2006). Additionally, the cognitive load of interpreting tactile cues in applications where the patient's attention is divided among multiple tasks, and how this might reduce the saliency of the cues, should be further explored (Gleeson et al., 2010b; Shah et al., 2018).

The optimal timing of providing somatosensory feedback also needs to be examined. For example, providing feedback for the entire duration of training can improve short term performance, but may limit motor learning. Conversely, providing feedback for only portions of training might produce poor initial performance, but improve motor skill retention (Winstein and Schmidt, 1990). Moreover, the conditions under which tactile feedback is most effective at improving task performance should be examined (e.g., whether it is most effective when supplementing another modality), as well as the temporal and spatial patterns and the location for applying the stimulation.

In addition, affective haptic feedback, used to render realistic feelings, has the potential to enhance remote patient-therapist communication. It can also be applied to reinvigorate the patient's interest when he/she is bored or frustrated during practice (Eid and Al Osman, 2015). While wearable haptic devices were designed to replicate a specific interaction or gesture such as comfort and affection (Culbertson et al., 2018a; Nunez et al., 2019, 2020), attention (Baumann et al., 2010) or social presence (Baldi et al., 2020), further exploration is needed in order to gain a better understanding of how to create realistic sensations, how to display them in complete synchronization with other display modalities (i.e., visual, auditory, olfactory, etc.), and how to integrate them in the right context during remote rehabilitation sessions. Other important challenges relate to touch etiquette in social interaction and how to incorporate social, cultural and individual differences with respect to the acceptance and meaning of affective touch (Eid and Al Osman, 2015).

Using the Technology at Home

Although the devices seem promising for home use and some have already been tested in at-home practice (Bao et al., 2018; Seim et al., 2020a,b) some gaps still need to be bridged in this regard. First, further studies are needed to explore the feasibility of using tactile devices by patients undergoing home-based telerehabilitation: whether patients can correctly wear and operate the device without assistance, whether the form of the device is compatible for patients with different impairments, the adherence of using or wearing the device (Seim et al., 2020a), and safety and technical problems that may arise when using it during the training period (Seo et al., 2020). Second, tactile devices need to be integrated into already existing or new telerehabilitation/virtual reality systems to provide the whole framework of sensorimotor training (Feintuch et al., 2006).

Rehabilitation platforms that are capable of intelligent, adaptable tactile feedback configurations, adjustable in terms of difficulty level, capable of measuring performance and progression and of providing exercises relevant to daily living activities as well as motivating the user's engagement could provide a more tailored training intervention to maximize improvements (Shull and Damian, 2015; Navarro et al., 2018). Additionally, there are other important issues related to telerehabilitation in general, such as web communication between the therapist and the patient, information security, and data storing that are beyond the technical-clinical outlook of our review.

CONCLUSIONS

The COVID-19 pandemic has highlighted the need for home-based telerehabilitation and at the same time has accelerated the adoption of a digital culture worldwide. Exploiting this opportunity together with the rapid developments in wearable haptic technologies offers a time window to advance sensorimotor neurorehabilitation, elevating it to innovative solutions for home-based therapies. Although there remain gaps and challenges that still need to be addressed jointly by scientists, technology developers and clinicians, wearable haptic devices, if correctly adapted, could potentially turn into cost-effective medical devices for use at home by individuals in need of rehabilitation treatments. The integration of tactile devices into home-based telerehabilitation practice has the potential to enhance patients' functional gains and quality of life through practice in an enriched environment with augmented tactile feedback and tactile interactions.

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All authors contributed to the article (drafting and writing) and approved the submitted version.

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