

Optimal physical activity across the lifespan for people of all abilities

Edited by

Ronald F. Zernicke and David Arthur Hart

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Optimal physical activity across the lifespan for people of all abilities

Topic editors

Ronald F. Zernicke — University of Michigan, United States

David Arthur Hart — University of Calgary, Canada

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EDITED AND REVIEWED BY
David Broom,
Coventry University, United Kingdom

*CORRESPONDENCE
David A. Hart
✉ hartd@ucalgary.ca

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Editorial: Optimal physical activity across the lifespan for people of all abilities

David A. Hart^{1*} and Ronald F. Zernicke^{2,3}

¹Department of Surgery, Faculty of Kinesiology, McCaig Institute for Bone & Joint Health, University of Calgary, Calgary, AB, Canada, ²Department of Orthopaedic Surgery, Michigan Medicine, School of Kinesiology, University of Michigan, Ann Arbor, MI, United States, ³Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI, United States

KEYWORDS

physical activity, exercise, MSK health, cardiovascular health, across the lifespan

Editorial on the Research Topic

Optimal physical activity across the lifespan for people of all abilities

Humans, like all current species, evolved within the context of the boundary conditions of Earth, including its 1 g gravity. In that context, we evolved to move, making us a dynamic species that subscribes to the “use it or lose it” principle for many of our tissues (1). Humans depend on motion and navigation through the environment to survive, and thus, depend on mechanical loading of our tissues to maintain the integrity of nearly all our physiological systems, as evidenced by the adverse effects of prolonged exposure to microgravity in space, following prolonged bed rest, and generalized inactivity. Inactivity and its accompanying diminished loading conditions on physiological systems pose a threat to health, and exercise is required to maintain and optimize health worldwide [reviewed in (2–5)]. Thus, *Homo sapiens* likely require constant and repetitive loading of our tissues during the day, adequate nutrition, and periods of rest (i.e., sleep) (6) to optimize quality of life and achieve wellness throughout life.

Much of the focus on the benefits of exercise has been on elite athletes who push the boundaries of our genetic inheritance to achieve higher and higher levels of accomplishment. Clearly, the abilities of Olympic athletes are examples of this, as are those of other amateur and professional athletes. These abilities are contingent upon intense exercise and training programs, along with optimal mental health, and they do provide new insights about the upper limits of human capabilities. However, they can also have consequences such as injuries to essential physiological systems, such as the musculoskeletal (MSK) system. In addition, focusing only on the extremes of exercise and functionality can cause us to lose sight of the fundamental premise that loading of our tissues—particularly those of the MSK and cardiovascular systems—is essential for health, and thus important for individuals of all ages and abilities. While all humans benefit from physical activity, women and men and different ethnicities may experience risks and benefits (7), so “one size may not fit all”.

In recent years, there has been a shift in many “modern” occupations from being physically demanding to involving prolonged periods of “inactivity” while sitting at a desk in front of a computer screen [reviewed in (8)]. For example, children and adolescents sit in school for much of the day and in front of their electronic devices, leading to extended periods of inactivity in otherwise healthy populations that are

growing and maturing, and thus setting a suboptimal “baseline” for several physiological systems during a critical phase of life (9, 10)! In addition to these populations, others of different ages may have compromised abilities to perform exercise as a result of limited access to programs, physical limitations due to injury, developmental deficits, and/or chronic diseases or complications from lifestyle choices and their consequences. These populations can still benefit from tailored, adaptive exercise programs that offer aerobic and/or resistive exercises \pm augmentation, which allow for maintenance of essential physiological systems.

To address many of the issues and challenges to meet those needs in populations across a wide spectrum of abilities, this Research Topic of articles was conceived and compiled. It consists of both original research reports and reviews. The Research Topic of articles includes 11 peer-reviewed and accepted submissions that provide excellent examples of how physical activity programs can benefit specific populations ranging from the young to the elderly with or without specific limitations, along with those individuals who are motivated to achieve excellence despite perceived limitations, as seen in the Paralympics.

The spectrum of articles in the Research topic addresses several conditions, diseases, and circumstances that impact a wide variety of populations. These include different types of exercise programs and activities that target specific populations such as neurodivergent children (Sapre et al.), patients with Parkinson’s disease (McKee et al.), individuals with spinal cord injuries (Martinez et al.), and elderly patients with changes in cognition (MacDonald et al.). Other articles assess the efficacy of physical activity programs (Muñoz-Cofré et al.) and the use of tele-exercise programs for individuals with difficulties accessing regular programs (Garrido et al.). The effectiveness of cycling as a means to achieving aerobic fitness is addressed (Mosser et al.), as is the use of neuromuscular electrical stimulation to offer potential benefits to various populations (Ackermann et al.). Other articles in this Research Topic provide insights into how physical activity may benefit specific populations, such as military veterans (Tinney and Nguyen) and those individuals affected by the consequences of infectious diseases, such as COVID-19 (Opielinski et al.). Finally, an article by Bonnevie-Svendsen et al. provides insights into some recently identified biomarkers in triathletes. Building on these results, it would be interesting in the future to investigate whether similar or different biomarkers are also identified as determinants of the efficacy of physical activity programs for the specific populations that are the focus of other articles in this Research Topic.

In summary, this Research topic focuses on addressing the need for and benefits of physical activity in populations across a wide spectrum of abilities. This Research Topic complements an earlier Research Topic that we edited, which focused on the benefits of physical activity for those aspiring to achieve at the highest levels (11). We intend for this Research Topic to highlight the need for and benefits of physical activity for *Homo sapiens* of all abilities to engage and perhaps to provide inspiration for some populations not covered in this Research Topic to develop and implement specialized physical activity programs, providing an even broader spectrum of positive health benefits for individuals whose abilities are limited or challenged by circumstances.

Author contributions

DH: Writing – review & editing, Writing – original draft. RZ: Writing – original draft, Writing – review & editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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EDITED BY

Ronald F. Zernicke,
University of Michigan, United States

REVIEWED BY

Deborah Riebe,
University of Rhode Island, United States
Bradley Douglas Hatfield,
University of Maryland, United States

*CORRESPONDENCE

Myles W. O'Brien
✉ myles.obrien@USherbrooke.ca

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Moderate intensity intermittent lifestyle physical activity is associated with better executive function in older adults

Emily MacDonald¹, Elisabeth G. Morrison²,
Madeline E. Shivgulam³, Liam P. Pellerine³, Derek S. Kimmerly³,
Nick W. Bray⁴, Said Mekari^{5,6} and Myles W. O'Brien^{5,6*}

¹Department of Neuroscience, Faculty of Science, Dalhousie University, Halifax, NS, Canada, ²School of Kinesiology, Acadia University, Wolfville, NS, Canada, ³Division of Kinesiology, School of Health and Human Performance, Faculty of Health, Dalhousie University, Halifax, NS, Canada, ⁴Faculty of Medicine, Memorial University of Newfoundland, St. John's, NL, Canada, ⁵Department of Medicine, Université de Sherbrooke, Sherbrooke, QC, Canada, ⁶Centre de Formation Médicale Du Nouveau-Brunswick, Université de Sherbrooke, Moncton, NB, Canada

Executive functions are among the first cognitive abilities to decline with age and age-related executive function slowing predisposes older adults to cognitive disorders and disease. Intermittent Lifestyle Physical Activity (ILPA) reflects brief, unplanned activity that occurs during routine daily activities and is operationalized as activity bouts <60s. Our understanding of short bouts of habitual physical activity and executive functions is limited. We tested the hypothesis that greater amounts of ILPA in moderate and vigorous intensity domains would be associated with better executive function in older adults. Forty older adults (26 females, 68 ± 6 , >55 years; body mass index: 26.6 ± 4.3 kg/m²) completed a Trail-Making-Task and wore an activPAL 24-hr/day for 6.2 ± 1.8 -days. For each intensity, total time and time spent in bouts <60 s were determined. Trail A (processing speed) and Trail B (cognitive flexibility) were completed in 25.8 ± 8.2 s and 63.2 ± 26.2 s, respectively. Non-parametric Spearman's rank correlations report that moderate ILPA (3.2 ± 3.2 min/day) and total-moderate physical activity (20.1 ± 16.0 min/day) were associated with faster Trail A (total-moderate physical activity: $\rho = -0.48$; moderate-ILPA: $\rho = -0.50$; both, $p < 0.003$) and Trail B time (total-moderate physical activity: $\rho = 0.36$; moderate-ILPA: $\rho = -0.46$; both, $p < 0.020$). However, the results show no evidence of an association with either vigorous physical activity or light physical activity (total time or ILPA bouts: all, $p > 0.180$). Moderate physical activity accumulated in longer bouts (>60 s) was not associated with Trail B time ($p = 0.201$). Therefore, more total moderate physical activity and shorter bouts (<60 s) may result in better executive functions in older adults.

KEYWORDS

physical activity intensity, short bout physical activity, cognitive aging, cognitive decline, Trail-Making-Task

Introduction

It is well-established that cognitive decline is a critical health risk to the aging population, with ~50% of adults ≥ 85 years old exhibiting evidence of cognitive impairments (1). Cognitive decline is initially characterized by the deterioration of executive functions, which are a set of cognitive processes encompassing skills such as

working memory, cognitive flexibility, planning, and regulating behavior (2). Worsening executive function is recognized as an early predictor for many neurological conditions, including dementia and Alzheimer's disease (3, 4). There is increasing support for regular physical activity as a useful strategy for slowing this cognitive decline, specifically in older adults (5). Our understanding of the impact between the intensity and duration of physical activity with executive functions in older adults is unclear but could prove useful in helping guide strategies that prevent the development of cognitive damages associated with age.

The World Health Organization physical activity guidelines recommend that adults >65 years old accumulate at least 150 min of moderate-to-vigorous physical activity per week (6). Habitual physical activity refers to daily leisure activities conducted at home or work (7). While laboratory-based studies have demonstrated that engaging in aerobic exercise training improves cognition (8), considerably less is known about the impact of free-living or real-world activity on cognitive aging. In middle-aged and older adults, higher self-reported physical activity was associated with an attenuated decrease in processing speed with age (9). Similarly, increased habitual self-reported physical activity was associated with a decreased decline in executive function in older adults with Alzheimer's disease (7). However, the influence of habitual activity, and specifically the intensity of free-living activity, on executive functions in healthy older adults remains understudied.

Strategies to help individuals incorporate more, moderate and vigorous intensity activity as part of their day-to-day life have been promoted. These include concepts such as "exercise snacks" and intermittent lifestyle physical activity (ILPA). Exercise snacks refer to brief (i.e., ~60 s), planned periodic bouts of physical activity throughout the day to replace a singular longer duration (10). Exercise snacking has been associated with improved physical function and balance in pre-frail older adults (11), muscle function in healthy older adults (12), and cardiovascular fitness in young adults (13). Although practically similar, ILPA reflects brief and *unplanned* bouts (<60 s) of physical activity of varying intensity integrated into an individual's daily routine (14). ILPA is a relatively novel concept in physical activity research, but preliminary findings suggest that more vigorous-ILPA may contribute to a reduction in all-cause (15), cancer-specific, and cardiovascular disease mortality (16, 17). We have previously documented that more time spent in moderate physical activity was associated with better cognitive flexibility and greater oxygenation of the prefrontal cortex during a Stroop Task (18). However, the impact of physical activity patterns and ILPA intensity on executive function is unclear. While epidemiological research documents a favorable impact of vigorous-ILPA on mortality (16, 17), it is unclear whether light- or moderate-intensity ILPA may also be linked with health benefits or whether more time spent engaging in ILPA leads to cognitive benefits in older adults.

The main objective of this study was to determine the relationship between ILPA with executive function as assessed via a Trail-Making-Task in cognitively healthy older adults. It was

hypothesized that more time spent in moderate-ILPA or -vigorous-ILPA would be associated with faster reaction times on the Trail-Making-Task.

Methods

Participants

This cross-sectional study recruited 40 older adults, >55 years (26 female) from the Acadia University Active Aging program. A sub-sample ($n = 32$) of the activity monitor data have been previously presented (18). However, the ILPA and Trail-Making-Task outcomes were not presented. This study answers a novel, independent research question. In the absence of a well-informed effect size, an estimated moderate effect size ($r = 0.50$), a bivariate correlational model calculated that a minimum of 29 participants were needed assuming a two-tailed, $\alpha = 0.05$ and $\beta = 80\%$ power (19). Participants had no physical limitations to exercise and a resting blood pressure <140/90 mmHg and resting heart rate <100 beats/min. All participants were healthy and had normal-to-corrected vision. None of the participants had a history of neurological or psychiatric disorders, color blindness, surgery with general anesthesia during the previous 6 months, involuntary tremors, epilepsy or drug/alcohol problems. Some participants were taking medications for hypothyroidism (Synthroid, $n = 4$) and high blood pressure (Teveten, $n = 1$ and Adalat XL, $n = 1$). Participants were excluded if they scored <25 out of 30 on the Mini-Mental State Examination (average: 29.4 ± 1.2). Research Ethics Board approval was obtained from Dalhousie University and Acadia University. Participants were informed of the methods and study design verbally and in writing before providing written informed consent.

Anthropometrics and Trail-Making-Task measurements

Height and weight were measured using a calibrated stadiometer and physician's scale (Health-O-Meter, McCook IL, USA) to the nearest 0.5-cm and 0.1-kg respectively. Body mass index was calculated as body mass (kg) \div height (m)².

The Trail-Making-Task is a widely recognized and validated cognitive assessment tool used in research (20). Participants completed both parts of the test: Part A (Trail A) and Part B (Trail B). Part A assess processing speed and involves participants drawing connecting lines between numbers in ascending order. Participants were instructed to, "Please take the pencil and draw a line from one number to the next, in order. Start at 1 [point to the number], then go to 2 [point], then go to 3 [point], and so on. Please try not to lift the pen as you move from one number to the next. Work as quickly and accurately as you can" (21). Emphasis was placed on both speed and accuracy. Participants were encouraged to correct any errors, and the total time required to complete the task was recorded in seconds. Part B of the Trail-Making-Task (Trail B) evaluated cognitive

flexibility and switching ability. Participants were given the same instructions as in Trail A but had to alternate between numbers in ascending order and letters in alphabetical order (1-A-2-B-3-C, etc.). The time required to complete Trail B was also measured in seconds.

Before administering the standardized version of the test, participants were provided with a brief practice trial to familiarize themselves with the task requirements. This practice trial was given prior to each part of the test to ensure that participants understood the instructions and could perform the task accurately.

Free-living activity monitoring

The activPAL inclinometer (V3, Pal Technologies LTD, Glasgow, UK) was used to objectively measure physical activity and sedentary time. The activPAL is a valid measure of free-living posture (22) and physical activity (23). All participants wore the activPAL 24-h/day for 5–7 days (6.2 ± 1.8 days) based on previous wear time recommendations (24). The activPAL was waterproofed and secured using a nitrile finger cot and a transparent medical dressing to the midline of their right thigh, one third of the way between the hip and knee (25).

The raw activPAL data were exported into PAL analysis (version 5.8.5) for data processing, this program produced a range of activity summaries, including an events and a 15s epoch file. Further processing of these summaries was conducted using a customized MATLAB program (MathWorks, Portola Valley, CA, USA) that produced daily averages of time awake, standing time, and sedentary time. An additional, openly available, LabVIEW (National Instruments, Austin, TX, USA) program determined time spent in each physical activity intensity via step rate thresholds determined based on body mass index (26).

Intermittent lifestyle physical activity

The activPAL provides an Events XYZ.csv file, which classifies raw acceleration counts into postural activities (i.e., sedentary, standing, or stepping) and includes timestamps of activity, tri-axial acceleration profiles, and the duration of each postural bout. Another customized LabVIEW bout-cadence program was created to calculate time spent in various intensities of physical activity. Sixty-second bouts were chosen based on the definition provided in a previous ILPA study (14). Using body mass index-tailored step rate thresholds (27), the program sorted through the Events XYZ file to categorize stepping bouts as light physical activity, moderate physical activity, or vigorous physical activity from the average cadence recorded via the activPAL and the bout duration. Light physical activity was characterized as anything $< 108.2 \pm 2.4$ steps/min, moderate physical activity as anything between 108.2 ± 2.4 and 134.5 ± 4.6 steps/min, and vigorous physical activity was anything $> 134.5 \pm 4.6$ steps/min. The program exported a.csv summary file which included daily totals of the frequency and duration (in minutes) in light physical activity, moderate physical activity, and, vigorous physical activity for < 60 -s

bouts, ≥ 60 -s bouts, and all bouts. ILPA is classified as short bouts < 60 s, bouts ≥ 60 s used for exclusively longer physical activity, total physical activity includes both short and long bouts.

Statistical analysis

All data were assessed for normality using a Shapiro-Wilk test and data were analyzed using non-parametric statistical tests. Specifically, the relationship between each physical activity intensity vs. Trail A and Trail B completion times were analyzed using Spearman’s Rank correlations. Interactions between each ILPA intensity with age or sex were determined for both Trail A and Trail B times. Exploratory analyses indicated no significant interactions were observed (age \times ILPA: all, $p > 0.15$; sex \times ILPA: all $p > 0.06$), indicating that correlational analyses can be conducted on the pooled sample and that neither sex nor age moderated this relationship in this specific study. All statistics were completed in SPSS Version 28.0 (IBM, NY). Statistical significance was accepted as $p < 0.05$. All data are presented as means \pm standard deviations.

Results

Data from 40 older adults (26 females) with an average age of 68 ± 6 years (56–83), a body mass index of 26.6 ± 4.3 kg/m², average heart rate of 69 ± 10 beats/min, an average systolic blood pressure of 124 ± 11 mmHg and diastolic blood pressure of 71 ± 9 mmHg were included in the current study (Table 1).

TABLE 1 Participant descriptive characteristics, habitual posture, and physical activity outcomes.

| Variable | Participant (<i>n</i> = 40) |
|---|----------------------------------|
| Age (years) | 68 \pm 6 (56–83) |
| Sex (males, females) | 14, 26 |
| Height (cm) | 165.3 \pm 9.8 (146.0–183.0) |
| Weight (kg) | 71.2 \pm 13.7 (41.0–107.0) |
| Body mass index (kg/m ²) | 26.6 \pm 4.3 (19.4–40.6) |
| MMSE (score/30) | 29.4 \pm 1.2 (26–30) |
| Step count (steps/day) | 9,203 \pm 3,439 (3,772–19,694) |
| Sedentary time (hours/day) | 9.1 \pm 1.6 (2.6–10.7) |
| Standing time (hours/day) | 6.3 \pm 1.4 (3.5–11.5) |
| Light physical activity-total (min/day) | 93.0 \pm 29.5 (35.3–155.4) |
| Total-moderate physical activity (min/day) | 20.1 \pm 16.1 (0.2–70.9) |
| Vigorous physical activity-total (min/day) | 2.4 \pm 3.1 (0.1–12.9) |
| Light physical activity duration ≥ 60 s (min/day) | 22.1 \pm 14.5 (4.1–67.5) |
| Moderate physical activity duration ≥ 60 s (min/day) | 16.9 \pm 15.2 (0.0–69.0) |
| Vigorous physical activity duration ≥ 60 s (min/day) | 2.1 \pm 2.9 (0.1–12.7) |
| Light-ILPA duration (min/day) | 70.9 \pm 22.8 (31.2–120.7) |
| Moderate-ILPA duration (min/day) | 3.2 \pm 3.2 (0.05–13.6) |
| Vigorous-ILPA duration (min/day) | 0.3 \pm 0.7 (0.03–2.9) |
| Light-ILPA frequency (bouts/day) | 363.0 \pm 115.3 (8.9–617.6) |
| Moderate-ILPA frequency (bouts/day) | 24.0 \pm 19.1 (1.4–83.3) |
| Vigorous-ILPA frequency (bouts/day) | 17.3 \pm 6.9 (1.7–42.1) |

Data presented as means \pm SD (range).
SBP, systolic blood pressure; DBP, diastolic blood pressure; MMSE, mini-mental state exam.

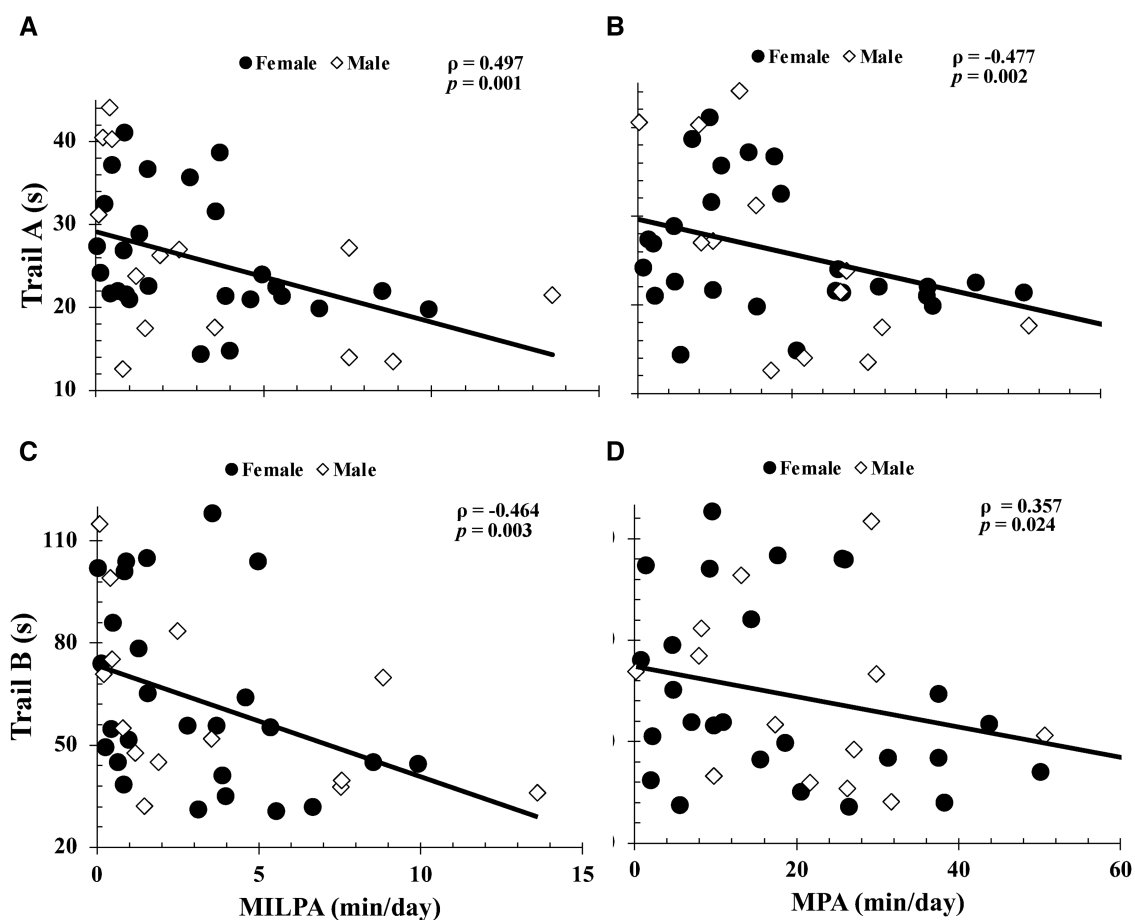


FIGURE 1

Relationships between trail A completion time with moderate intermittent lifestyle physical activity (moderate-ILPA) duration (A), moderate physical activity duration (B), and between trail B completion time vs. moderate-ILPA duration (C) and moderate physical activity duration (D). Relationships were determined via Spearman's Rank Correlations. Data are presented for $n = 40$.

Participants accumulated 9.1 ± 1.6 h/day of sedentary time and 6.3 ± 1.4 h/day of standing time. The completion times for Trail A and Trail B were 25.8 ± 8.2 s and 63.2 ± 26.2 s, respectively. Total-moderate physical activity, moderate-ILPA, and exclusively longer bouts (≥ 60 s) of moderate physical activity were engaged in for an average of 20.1 ± 16.0 min/day, 3.2 ± 3.2 min/day and 16.9 ± 15.2 min/day, respectively. Light physical activity, on average, was engaged in for 6.5% of the day, moderate physical activity for 1.4% of the day and vigorous physical activity for 0.02% of the day.

More time spent engaged in total-moderate physical activity and moderate-ILPA were associated with faster Trail A (total-moderate physical activity: $\rho = -0.48$; moderate-ILPA: $\rho = -0.50$; both, $p < 0.003$) and Trail B completion times (total-moderate physical activity: $\rho = -0.36$; moderate-ILPA: $\rho = -0.46$; both, $p < 0.020$) (Figure 1). In contrast, time spent in moderate physical activity bouts lasting ≥ 60 s (16.9 ± 15.2 min/day) was negatively correlated with Trail A completion time ($\rho = -0.38$ $p = 0.02$), but not with Trail B ($\rho = -0.21$ $p = 0.20$). As seen in Figures 2, 3, neither total- or ILPA for vigorous or light physical activity, were associated with Trail A or Trail B performance (all, $p > 0.18$).

Discussion

The purpose of this study was to examine the relationship between intensity based ILPA durations and executive function in cognitively healthy older adults. Consistent with our hypothesis, more time spent in total-moderate physical activity and moderate-ILPA was associated with faster completion times on both Trail conditions. However, unexpectedly, vigorous-ILPA was not associated with Trail task performance (Figure 3). Studying the associations between physical activity intensity and executive function is of importance with advancing age, as individuals become more susceptible to cognitive decline. The findings of this study provide support for the beneficial impact of brief periods of moderate physical activity on executive function in older adults that may enhance cognitive well-being and positions easy-to-do activity as an important part of healthy cognitive aging.

A decline in executive function is an early predictor for a range of neurological conditions (3). Our study demonstrated that both moderate-ILPA and total-moderate physical activity were associated with higher processing speed (Trail A) and cognitive

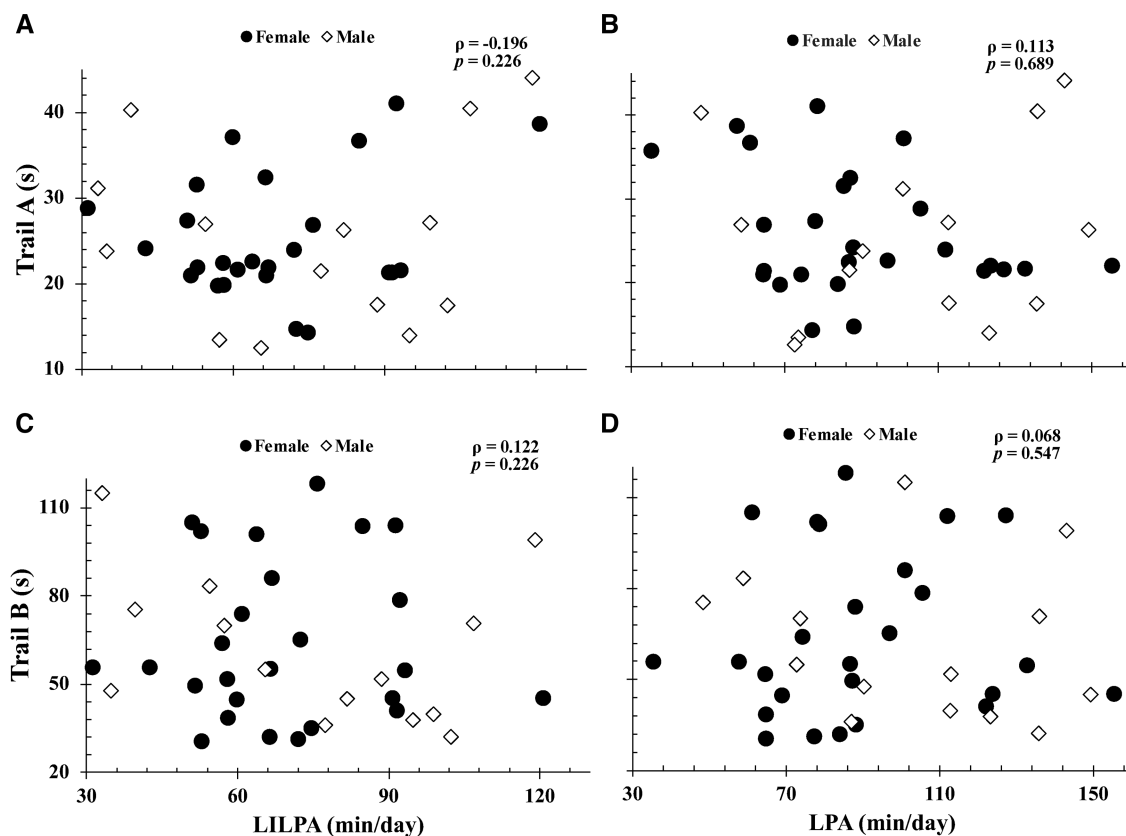


FIGURE 2

Relationships between trail A completion time with light intermittent lifestyle physical activity (light-ILPA) duration (A), light physical activity duration (B), and between trail B completion time vs. light-ILPA duration (C) and light physical activity duration (D). Relationships were determined via Spearman's Rank Correlations. Data are presented for $n = 40$.

flexibility (Trail B). In contrast longer bouts (≥ 60 s) of moderate physical activity were not associated with Trail B performance. These findings demonstrate that the association of faster reaction times and thus, a more favorable executive function with physical activity is primarily associated with ILPA (< 60 s bouts), not exclusively longer bouts (> 60 s). The relationship with both Trail A and Trail B indicates that moderate physical activity may be beneficial for both lower-level (e.g., processing speed) and higher-order cognitive processes (e.g., cognitive flexibility). It is important to note that while the results indicate that moderate ILPA may be beneficial, total moderate physical activity showed the same benefits. Therefore, this study is adding to the previous literature as it is well established that moderate physical activity can improve cognition, however, short bouts (ILPA) have been understudied. These observations are encouraging as brief periods of moderate physical activity may be more feasible to conduct than longer bouts. Furthermore, engaging in higher intensity physical activity is often more difficult for some older adults (28). Walking is the most common form of physical activity among older adults (29) and brisk walking is typically conducted at a moderate intensity (~ 100 – 110 steps/min) (30). Therefore, the present observations may inform the design of future movement interventions for older adults that target improvements in executive function.

Increased physical activity is associated with improved cognitive function and decreased cognitive decline with age for older adults with, and without impairment (31). Research has found an association between objectively measured higher intensity physical activity and better cognitive function, however, there was no association found between increased total physical activity duration and increased cognitive function (32). Additionally, increased self-reported physical activity intensity was associated with reduced cognitive decline in older men (33). Accordingly, it may not be longer total duration of physical activity, but rather, higher intensity that is important. The prefrontal cortex is recognized as the key structure for executive function (34) and it has been demonstrated that physical activity increases both blood oxygenation (35) and arousal (36) in the prefrontal cortex. Furthermore, it has been demonstrated that engaging in more moderate physical activity is linked to preserving volume of the dorsolateral prefrontal cortex with age, compared to those who are insufficiently active (37). Accordingly, the relationships observed may be due to the positive impact of moderate-ILPA on brain structures associated with executive function. Other research indicates that more physical activity increases levels of brain-derived neurotrophic factor, which is associated with improved brain function and plasticity (36). In addition to these prefrontal cortex processes

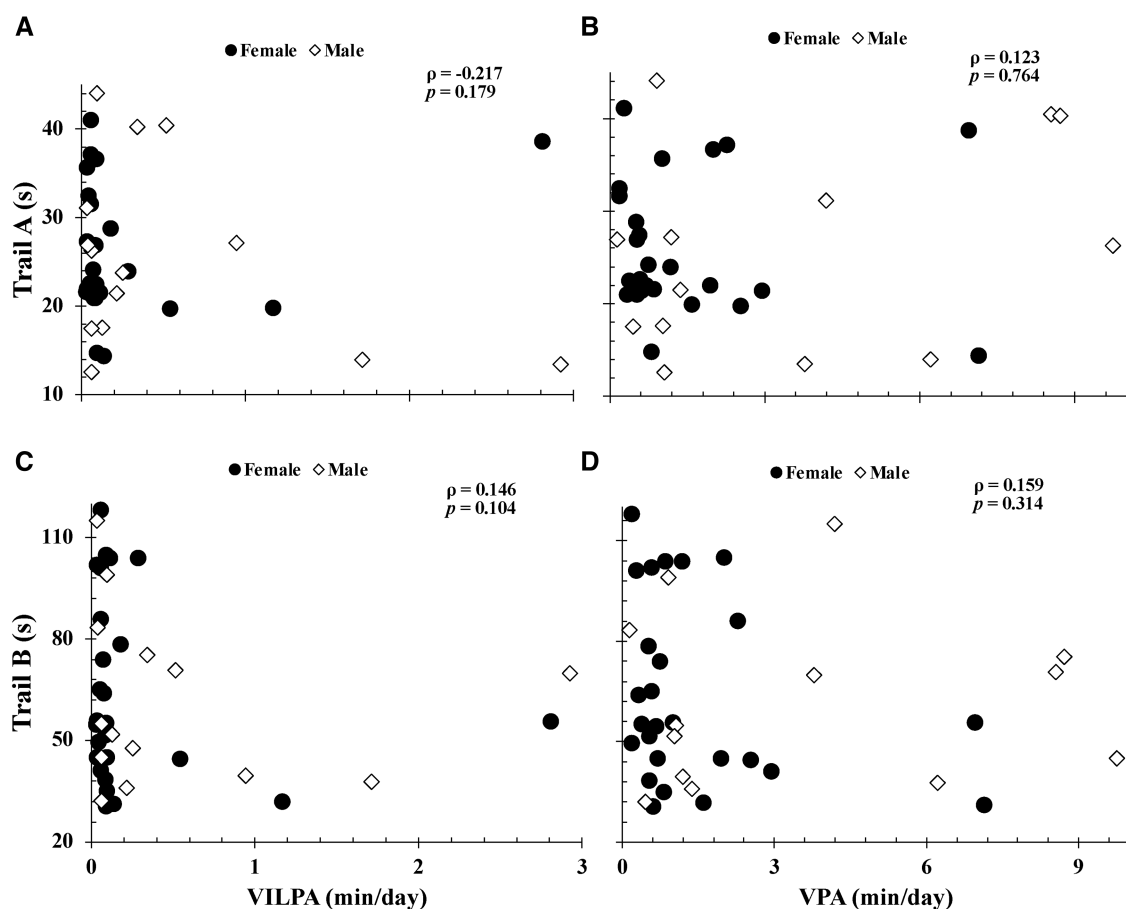


FIGURE 3

Relationships between trail A completion time with vigorous intermittent lifestyle physical activity (vigorous-ILPA) duration (A), vigorous physical activity duration (B), and between trail B completion time vs. vigorous-ILPA duration (C) and vigorous physical activity duration (D). Relationships were determined via Spearman's Rank Correlations. Data are presented for $n = 40$.

and improved neuroplasticity, exercise has demonstrated the potential to reduce neuroinflammation, which plays a role in the development of neurological disorders with declining executive function, such as Alzheimer's (38). All factors mentioned could explain the mechanistic links between ILPA and executive function, and the protective nature of exercise on cognitive health. Future work incorporating these mechanistic measures are warranted.

As reported with the World Health Organization guidelines, moderate-to-vigorous physical activity is recommended for improved health in older adults (6). Our results are consistent with this, as our average for total moderate physical activity was approximately 150 min/week, and more total moderate physical activity was associated with faster completion times for both Trail A and B tasks. While moderate-ILPA only represented 1.4% of participants daily time, it was also associated with faster completion times on both tasks, as such, future interventional research on increasing moderate-ILPA is warranted. While the specific amount of moderate-ILPA that translates to cognitive benefits are unclear, more moderate-ILPA in general is associated with executive function. Vigorous physical activity was not associated with either of the Trail-Making-Tasks. It should be noted that in our

participants, the duration of vigorous physical activity was much lower than that of moderate and light physical activity, thus, the minimal range of time spent in vigorous physical activity may be insufficient to reveal a correlational relationship. Additionally, the moderate-ILPA data has a much larger variance, which is beneficial for correlational analysis, compared to the vigorous-ILPA data (see Figures 1, 3). Interventional models aimed at promoting better executive functions among cognitively healthy older adults should consider moderate physical activity, and specifically studying the impact of integrating more brief periods of moderate physical activity into their lifestyle on cognitive outcomes.

The primary limitation of the study is its cross-sectional design and therefore cannot determine causality. However, the work is important in directing future intervention studies and applies novel objectively measured activity outcomes. Our participants were cognitively healthy older adults, and our observations may not be extrapolated to adults with cognitive impairments who may be less active (39). In these populations, there is a possibility that more light physical activity or less sedentary time may be useful for individuals with cognitive impairments. The definition for older adults being >55 or >65 years is ambiguous, additionally,

these results may not be generalized to older adults above the age of 85. This study did not investigate the mechanistic links of the pathways that might explain the association between ILPA and executive function, or the specific type of physical activity conducted by participants. However, our study is strengthened by its consideration of ILPA, a novel approach to physical activity, and its relationship with executive functions in older adults. Our observations provide valuable insights to a relatively understudied perspective regarding the most optimal physical activity intensity and pattern for healthy cognition.

Among cognitively healthy older adults, engaging in more moderate-ILPA and more total-moderate physical activity was associated with faster completion times in the Trail-Making-Task, indicating better executive function. Given that impairments in executive functions are the initial characteristics of cognitive decline, strategies that investigate the impact of- and promote more brief periods of moderate physical activity, may be easy to integrate as lifestyle behaviors that improve cognitive health.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, upon reasonable request.

Ethics statement

The studies involving humans were approved by Acadia University and Dalhousie University Research Ethics Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

EM: Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft. EGM: Data curation,

Investigation, Methodology, Writing – review & editing. MS: Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. LP: Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. Software. DK: Data curation, Investigation, Methodology, Supervision, Writing – review & editing. NB: Data curation, Investigation, Methodology, Supervision, Writing – review & editing. SM: Data curation, Investigation, Methodology, Supervision, Writing – review & editing. MO: Conceptualization, Formal Analysis, Methodology, Project administration, Supervision, Writing – original draft.

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EDITED BY

Ronald F. Zernicke,
University of Michigan, United States

REVIEWED BY

José Alexandre Bachur,
University of Franca, Brazil
Andrian Kuch,
Chapman University, United States

*CORRESPONDENCE

Rodrigo Muñoz-Cofré,
✉ rodrigomunozcofre@gmail.com

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Comparison of distance covered, physiological cost, and perceived exertion in four six-minute walk test protocols

Rodrigo Muñoz-Cofré^{1*}, Mariano del Sol¹, Pablo A. Lizana^{2,3},
Alejandro Gómez-Bruton⁴, María José Fuentes Andaur⁵,
Erika Soto Fierro⁵, Gabriela Osorio Gonzalez⁵,
Paul Medina-González⁶, Fernando Valenzuela-Aedo¹ and
Máximo Escobar-Cabello⁶

¹Programa de Doctorado en Ciencias Morfológicas, Universidad de la Frontera, Temuco, Chile,

²Laboratory of Epidemiology and Morphological Sciences, Instituto de Biología, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile, ³Centro de Investigación Interdisciplinaria en Biomedicina, Biotecnología y Bienestar (C3B), Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile, ⁴Exer-GENUD (EXERCISE-Growth, Exercise, Nutrition and Development Research Group), Faculty of Health and Sport Sciences, Department of Physiatry and Nursing, University of Zaragoza, Zaragoza, Spain,

⁵Escuela de Kinesiología, Universidad Católica del Maule, Talca, Chile, ⁶Departamento de Kinesiología, Facultad de Ciencias de la Salud, Universidad Católica del Maule, Talca, Chile

Objective: There is evidence that indicates that the Walked Distance (WD) in the 6-Minute Walk Test (6MWT) would be sensitive to the type of track and encouragement. The aim of study was compared the impact of track type and verbal encouragement provided in the 6MWT on WD, physiological cost, perceived exertion, and gait efficiency in healthy young adults unfamiliar with the test.

Method: WD, heart rate, subjective sensation of dyspnea (SSD), and fatigue (SSF) were measured in four 6MWT protocols: i) 30 m linear track and protocolized encouragement (LT + PE), ii) 30 m linear track and constant encouragement (LT + CE), iii) 81 m elliptical track and protocolized encouragement (ET + PE), and iv) 81 m elliptical track and constant encouragement (ET + CE). In addition, the Gait Efficiency Index (GIE) associated with physiological cost, dyspnea and fatigue was calculated and compared between the different protocols.

Results: The WD was significantly higher in the ET + CE protocol. The percentage of the heart rate reserve used (%HRRu) at minute 6 was higher in the ET + CE protocol. The SSD and SSD had difference in startup time between the protocols. The GIE was higher in %HRRu, SSD, and SSF for the ET + CE protocol.

Conclusion: The ET + CE protocol showed a significant increase in WD during the 6MWT in healthy young adults. Although it obtained the highest physiological cost, it did not present perceptual differences when entering cardiopulmonary assessment windows relevant to a more efficient test for the participant. It is advisable to discuss, based on the findings, the fundamental objective of the 6MWT and national and international recommendations to achieve a result as close as possible to the real maximal effort.

KEYWORDS

walk test, exercise test, respiratory function tests, physical endurance, physical exertion

1 Introduction

The 6-Minute Walk Test (6MWT) has been studied extensively since the 1960s. Since then, it has developed significantly due to the evolution of disciplines that share the 6MWT as an aerobic capacity assessment test (Rabinovich et al., 2004). Its use ranges from diagnosing functional capacity in healthy individuals to predicting morbidity and mortality in subjects with respiratory system dysfunctions (McGavin et al., 1976). In 2002, the American Thoracic Society (ATS) published its practical guide to standardize the application of the 6MWT (ATS Committee on Proficiency Standards for Clinical Pulmonary Function Laboratories, 2002). In 2014 the ATS joint efforts with the European Respiratory Society to develop a systematic review and a technical standard to clarify the use and applications of the 6MWT (Holland et al., 2014; Singh et al., 2014). In Chile, also intending to standardize the 6MWT, the Chilean Society of Respiratory Diseases (Gutiérrez et al., 2009) published the 6MWT procedure manual. However, large differences continue to be observed in the relationship of 6MWD to clinical outcomes, the reference equations for 6MWD, instructions, stimulus, track length, and course location and design.

Despite these efforts, the evaluators who apply the 6MWT have not been able to unify their criteria, and the literature reports a significant diversity in the evaluation of the 6MWT, which makes it difficult to compare outcomes. In this sense, a growing number of studies are comparing different ways of executing the 6MWT. Analyzing respiratory rehabilitation centers in Latin America and the Iberian Peninsula, Tramontini et al. (2005) determined that more than 90% of the institutions performed the 6MWT with track of different distances (between 17 and 90 m) and different time data and verbal encouragement. In terms of the space layout, Sciurba et al. (2003), in their multicenter study of the 6MWT in patients with emphysema, found that the subjects walked on average 33 m more when performing the test on a circular track. By contrast, straight tracks of 15 and 50 m showed no significant differences between them.

Verbal encouragement has also been shown to affect the performance of subjects who do the 6MWT. Guyatt et al. (1984) determined that using phrases at regular intervals leads to an increase in 6MWT distance. Although the recommendation indicates recording physiological and perceptual parameters at the beginning and end of the test, different studies currently agree on the usefulness of minute-by-minute monitoring. In this context, in 2001, Escobar et al. reported the temporal control of physiological and perceptual variables with constant encouragement during the 6 minutes of the test in healthy children. The researchers concluded that this methodology showed a greater walked distance (WD) than the standardized encouragement every 1 minute. Therefore, the type and frequency of the encouragement might also be relevant when analyzing the performance and physiological cost of the 6MWT.

Human gait presents a pattern of successive and rhythmic strides that depend on an energy reserve for motor expression (Farris and Sawicki, 2012). In this context, energy optimization according to speed, whether walking or running, is fundamental (Saibene and Minetti, 2003). In this sense, the performance in

meters obtained in the 6MWT acts synergistically with the physiological cost and perceived fatigue to adjust the level of gait efficiency. Muñoz et al. (2016) highlighted the need to balance the integration between perceived exertion, physiological cost, and performance to control variability in the 6MWT. Thus, considering the layout of the physical space, verbal encouragement, and the variables to be recorded is essential to standardize the 6MWT.

Therefore, this study aimed to compare the impact of track type and verbal encouragement provided in the 6MWT on WD, physiological cost, perceived exertion, and gait efficiency in healthy young adults unfamiliar with the test.

2 Materials and methods

2.1 Participants

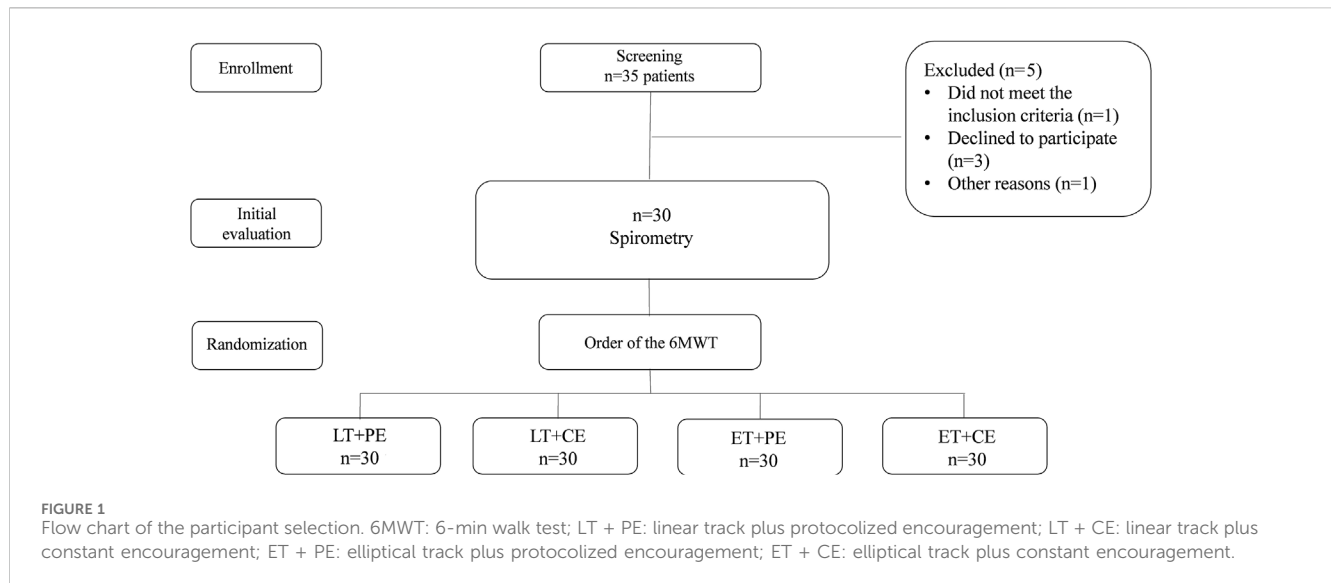
A cross-sectional comparative study was conducted between December 2016 and April 2017. The sample size was calculated from the total population of 4,839 university students through the sample size calculation software Ene 3.0[®]. With a significance level of 0.05, a statistical power of 80%, a dropout rate of 10%, a mean of 820 m, and a standard deviation of 12 m in the WD (Muñoz et al., 2016), the sample calculation was 32 students from 18 to 25 years of age. The inclusion criteria were 1) no history of morbid conditions (diabetes, heart problems, asthma, etc.), 2) a body mass index (BMI) between 18.5 and 24.9 kg/m², 3) a forced expiratory volume in the first second (FEV₁) >80% of the predicted value, 4) no cognitive alterations that impeded performing the test, and 5) unfamiliarity with the 6MWT (Figure 1). The study was explained orally to each participant, and then if they decided to participate volunteers read and signed the informed consent.

2.2 Forced vital capacity

Forced vital capacity was measured in a plethysmograph (Platinum Elite Model DL[®], St. Paul, Minnesota, United States). The subjects ventilated to tidal volume through the pneumotachograph for five respiratory cycles, and they were instructed to take a maximal inspiratory maneuver and then a maximal forced expiration. The best test of a minimum of three acceptable and reproducible maneuvers was selected (Graham et al., 2019).

2.3 6MWT protocols

The 6MWTs were performed on an 18 m × 38 m concrete surface, with no roof, at 09:00 a.m. (approximately 18°C), one test per day, on four consecutive days. Four 6MWT protocols were applied: 1) 30 m linear track and protocolized encouragement (LT + PE) (ATS Committee on Proficiency Standards for Clinical Pulmonary Function Laboratories, 2002), 2) 30 m linear track and constant encouragement: It consisted of repeating the following phrase every 15 s: “You are doing well. Keep up the good work” (LT + CE), 3) 81 m elliptical track and protocolized



encouragement (ET + PE), and 4) 81 m elliptical track and constant encouragement (ET + CE) (Muñoz et al., 2015). Three evaluators participated in applying the 6MWT: The first evaluator delivered instructions and encouragements depending on the protocol. The second one was in charge of time and recorded the data, and the third evaluator recorded the number of turns and WD. All participants performed the 6MWT with the four proposed protocols. The order of the protocols was distributed through a probability mode without replacement (Figure 1).

In addition, supine heart rate (SHR) was measured in all participants after five minutes of rest (Medina et al., 2015). During the 6MWT, the modified Borg (1982) scale was used to quantify the subjective sensation of dyspnea (SSD) and fatigue (SSF) (Fletcher et al., 2001). A heart rate monitor (Polar®FS3, Kempele, Finland) monitored the working heart rate (Fletcher et al., 2001) from minutes zero to six (WHR6MWT). In the three minutes after completion of the 6MWT, recovery was recorded in a standing position. The percentage of heart rate reserve used (%HRRu) was obtained from the following formula (Medina et al., 2015): $\%HRRu = [100 \times (WHR6MWT - SHR)] / [(220 - age) - SHR]$.

The data recorded were WD in m, physiological cost in %HRRu, and SSD and SSF in values of 0/10.

2.4 Gait efficiency index

The analysis of the physiological cost of walking and transportation by Medina et al. (2015) was used to determine gait efficiency. This Gait Efficiency Index (GEI) was obtained by applying the following formulas: GEI and physiological cost: $\% (oWD - rWD) / \text{Physiological cost}$, GEI, and dyspnea: $\% (oWD - rWD) / SSD \times 100$, GEI, and fatigue: $\% (oWD - rWD) / SSF \times 100$.

The numerator is the percentage difference between the obtained value during the 6MWT (oWD) minus the reference value (rWD), according to Osses et al. (2010). In the denominator, the %HRRu at minute 6 was used for physiological cost, the value of the modified Borg scale of dyspnea and fatigue for perception at

minute 6 ($\times 100$). The higher the index presents positive values, the greater the efficiency (for the same performance, less consumption of the energy reserve would be required).

2.5 Statistical analysis

The data are presented as means \pm SD unless otherwise stated. The Shapiro-Wilk test was used to determine data normality. The comparison of physiological variables and ventilatory function between genders was compared using Student's *t* tests for unpaired samples or Mann-Whitney U. The variables obtained during the 6MWT were analyzed by comparing minute to minute (from minute 0 to 6 corresponding to the test and from minute 7 to 9 corresponding to the recovery phase). The ANOVA test repeated measures of Friedman were used to compare WD, HR, SSF, and SSD among protocols, depending on the data distribution. Significant differences were considered significant when $p < 0.05$. The statistical analysis was performed with GraphPad Prism (version 5.0®, San Diego, United States).

3 Results

A total of 35 subjects were recruited; one did not meet the inclusion criteria, three declined to participate and one for other reasons (Figure 1). The distribution by gender was 11 women and 19 men, the mean age was close to 19.10 ± 2.17 years, and the basic physiological variables and ventilatory function were within normal parameters. The general characteristics of the participants are shown in Table 1.

Concerning the WD the ET + CE protocol (784 ± 85 m) was significantly higher than ET + PE (708 ± 94 m), LT + CE (713 ± 68 m) and LT + PE (672 ± 84 m) (Figure 2A). The temporal control of %HRRu, was significantly higher at minute 6 in the ET + CE test in relation to the LT + PE test (Table 2). On the other hand, dyspnea, and fatigue on the test showed no significant differences among the different protocols (Table 3).

TABLE 1 General characteristics of the sample.

| Variables | Total sample | Male (n = 19) | Female (n = 11) | p-value |
|--------------------------------|----------------|----------------|-----------------|----------------------|
| Age (years) | 19.10 ± 2.17 | 19.05 ± 2.04 | 19.18 ± 2.48 | 0.158 ^{MW} |
| Weight (kg) | 63.06 ± 8.61 | 67.84 ± 6.49 | 54.82 ± 4.62 | 0.0001 ^{MW} |
| Height (m) | 1.66 ± 0.08 | 1.72 ± 3.59 | 1.56 ± 4.3 | 0.0001 ^{MW} |
| BMI(kg/m ²) | 22.73 ± 2.18 | 22.91 ± 2.30 | 22.42 ± 2.03 | 0.279 ^{MW} |
| HR (bpm) | 75.10 ± 6.90 | 73.21 ± 7.35 | 78.36 ± 4.74 | 0.188 ^{MW} |
| RR (cpm) | 18.03 ± 1.44 | 17.95 ± 1.51 | 18.18 ± 1.40 | 0.254 ^t |
| SBP (mmHg) | 112.64 ± 4.52 | 113.95 ± 4.43 | 110.39 ± 3.88 | 0.156 ^t |
| DBP (mmHg) | 66.99 ± 6.07 | 67.11 ± 5.73 | 66.80 ± 6.90 | 0.335 ^t |
| MAP (mmHg) | 82.00 ± 4.94 | 83.00 ± 4.69 | 81.00 ± 5.47 | 0.265 ^t |
| FVC (L) | 4.68 ± 0.99 | 5.33 ± 0.56 | 3.56 ± 0.28 | 0.0001 ^t |
| Predicted FVC (%) | 111.13 ± 10.49 | 113.42 ± 11.27 | 107.18 ± 7.96 | - |
| FEV ₁ (L) | 4.02 ± 0.76 | 4.46 ± 0.60 | 3.26 ± 0.18 | 0.0001 ^{MW} |
| Predicted FEV ₁ (%) | 110.20 ± 12.37 | 110.32 ± 14.79 | 110.00 ± 7.07 | - |
| FEF 25%–75% (L/s) | 4.45 ± 1.15 | 4.65 ± 1.36 | 4.10 ± 0.52 | 0.182 ^t |
| Predicted FEF 25%–75% (%) | 105.43 ± 26.72 | 102.95 ± 30.59 | 109.28 ± 18.80 | - |
| FEF max (L/s) | 8.52 ± 1.63 | 9.35 ± 1.43 | 7.09 ± 0.69 | <0.001 ^t |
| Predicted FEF max (%) | 109.50 ± 16.74 | 109.37 ± 18.09 | 109.28 ± 14.95 | - |

Vital sign measurements were performed in the supine position and after resting for 5 min in this position. n: number of subjects; bpm: beats per minute; Kg: kilograms; m: meters; BMI: body mass index; kg/m²: kilograms/square meters; HR: heart rate; bpm: beats per minute; RR: respiratory rate; cpm: cycles per minute; SBP: systolic blood pressure; mmHg: millimeters of mercury; DBP: diastolic blood pressure; MAP: mean arterial pressure; FVC: forced vital capacity; L: liters; FEV₁: forced expiratory volume in the first second; FEF, 25%–75%: forced expiratory flow between 25% and 75% of vital capacity; L/s: liters per second; FEFmax: maximum forced expiratory flow; m: meters; t: t de Student; MW: U Mann-Whitney.

The results of the GEI are presented in **Figure 2**. The ET + CE protocol delivered significantly higher efficiency for %HRRu (**Figure 2B**), SSD (**Figure 2C**), and SSF (**Figure 2D**) compared to the linear circuits. The LT + PE protocol showed a negative and significantly lower GEI than the ET + CE protocol in the variables %HRRu, SSD, and SSF. In summary, it could be inferred that the ET + CE protocol has higher performance in WD with less energy reserve consumption.

4 Discussion

The current study observed that regulated verbal encouragement and the track where the 6MWT is performed significantly affect the performance in meters, physiological cost, and perceived exertion. There is a greater performance in meters with the ET + CE with a similar or lower transportation cost than the other protocols (**Figure 2**; **Tables 2, 3**). Thus, the elliptical track and the constant encouragement allow for a gait with more efficient characteristics (**Medina et al., 2015**) (**Figures 2A–C**).

4.1 Distance covered

The results indicate a significant increase in the WD of the ET + CE protocol compared to the LT + PE, LT + CE, and ET + PE. This coincides with the report by **Sciurba et al. (2003)**, who

observed that the WD on continuous oval tracks was greater by 92 feet (≈28 m) compared to straight tracks. **Bansal et al. (2008)** reported a difference of 13.17 m more in performance in subjects who performed the test on a continuous rather than a straight track. In addition, **Muñoz et al. (2015)** evaluated the impact of the track on the performance of the 6MWT in university students, comparing two tracks—one straight of 30 m and another elliptical of 400 m—finding that participants walking in the elliptical track performed a higher WD than when walking on the linear track (809.0 ± 8.7 m vs. 764.0 ± 12.2 m; $p = 0.034$). These results are consistent with the results reported in this study, where the WD was higher on the elliptical track.

The differences in WD may be due to constant accelerations and decelerations in gait not occurring on the elliptical track, which are present on a straight track with a delimited length. In this respect, **Medina et al. (2016)** proposed that gait be assessed in older adults on an elliptical track because this track would allow a gait pattern that would better resemble natural conditions, as opposed to a straight unidirectional track, where the displacement would be conditioned by turns. In this sense, **Pinochet et al.** indicate that the changes in direction that the subject undergoes during the turns on the one-way track cause the walking speed to decrease. At the same time, vision would be a distracting factor on a straight track because, for a few seconds, the subject focuses on the endpoint of the track and the subsequent turn, neglecting the objective of the test, which is to walk as fast as possible (**Pinochet et al., 2003**). Therefore, these three factors (vision, changes of direction, and loss of the test objective)

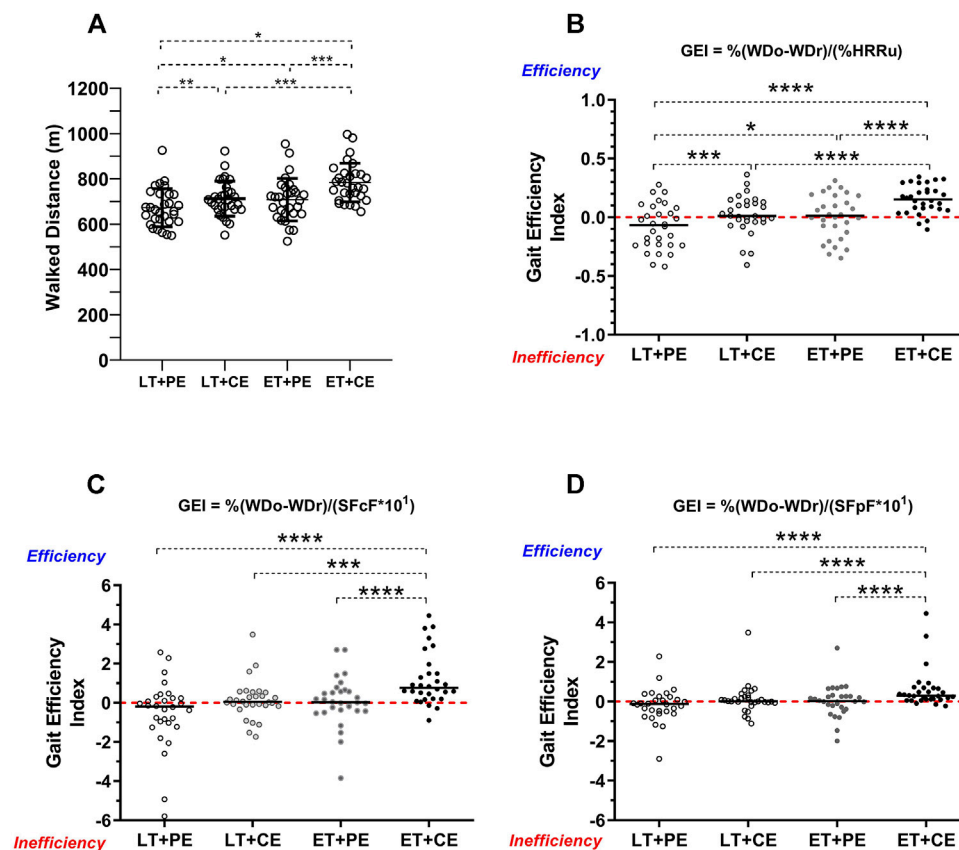


FIGURE 2

Walked distance and gait efficiency of the study sample. LT + PE: linear track plus protocolized encouragement; LT + CE: linear track plus constant encouragement; ET + PE: elliptical track plus protocolized encouragement; ET + CE: elliptical track plus constant encouragement; GEI: gait efficiency index; oWD: obtained walked distance; rWD: reference walked distance; %HRRu: percentage of heart rate reserve used; (A) walked distance according to tracks and verbal encouragement; (B) comparison of gait efficiency index according to the percentage of heart rate reserve used; (C) comparison of gait efficiency index according to subjective sensation of dyspnea; (D) comparison of gait efficiency index according to subjective sensation of fatigue; *: $p < 0.05$; **: $p < 0.001$; ***: $p < 0.001$; ****: $p < 0.0001$. Statistical tests used: Kruskal–Wallis and *post hoc* Dunn.

TABLE 2 Temporal control of percentage of heart rate reserve used according to the implementation protocol of the 6MWT in asymptomatic and healthy university students in Talca, Chile.

| Type | Time | LT + PE | LT + CE | ET + PE | ET + CE | <i>p</i> -value |
|--------------|------|-------------------------|-------------------------|-------------------------|--------------------------|-----------------|
| Standing | M0 | 10.6 ± 7.8 [7.7–13.5] | 9.9 ± 8.6 [6.8–13.2] | 11.6 ± 7.8 [8.7–14.6] | 12.6 ± 10.6 [8.6–16.5] | 0.682 |
| Walking Test | M1 | 41.5 ± 15.3 [35.8–47.2] | 49.5 ± 14.3 [44.2–54.9] | 42.7 ± 15.7 [36.9–48.6] | 45.1 ± 17.8 [38.5–51.8] | 0.222 |
| | M2 | 46.8 ± 16.8 [40.6–53.1] | 54.6 ± 15.8 [48.7–60.5] | 49.4 ± 16.2 [43.4–55.4] | 54.1 ± 14.7 [48.6–59.5] | 0.179 |
| | M3 | 49.4 ± 17.3 [42.9–55.8] | 55.9 ± 16.2 [49.9–62.0] | 53.7 ± 13.5 [48.7–58.8] | 59.4 ± 13.9 [54.3–64.6] | 0.084 |
| | M4 | 52.6 ± 17.1 [46.2–55.9] | 58.5 ± 16.1 [52.5–64.5] | 55.9 ± 15.1 [50.3–61.6] | 60.9 ± 14.4 [55.5–66.3] | 0.207 |
| | M5 | 54.8 ± 17.9 [48.1–61.5] | 61.7 ± 15.2 [55.9–67.4] | 58.2 ± 16.9 [51.8–64.5] | 64.4 ± 13.6 [59.4–69.5] | 0.352 |
| | M6 | 58.5 ± 15.9 [52.5–64.4] | 66.6 ± 13.5 [61.6–71.6] | 60.1 ± 16.0 [54.2–66.1] | 69.8 ± 12.7* [65.0–74.5] | 0.009 |
| Recovery | M7 | 29.7 ± 13.0 [24.8–34.6] | 33.9 ± 17.3 [27.4–40.4] | 31.3 ± 15.2 [25.6–37.0] | 37.7 ± 17.1 [31.3–44.0] | 0.228 |
| | M8 | 25.6 ± 11.9 [21.2–30.1] | 26.0 ± 14.6 [20.5–31.4] | 25.6 ± 12.8 [20.8–30.3] | 28.3 ± 14.2 [23.0–33.6] | 0.838 |
| | M9 | 19.8 ± 8.3 [16.7–22.9] | 21.8 ± 13.4 [16.8–26.8] | 23.1 ± 11.1 [18.9–27.2] | 23.6 ± 12.1 [19.0–28.1] | 0.589 |

Mean ± standard deviation and 95% confidence intervals for the temporal behavior of the percentage of heart rate reserve according to the performance protocols for the 6MWT. M: minute; LT + PE: linear track plus protocolized encouragement; LT + CE: linear track plus constant encouragement; ET + PE: elliptical track plus protocolized encouragement; ET + CE: elliptical track plus constant encouragement. The inter-subject *p*-value considers the general comparison for every minute of the test among the different implementation protocols. Friedman test was used. Italic values represent the * $p < 0.05$, LT + PE, vs. ET + CE.

TABLE 3 Temporal control of the SSF and SSD according to the implementation protocol of the 6MWT in asymptomatic and healthy university students in Talca, Chile.

| Type | Time | Subjective sensation of fatigue | | | | | Subjective sensation of dyspnea | | | | |
|--------------|------|---------------------------------|---------|-----------|---------|-----------------|---------------------------------|---------|---------|---------|-----------------|
| | | LT + PE | LT + CE | ET + PE | ET + CE | <i>p</i> -value | LT + PE | LT + CE | ET + PE | ET + CE | <i>p</i> -value |
| Standing | M0 | 0 [0–1] | 0 [0–1] | 0 [0–1] | 0 [0–1] | 0.190 | 0 [0–1] | 0 [0–1] | 0 [0–1] | 0 [0–1] | 0.112 |
| Walking Test | M1 | 0 [0–2] | 0 [0–4] | 0 [0–3] | 0 [0–3] | 0.511 | 0 [0–2] | 0 [0–4] | 0 [0–3] | 0 [0–3] | 0.060 |
| | M2 | 0 [0–3] | 1 [0–6] | 0 [0–4] | 0 [0–3] | 0.467 | 0 [0–3] | 1 [0–5] | 0 [0–4] | 0 [0–3] | 0.078 |
| | M3 | 1 [0–4] | 1 [0–5] | 1 [0–3] | 1 [0–4] | 0.311 | 1 [0–4] | 1 [0–5] | 1 [0–4] | 0 [0–4] | 0.128 |
| | M4 | 1 [0–4] | 1 [0–5] | 1 [0–4] | 1 [0–4] | 0.893 | 1 [0–4] | 1 [0–5] | 1 [0–4] | 1 [0–4] | 0.566 |
| | M5 | 1 [0–5] | 1 [0–4] | 1,5 [0–5] | 1 [0–5] | 0.721 | 1 [0–5] | 1 [0–6] | 2 [0–5] | 1 [0–5] | 0.266 |
| | M6 | 1 [0–5] | 2 [0–6] | 1,5 [0–5] | 1 [0–5] | 0.559 | 1 [0–5] | 2 [0–6] | 2 [0–5] | 1 [0–5] | 0.156 |
| Recovery | M7 | 0 [0–3] | 1 [0–4] | 0 [0–3] | 0 [0–3] | 0.248 | 0 [0–3] | 1 [0–4] | 1 [0–3] | 0 [0–3] | 0.100 |
| | M8 | 0 [0–3] | 0 [0–3] | 0 [0–2] | 0 [0–2] | 0.829 | 0 [0–2] | 0 [0–3] | 0 [0–2] | 0 [0–2] | 0.507 |
| | M9 | 0 [0–2] | 0 [0–2] | 0 [0–2] | 0 [0–2] | 0.883 | 0 [0–2] | 0 [0–2] | 0 [0–2] | 0 [0–2] | 0.697 |

Median and minimum-maximum values in parenthesis of the temporal behavior of the subjective sensation of fatigue on a scale from 0 to 10 according to the 6MWT, implementation protocols. LT + PE: linear track plus protocolized encouragement; LT + CE: linear track plus constant encouragement; ET + PE: elliptical track plus protocolized encouragement; ET + CE: elliptical track plus constant encouragement. The inter-subject *p*-value considers the general comparison for every minute of the test among the different implementation protocols. Friedman test was used.

would decrease the mechanical efficiency of walking on a linear track compared to an elliptical one, a situation supported by the results obtained in this study (Figure 2A).

Continuous verbal encouragement improved the WD, which is observed when contrasting the constant encouragement protocol (ET + CE and LT + CE) with the protocolized protocol (ET + PE and LT + PE). Verbal encouragement motivates people to increase their commitment and reach real exertion in maximal effort tests, recommended in several protocols (Cabillic et al., 2011; Marinho et al., 2014) and ATS regulations (Holland et al., 2014; Marinho et al., 2014; Singh et al., 2014). Finally, from the cardio-metabolic point of view, it provokes a more effective physiological response in accordance with the expected workload for physical performance tests in indicators such as VO₂max and maximal HR (Midgley et al., 2017).

4.2 Physiological cost

The %HRRu exhibited a rapid rise between standing (minute 0) and minute 1 and then followed the same but less pronounced pattern, which was similar for all the protocols. This agrees with the report by Escobar et al. (2001), who performed the 6MWT with continuous encouragement in healthy Chilean children. Muñoz et al. (2015) and Baeza et al. (2014), in university students and patients with chronic obstructive pulmonary disease (COPD), respectively, observed the same pattern. In the recovery phase, once the test was over, an abrupt drop in HR was observed, which did not reach the baseline shown in standing. This is supported by what was stated by Ostojic et al. (2010), who indicated that HR recovery during the first minute after work is slower after high-intensity exercise because the reactivation of the parasympathetic system is delayed through the vagus nerve.

The highest %HRRu values occur in the final minute of the test for the ET + CE protocol (Table 2), with no significant differences in the SSF and SSD. Parallel to this phenomenon, the highest WD was reached. These factors are consistent with greater walking efficiency in the ET + CE protocol (Figure 2B). In this context, The ET + CE group was closer to reaching the real maximal exertion.

4.3 Perceived dyspnea and fatigue

The SSD and SSD had difference in startup time between the protocols (Table 3). The type of track used in the 6MWT seems to be the factor that makes the difference to the SSF because, in the protocols with linear track (LT + PE-LT + CE), the SSF appears earlier than those with elliptical track. In this context, muscle recruitment during speed changes would play a fundamental role in this track. In this respect, Gandevia (2001) indicates that muscle fatigue, although it resides in the brain, originates in muscle fibers. In this context, the appearance of “peripheral fatigue” due to the turns made on the linear track would make it difficult to maintain a constant walking pace, ultimately impacting the WD. Thus, these indicators could be used to indirectly qualify the behavior of different mechanisms of exertion during walking at intensities and times greater than the walking required for daily life activities.

The appearance of SSF in the lower limbs after SSD could be illustrative of “better” or “worse” muscle resistance during aerobic exercise (Santos et al., 2020). The theory posits that the increase in respiratory rate due to the higher loads imposed by exercise gradually increases the expiratory reserve volume, causing a decrease in inspiratory capacity (Lutfi, 2017). In addition, it would alter the distribution of oxygen in the periphery, triggering skeletal muscle fatigue and resulting in a significant reduction in WD on the 6MWT (Figure 2A). This would explain the time of onset

of SSD and SSF, which, although they did not present significant differences, were expressed in different ways. Continuous encouragement added to the linear track made the SSF appear before the SSD. This may be related to the faster recruitment of all the lower limb muscles and how the encouragement would achieve this phenomenon (Segers et al., 2007).

4.4 Gait efficiency index

Figure 2 represents the proposed GEI for the four protocols according to the behavior of %HRRu (Figure 2B), SSD (Figure 2C), and SSF (Figure 2D). The ET + CE protocol proved significantly more efficient in all three variables than the other 6MWT protocols (Figure 2B). This is consistent with reports for reaching the physiological (Bassett, 2002) and mechanical (Saibene and Minetti, 2003) steady state of optimal walking speed with the lowest possible consumption. Therefore, the results obtained in this study make it possible to infer the minimum requirements of space and encouragement to evaluate and intervene in the context of optimal levels of locomotion in human beings. This would explain the greater WD (Figure 2A) with no significant changes in perceived exertion (Table 3).

4.5 Interaction of physiological cost and perceived exertion

The variables physiological cost, SSF, and SSD on the 6MWT did not show any significant differences among the different protocols (Tables 2, 3). However, these parameters presented different behaviors according to the protocol applied. If we consider what was proposed by Muñoz et al. (2015) in relation to i) a %HRRu between 55% and 90% (corresponding to a $\dot{V}O_2\text{máx}$ between 40% and 85% (Fletcher et al., 2001), ii) an SSD of 2–4 points (“light” to “somewhat heavy” exertion), and iii) SSF of 0.5–2 points (“very, very light” to “light” equivalent to a workload between 30% and 49% of the maximum voluntary contraction) (Borg, 1982), as control ranges in the execution of the 6MWT. In the protocols with protocolized encouragement (LC + PE; EC + PE), the %HRRu exceeds 55% at minutes 4 and 6. Moreover, the SSD reaches two points at minutes 2 and 3, respectively. Likewise, constant encouragement (LT + CE; ET + CE) made it possible to exceed 55% of %HRRu at minutes 3 and 2. Associated with this behavior, the SSD exceeded two points at minute two in both protocols (Figures 3B,D), respectively. This is consistent with Escobar et al. (2001), who pointed out that despite the correlation between the variables SSD and HR, subjective perceptions do not show a notable increase like HR. Finally, in the ET + CE protocol, entry into the control range in the SSD is earlier than in the SSF. In this regard, this behavior could explain, in part, the greater performance obtained with this modality since, first, it allows entry to cardiorespiratory overload (SSD), which has been reported to be better tolerated than peripheral overload (SSF) (Zghal et al., 2015). Thus, the test could be performed with a greater cardiopulmonary vs. musculoskeletal or neuromotor component, guaranteeing better tolerance in the muscle *in situ* for the 6MWT.

4.6 Limitations and projections

The limitations of the present study include the specificity of the sample studied. In such a scenario, the projections of these results first involve applying the ET + CE model in different age ranges and functional contexts to characterize the population with dysfunction. However, it has the strength of studying a homogeneous sample to observe changes in the different 6MWT protocols. On the other hand, the tools used to determine physiological cost and perceived fatigue do not present the maximum clinical rigor. In this context, we seek to improve the measurements by incorporating oxygen consumption as a reference indicator. On the other hand, an important projection is to explore in relation to the minimum necessary distance of the elliptical track, with the purpose of strengthening clinical applicability.

5 Conclusion

The results of this study make it possible to report that the protocol with ET + CE presented a significant increase in the WD during the 6MWT in healthy young adults unfamiliar with this test. This protocol obtained the greatest physiological cost and demonstrated no perceived differences in the entry to cardiopulmonary assessment windows relating to a test of greater efficiency for the participant. Given the differences found in this study, it is necessary to discuss the fundamental objective of the 6MWT and the national and international recommendations to obtain a result as close as possible to the true maximum exertion.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Comité de Ética de Universidad Católica del Maule. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

RM-C: Writing–review and editing, Writing–original draft, Visualization, Validation, Methodology, Investigation, Formal Analysis, Data curation, Conceptualization. MS: Writing–review and editing, Writing–original draft, Visualization, Supervision. PL: Writing–review and editing, Writing–original draft, Validation, Supervision, Methodology. AG-B: Writing–review and editing, Writing–original draft, Validation, Supervision, Investigation. MF: Writing–review and editing, Writing–original draft, Methodology, Investigation, Data curation, Conceptualization. EF: Writing–review and editing, Writing–original draft, Methodology, Investigation, Data

curation, Conceptualization. GG: Writing-review and editing, Writing-original draft, Methodology, Investigation, Data curation, Conceptualization. PM-G: Writing-review and editing, Writing-original draft, Methodology, Investigation, Formal Analysis, Conceptualization. FV-A: Writing-review and editing, Writing-original draft, Supervision, Data curation. ME-C: Writing-review and editing, Writing-original draft, Validation, Supervision, Methodology, Investigation, Formal Analysis, Conceptualization.

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EDITED BY

Ronald F Zernicke,
University of Michigan, United States

REVIEWED BY

Bruno Costa Teixeira,
Minas Gerais State University, Brazil
Norbert Maassen,
Hannover Medical School, Institute of Sports
Medicine, Germany

*CORRESPONDENCE

Martin Bonnevie-Svendsen,
✉ martin.bonnevie@gmail.com

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Transient changes in L-arginine, asymmetric and symmetric dimethyl arginine in triathletes following Norseman Xtreme Triathlon

Martin Bonnevie-Svendsen^{1,2*}, Christoffer Nyborg²,
Vibeke Bratseth³, Jørgen Melau^{2,4} and Jonny Hisdal^{1,2}

¹Department of Clinical Medicine, Faculty of Medicine, University of Oslo, Oslo, Norway, ²Department of Vascular Surgery, Section of Vascular Investigations, Aker, Oslo University Hospital, Oslo, Norway, ³Oslo Center for Clinical Heart Research-Laboratory, Oslo University Hospital, Department of Cardiology, Oslo, Norway, ⁴Joint Medical Services, Norwegian Armed Forces, Sessvollmoen, Norway

Arterial vasodilation is dependent on nitric oxide synthesized from L-arginine by endothelial nitric oxide synthase. Triathletes are reported to display altered serum concentrations of nitric oxide metabolites such as L-arginine, asymmetric dimethyl arginine (ADMA) and symmetric dimethyl arginine (SDMA) shortly after completing long-distance triathlon races. In other populations, similar changes to nitric oxide metabolites are established risk markers of cardiovascular disease. The objective of this study was to assess serum concentrations of metabolites for endothelial nitric oxide synthesis in triathletes one week following a long-distance triathlon race. In this prospective observational study, we used high-performance liquid chromatography to measure circulating concentrations of L-arginine, ADMA, and SDMA in triathletes. Venous blood samples were collected before, immediately after, day one, and one week following the triathlon race. Serum concentrations and L-arginine/ADMA ratio were determined for each time-point and compared to baseline. L-arginine/ADMA ratio was reduced on day one (147 ± 32 vs 163 ± 40 , $p < 0.02$). ADMA was reduced immediately after and increased at day one and remained elevated at one week ($0.29 \pm 0.05 \mu\text{M}$, $p < 0.001$, $0.44 \pm 0.08 \mu\text{M}$, $p < 0.001$ and $0.42 \pm 0.07 \mu\text{M}$, $p = 0.04$, respectively vs $0.40 \pm 0.05 \mu\text{M}$). SDMA was increased at all time-points when compared to baseline ($0.48 \pm 0.10 \mu\text{M}$, $p < 0.001$, $0.53 \pm 0.11 \mu\text{M}$, $p < 0.001$ and $0.42 \pm 0.08 \mu\text{M}$, $p = 0.048$ vs $0.38 \pm 0.05 \mu\text{M}$). L-arginine was only decreased immediately after ($46.0 \pm 9.3 \mu\text{M}$ vs. $64.6 \pm 16.1 \mu\text{M}$, $p < 0.001$). Long-distance triathlon racing induces altered levels of metabolites for endothelial nitric oxide production that mostly normalizes within one week following racing. The clinical relevance of these transient changes has yet to be elucidated in the athletic population.

KEYWORDS

triathlon, NO, endothelium, atherosclerosis, l-arginine, ADMA, SDMA

Abbreviations: ADMA, Asymmetric dimethyl arginine; CVD, Cardiovascular disease; eNOS, Endothelial nitric oxide synthase; NO, Nitric oxide; NXTRI, Norseman Xtreme Triathlon; SDMA, Symmetric dimethyl arginine.

1 Introduction

Long-distance triathlon races provide a compelling window to observe the boundaries of human cardiovascular physiology. The physical stress induced by 3.8 km swimming, 180 km cycling, and 42 km running is evident in the numerous reports of deviations from normal physiology in triathletes. Observations during and after races include altered ventricular function, pulmonary edema, hyperthermia, hypothermia, electrolyte disturbances, and serum biomarkers well outside physiological reference ranges (Claessens et al., 1999; Danz et al., 2016; Hoiseth et al., 2021; Nyborg et al., 2020; Olcina et al., 2019; Pingitore et al., 2011). The Norseman Xtreme Triathlon (NXTRI) is an annual race that offers athletes an added challenge of inhospitable racing conditions. Athletes face water temperatures as low as 14°C, ambient temperatures down to 6°C, an excess of 5,000 m of total elevation gain, and a marathon run that ends at an exposed mountain peak 1880 m above sea level (Melau et al., 2019). The rising popularity of NXTRI and other triathlon events in the last decades aligns with guidelines that recommend physical exercise to prevent cardiovascular disease (CVD) (Bull et al., 2020; Dahler et al., 2014). However, a U-shaped relationship between exercise volume and CVD mortality has been reported (Schnohr et al., 2015). The potential of excessive exercise to induce negative health consequences remains a topic of discussion (Eijssvogels et al., 2016; Isath et al., 2023). Indeed, endurance athletes have been shown to display accelerated coronary artery atherosclerosis (Mohlenkamp et al., 2008). In search of mechanisms that could explain atherosclerosis in athletes, endothelial cells and their production of nitric oxide (NO) are relevant on grounds of their established anti-inflammatory and cardioprotective properties (Botts et al., 2021). Endothelial cells facilitate vasodilation by synthesizing NO from the essential amino acid L-arginine (Palmer et al., 1988; Schmidt et al., 1988). While three different isozymes have been shown to contribute to vascular NO synthesis, endothelial NO synthase (eNOS) is commonly considered the major regulator of NO production (Garcia and Sessa, 2019). Under certain conditions, other proteins and enzymes, such as hemoglobin and xanthine oxidoreductase may generate NO from reduction of nitrite or nitrate (Garcia and Sessa, 2019). In the endothelium, eNOS activity is influenced by the activity of methylated forms of L-arginine: asymmetric dimethyl arginine (ADMA) inhibits NO synthesis by competing for the binding site of L-arginine on eNOS (Vallance and Leiper, 2002; Vallance et al., 1992). Symmetric dimethyl arginine (SDMA) competes with L-arginine for transport across the endothelial cell membrane, and thus may indirectly suppress NO synthesis (Bode-Boger et al., 2006; Strobel et al., 2012). NO synthesis may to some extent be influenced by homoarginine, which is another substrate for NO synthesis by eNOS. Because homoarginine displays a lower K_m than L-arginine it has been suggested that elevated levels of homoarginine may inhibit NO synthesis by competing with L-arginine for cellular uptake (Moali et al., 1998). Of clinical relevance, elevated levels of ADMA and SDMA are reported as independent risk factors for CVD and mortality (Schlesinger et al., 2016). Furthermore, it is well established that prolonged strenuous exercise causes a range of physiological changes that may impact endothelial function, including inflammation and altered bioavailability of essential nutrients (Danielsson et al., 2017; Neubauer et al., 2008; Nyborg et al., 2021a;

Storsve et al., 2020). Triathletes at NXTRI have previously displayed impaired endothelial cell function, demonstrated by blunted arterial flow-mediated dilation following race completion (Nyborg et al., 2021b). Congruent with this observation, NXTRI participants also display reduced levels of L-arginine as well as elevated levels of ADMA and SDMA after racing (Nyborg et al., 2021a). Collectively, the above observations prompt further investigation into the potential cardiovascular consequences of exercise-induced changes to NO metabolism in athletic populations. There is a paucity of literature on the behavior of NO metabolites beyond the initial 24 h following physical exercise. Therefore, the purpose of this study is to assess the serum concentrations of L-arginine, ADMA, SDMA, and L-arginine/ADMA ratio up to one week after completion of a triathlon competition.

2 Methods

2.1 Design and study population

In this prospective observational study, we recruited adult triathletes partaking in the annual NXTRI during 2019–2022. Invitation to voluntarily participate in the study was issued via email to all athletes ($n = 578$) registered for the NXTRI via email and on the race organizer's website in the period July to August year 2019, 2021, and 2022. All athletes above the age of 18 who could attend the planned one-week follow-up examination were included ($n = 25$). Exclusion criteria included the presence of established kidney or liver disease. Subjects were asked to report on past medical history via a questionnaire issued within 48 h before the race. This included questions on existing medical disorders, drug use, and timing of menstrual cycle. A note was made of subjects who reported existing cardiovascular or metabolic disease and their results were assessed for outliers. The study was approved by the Regional Committee for Medical and Health Research Ethics in Norway (REK Sør-Øst 2016/932 and 481,115) and was conducted per the declaration of Helsinki. All participants were required to give written informed consent before being included in the study.

2.2 Blood sampling and laboratory analyses

Venous blood samples were collected at four time-points: within 48 h before the race start (baseline), within 60 min after the race finish (immediately after), at noon the day after completing the race (day one), and six to nine days after the race (one week). The blood samples were drawn from an antecubital vein into vacutainers containing silica particles and gel separators and allowed to clot at room temperature for 30 min. They were further centrifuged at 2000 g for 10 min to make serum. Serum was pipetted and transferred to freeze-resistant vials and then refrigerated. We transported the refrigerated samples to Oslo University Hospital (Aker Sykehus, Oslo, Norway) for storage at -80°C in the hospital biobank until analysis. Analyses were performed November 2023 at Oslo University Hospital (Ullevål Sykehus, Oslo, Norway) by high-performance liquid chromatography and pre-column derivatization with o-phthalaldehyde (Sigma Chemicals CO, St Louis, MO, USA) for levels of L-arginine, ADMA and SDMA (inter-assay coefficients of variation: L-arginine 5.9%; ADMA 7.0%; SDMA 6.6%).

TABLE 1 Subject characteristics.

| | Mean \pm SD |
|------------------------------------|-----------------|
| Age (yr) | 40.4 \pm 9.8 |
| Race seasons completed (yr) | 6.8 \pm 3.6 |
| Full-distance triathlons completed | 7.0 \pm 10.2 |
| Body mass (kg) | 74.6 \pm 9.7 |
| Height (m) | 1.78 \pm 0.07 |
| BMI | 23.4 \pm 4.7 |
| Weekly endurance training (h) | 14.4 \pm 4.7 |
| Weekly resistance training (h) | 1.0 \pm 0.8 |
| NXTRI swim time (h) | 1.4 \pm 0.4 |
| NXTRI cycling time (h) | 7.0 \pm 1.2 |
| NXTRI run time (h) | 5.4 \pm 1.2 |
| NXTRI finish time (h) | 14.0 \pm 2.5 |

2.3 Data management and statistics

Data for each test variable were plotted for visual assessment of distribution. One data point for SDMA in a single subject was deemed unphysiological and discarded from the analysis as a measurement error. One-way repeated measures ANOVA with time points as a within-subjects factor was conducted for L-arginine, ADMA, SDMA, and L-arginine/ADMA ratio at all four time points. Post-hoc paired t-tests were performed to compare each time point against the baseline. We applied the Holm-Sidak method to correct for multiple comparisons. Statistical significance was set to p -values < 0.05 . Results are given as means \pm SD. All statistical analyses and plots were created in SigmaPlot (version 15.0.0.13, Inpixon, Palo Alto, California, USA).

3 Results

3.1 Subjects

25 participants (male = 18, female = 7) from the 2019, 2021 and 2022 edition of NXTRI were included in the study. Two subjects failed to complete the race, and a further two failed to present to examination at one week follow-up due to illness and unknown reasons. 21 subjects (male = 16, female = 5) completed the race and attended testing at all time points. The subject characteristics are presented in Table 1.

3.2 Laboratory analyses of NO metabolites

Mean values and standard deviation for L-arginine, ADMA, SDMA, and L-arginine/ADMA ratio are presented in Figure 1. L-arginine decreased markedly from baseline ($64.6 \pm 16.1 \mu\text{M}$) to immediately after ($46.0 \pm 9.3 \mu\text{M}$, $p < 0.001$) with no difference from baseline at later time points. Similarly, ADMA was reduced

from baseline ($0.40 \pm 0.05 \mu\text{M}$) to immediately after ($0.29 \pm 0.05 \mu\text{M}$, $p < 0.001$) before increasing at day one ($0.44 \pm 0.08 \mu\text{M}$, $p < 0.001$) and remaining elevated at one week ($0.42 \pm 0.07 \mu\text{M}$, $p = 0.04$). SDMA displayed an increase from baseline ($0.38 \pm 0.05 \mu\text{M}$) to immediately after ($0.48 \pm 0.10 \mu\text{M}$, $p < 0.001$), with a further increase on day one ($0.53 \pm 0.11 \mu\text{M}$, $p < 0.001$) and numerically higher levels at one week ($0.42 \pm 0.08 \mu\text{M}$, $p = 0.048$). Finally, the L-arginine/ADMA ratio remained unchanged from baseline (163 ± 40) to immediately after ($164 \pm 42 \mu\text{M}$, $p < 0.001$), with a reduction on day one (147 ± 32 , $p < 0.02$) and a return towards baseline at one week (163 ± 37 , $p < 0.98$). The changes in serum concentrations for each subject at all time points are presented in Figure 2.

4 Discussion

4.1 Main findings

The main finding in the present study is that triathletes display transient changes in serum concentrations of NO metabolites that mostly normalizes in the week after completing a long-distance triathlon. Specifically, the L-arginine/ADMA ratio was reduced and ADMA and SDMA increased the day after the race, with a return to baseline one week later for all parameters except ADMA, which remained slightly elevated. The reported changes in NO metabolites are congruent with a transient reduction in NO synthesis.

4.2 NO metabolites in the general population

To the best of our knowledge, there are no established reference ranges for the NO metabolites examined in this study. When comparing our data to a large sample ($n = 3,952$) of the general population by Schwedhelm et al. (2014), L-arginine were considerably lower in NXTRI athletes with a mean of $46.0 (\pm 9.3 \mu\text{M})$ immediately after the race, compared to a median of 152 (25th; 75th percentile, 120; 188 μM) reported by Schwedhelm et al. The lower L-arginine also means NXTRI athletes displayed a lower L-arginine/ADMA ratio than that calculated from Schwedhelm's data. Specifically, the L-arginine/ADMA ratio was reduced and ADMA and SDMA increased the day after the race, with a return to baseline one week later for all parameters except ADMA, which remained slightly elevated (Schwedhelm et al., 2014). However, such comparison should be interpreted with some caution as differences in analysis methodology could well contribute to discrepancies.

4.3 NO metabolites after exercise

Our results correlate with observations from Nyborg et al. (2021a), who found a similar pattern of depressed L-arginine/ADMA ratio and elevated ADMA and SDMA one day after a past edition of the NXTRI. Furthermore, Mieszkowski et al. (2023) made similar reports of elevated ADMA and SDMA in runners 24 h after completing an ultramarathon race. In contrast to our

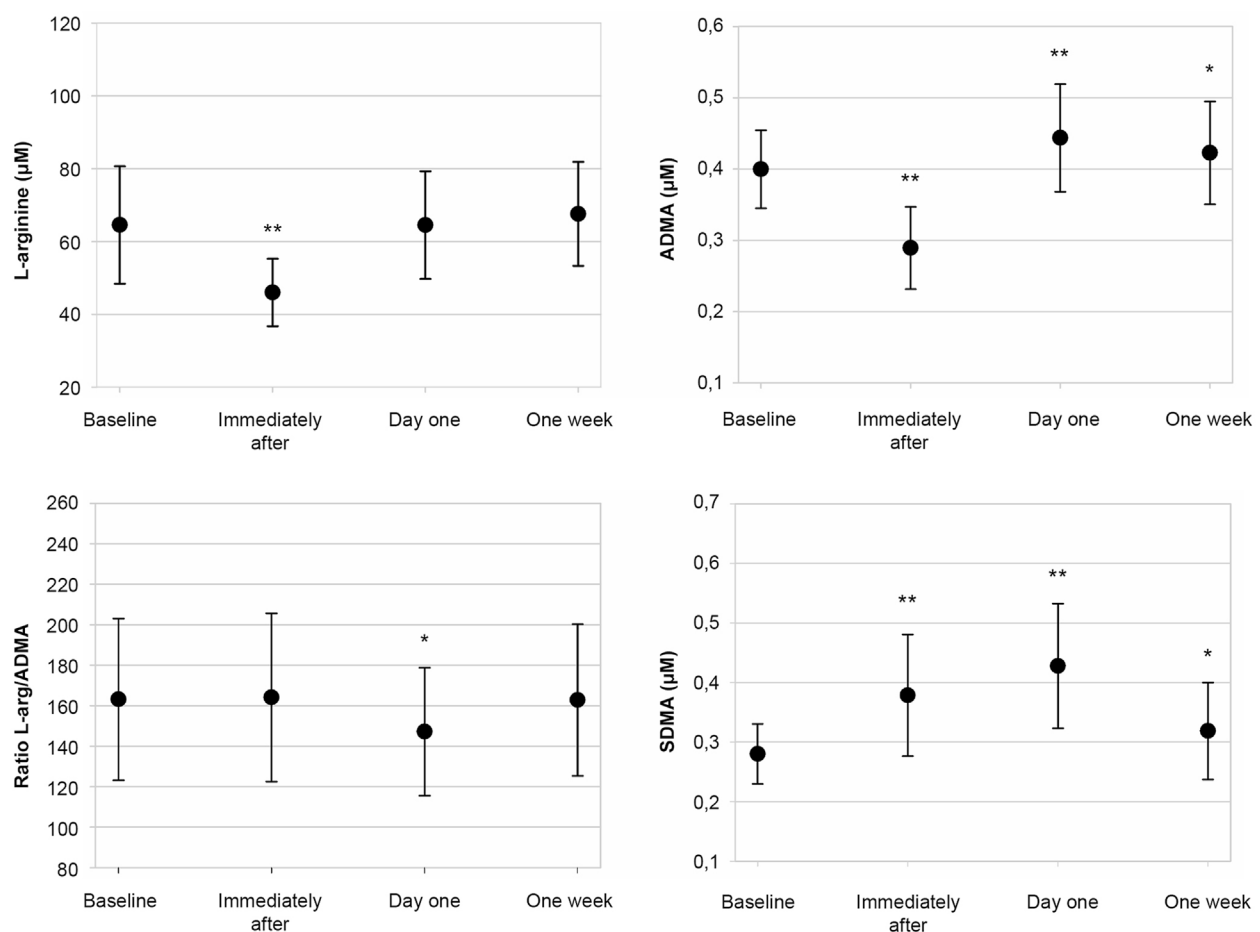


FIGURE 1

Scatter plot of serum concentration of NO metabolites. Mean serum concentrations and standard deviation at baseline, immediately after, day one, and 1 week. Statistically significant difference from baseline is illustrated with * ($p < 0.05$) and ** ($p < 0.001$).

results, these runners displayed no change in the L-arginine/ADMA ratio. It is possible that this discrepancy could be explained by differences in work duration, exercise intensity, or differences in exercise modalities between triathlon and ultramarathons. More lenient exercise protocols have shown conflicting results with the studies mentioned above. [Riccioni et al. \(2015\)](#) found elevated plasma L-arginine and L-arginine/ADMA ratio, with depressed ADMA and SDMA concentrations immediately after 10 min of treadmill walking in subjects with coronary artery disease. Similarly, increased L-arginine and decreased ADMA and SDMA concentrations have been reported following cardiopulmonary exercise tests in subjects with chronic heart failure ([Drohomirecka et al., 2023](#)). Furthermore, [Argunova et al. \(2022\)](#) observed that five to ten days of 40 min of daily treadmill workouts appeared to stabilize ADMA concentrations in patients with coronary artery disease. Collectively, it appears that modest aerobic exercise may promote short-term NO synthesis and endothelial cell function in patients with CVD. Whereas vigorous endurance exercise of prolonged duration appears to shift NO metabolites in a direction that may lead to transiently impaired NO synthesis in athletes.

4.4 Proposed mechanisms for altered NO metabolite concentrations

The mechanisms underlying altered levels of L-arginine, ADMA and SDMA after exercise have yet to be fully elucidated. During exercise, cardiac output increases, and blood flow is redistributed to meet the oxygen demand in the working muscles. This redistribution is facilitated by vasodilation in the involved skeletal muscles ([Joyner and Casey, 2015](#)). The authors deem it plausible that the decreased L-arginine immediately after finish could be a result of substrate depletion from the prolonged duration of exercise during NXTRI. It has been speculated that homoarginine, which is considered a weaker substrate for NO synthesis, could impact the cellular uptake of L-arginine if the balance between homoarginine and L-arginine is shifted sufficiently in favor of the former ([Moali et al., 1998](#)). As we did not measure homoarginine in our sample we cannot conclude on its potential role. Past studies on NXTRI athletes have shown increased creatine kinase and elevated markers of inflammation post-race ([Nyborg et al., 2020](#)). We have therefore argued that post-race increases in ADMA and SDMA in triathletes may be due to increased proteolysis from exercise-induced muscle damage and inflammation ([Nyborg et al., 2021a](#)). Furthermore, ADMA and SDMA are both excreted via the kidneys and to a lesser

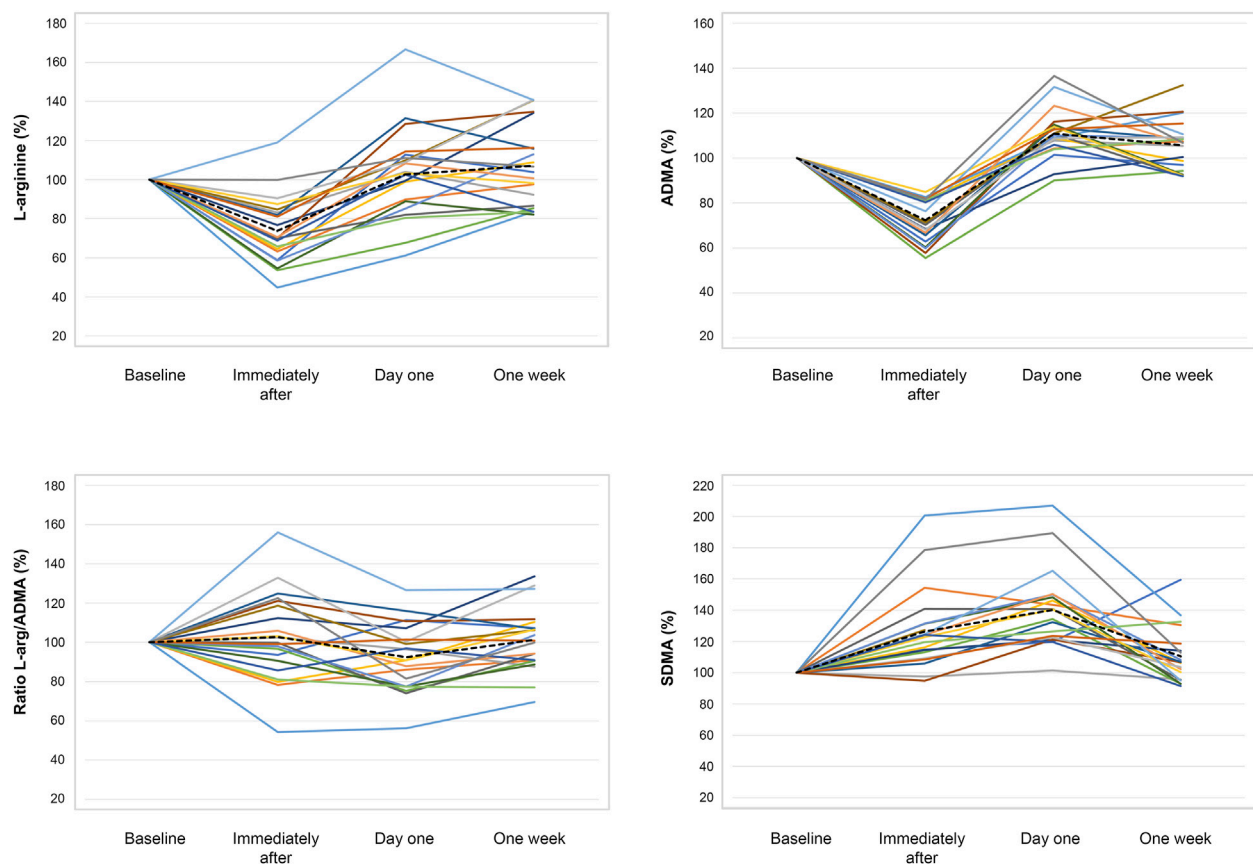


FIGURE 2

Changes to individual subject serum concentrations. Serum concentrations are given in % of the concentration at baseline for each subject. The mean of all samples at a given time is illustrated by the dotted line.

extent cleared by the liver (Siroen et al., 2025). As NXTRI athletes have been shown to display increased serum concentrations of both creatinine and liver enzymes after racing, it could be that reduced clearance by the liver and kidneys contributes to the elevated ADMA and SDMA values (Nyborg et al., 2020).

4.5 NO metabolites as prognostic marker for CVD

The consequences of exercise-induced changes in NO metabolism in the athletic population have yet to be elucidated. Elevated ADMA and SDMA have been associated with increased risk of all-cause mortality, cardiovascular disease or worsened prognosis in a range of conditions and populations. These include heart failure, type 2 diabetes mellitus, critically ill patients, and patients with cardiac arrest (Keller et al., 2020; Lee et al., 2022; Wirth et al., 2017; Zobel et al., 2017). In the general population, higher levels of ADMA are associated with all-cause mortality and CVD, whereas high SDMA is associated with all-cause mortality (Schlesinger et al., 2016). Furthermore, a higher arginine/ADMA ratio has been associated with reduced incidence of cardiovascular events and atherosclerotic development in high-risk and general populations, respectively (Notsu et al., 2015; Yu et al., 2017). To the best of our knowledge, the prognostic value of

NO metabolites has yet to be described in the athletic population. Furthermore, it is not yet established whether a transient change in NO metabolites post-exercise carries the same prognostic value as altered baseline values. It is prudent to consider that several established risk factors for CVD, such as cigarette smoking, hypertension, and dyslipidemia affect risk in a dose-dependent manner (Bhat et al., 2008; Zhang et al., 2019). If exercise-induced changes to NO metabolites were indeed predictive of CVD in triathletes, it would be logical to assume their impact is dose-dependent. It is our experience, that the duration of long-distance triathlon races far exceeds the duration of workouts triathletes undertake in regular training. Importantly, triathletes train far more often than they race. We, therefore, suggest that future studies should seek to explore the behavior of NO metabolites in triathletes after their day-to-day exercise. Furthermore, prospective studies with longer follow-up duration could help clarify whether exercise-induced changes in NO metabolites translate to altered risk for CVD or if these changes represent benign physiological adaptations.

4.6 Strengths and shortcomings

The present study provides descriptive data on NO metabolites in triathletes following workloads that would typically be considered

impractical for testing in controlled laboratory conditions. This allows insight into physiological responses that would otherwise remain unexplored. The novelty of the present study is the extended follow-up period beyond what has previously been reported in the athletic population. Nevertheless, the results should be interpreted with some caution. Of note, we only measured concentrations of L-arginine, ADMA, and SDMA in serum, whereas the synthesis of NO by eNOS occurs intracellularly. Extracellular concentrations of NO metabolites may not proportionally reflect the activity of intracellular eNOS activity. However, the present results align with past observations of transiently reduced vascular responsiveness following the NXTRI, as expressed via lowered flow-mediated dilation with concomitantly reduced L-arginine and elevated markers of inflammation (Nyborg et al., 2021b; Nyborg et al., 2021a). We therefore consider it plausible that the changes to L-arginine/ADMA ratio, ADMA, and SDMA of 9.0, 11.0, and 38.9% might contribute to lowered NO synthesis and blunted end-organ activity. The participants in this study were not screened for CVD other than by a questionnaire. While all but three subjects reported no history of CVD or pre-existing conditions with known impact on NO precursors, we cannot entirely rule out that undetected medical conditions may have influenced our results. The results are therefore best regarded as an observation of NO metabolite behavior in triathletes irrespective of any conditions they may or may not have. While this could be considered a methodological weakness, the fact remains that altered NO metabolites have shown prognostic value in both healthy and diseased populations (Keller et al., 2020; Schlesinger et al., 2016; Yu et al., 2017). We therefore argue that the current observations are still worthwhile consideration.

5 Summary

This study demonstrates transient changes in serum L-arginine/ADMA ratio, SDMA, and ADMA concentrations in the week following a long-distance triathlon. Deviations from baseline serum concentration mostly normalized within one week, except for ADMA which remained slightly elevated. These changes are consistent with temporarily reduced substrate availability for endothelial NO production and could be an expression of transiently suppressed endothelial cell function. Future studies should seek to elucidate whether exercise-induced changes to NO metabolites are a benign physiological phenomenon or one that contributes to the risk of future CVD.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Regional Committees for Medical and Health Research Ethics, Sør-Øst.

The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MB-S: Data curation, Investigation, Project administration, Writing–original draft. CN: Conceptualization, Investigation, Project administration, Writing–review and editing. VB: Formal Analysis, Writing–review and editing. JM: Conceptualization, Investigation, Writing–review and editing. JH: Conceptualization, Methodology, Project administration, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fphys.2024.1451038/full#supplementary-material>

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EDITED BY

Ronald F. Zernicke,
University of Michigan, United States

REVIEWED BY

Akira Tamaki,
Hyogo Medical University, Japan
Massimiliano Gobbo,
University of Brescia, Italy

*CORRESPONDENCE

Paul W. Ackermann
✉ paul.ackermann@ki.se

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Unlocking the potential of neuromuscular electrical stimulation: achieving physical activity benefits for all abilities

Paul W. Ackermann^{1,2*}, Robin Juthberg¹ and Johanna Flodin¹

¹Integrative Orthopedic Laboratory, Department of Molecular Medicine and Surgery, Karolinska Institutet, Stockholm, Sweden, ²Department of Trauma, Acute Surgery and Orthopedics, Karolinska University Hospital, Stockholm, Sweden

Neuromuscular Electrical Stimulation (NMES) uses electrical impulses to induce muscle contractions, providing benefits in rehabilitation, muscle activation, and as an adjunct to exercise, particularly for individuals experiencing immobilization or physical disability. NMES technology has significantly progressed, with advancements in device development and a deeper understanding of treatment parameters, such as frequency, intensity, and pulse duration. These improvements have expanded NMES applications beyond rehabilitation to include enhanced post-exercise recovery, improved blood glucose uptake, and increased lower limb venous return, potentially reducing thrombotic risks. Despite its benefits, NMES faces challenges in user compliance, often due to improper electrode placement and discomfort during treatment. Research highlights the importance of optimizing stimulation parameters, including electrode positioning, to improve both comfort and treatment efficacy. Recent innovations, such as automated processes for locating optimal stimulation points and adaptable electrode sizes, aim to address these issues. When combined with wearable technologies, these innovations could improve NMES treatment adherence and deliver more consistent, long-term therapeutic outcomes for patients with various physical limitations. Together, these developments indicate a promising future for NMES, presenting a valuable tool to enhance the benefits of physical activity across diverse populations, from rehabilitative care to broader health and wellness applications.

KEYWORDS

neuromuscular electrical stimulation, immobilization, muscle strengthening, exercise, blood flow, venous thromboembolism, motor points

Introduction

Neuromuscular electrical stimulation (NMES) is a treatment method used to create muscle contractions through electrical impulses. NMES mimics the body's nervous system during voluntary muscle activation, but instead of the signal originating in the brain, it comes from an electrical stimulator. This is achieved by placing electrodes on the skin over the target muscle.

The use of electricity for medical treatment dates back to ancient Egypt and Greece, where electric eels were used for pain relief. Modern NMES evolves from Galvani's 18th century discovery that electric current can induce muscle contraction (1). Today, electrical stimulation is applied in various medical contexts, such as transcutaneous

electrical nerve stimulation (TENS) for pain management (2) and NMES in rehabilitation settings. NMES is commonly used to strengthen weakened muscles, reduce muscle atrophy during immobilization (e.g., after surgery or injury), and complement exercise to optimize training effects (3, 4).

However, current NMES protocols still suffer from poor compliance and inadequate efficacy, attributed to limited/insufficient user proficiency regarding repeated application of electrodes in the correct placement. Research has shown that electrode placement based on a prior manual search of the optimal points and individual adaption of electrode dimensions significantly improves treatment effectiveness and comfort (5).

Recent innovations have introduced an automated search process that identifies the optimal stimulation points and electrode sizes for each patient, ensuring consistent results and improved compliance with NMES treatment (6). Combined with wearable technologies, such as garment-based applications, these advancements hold the potential to enhance treatment adherence and improve long-term outcomes for patients with physical disabilities.

General considerations of NMES usage

Settings for optimal NMES usage

Studies have shown that the NMES parameters also affect the comfort and effectiveness of the stimulation (3, 7–9). Several parameters can be adjusted during NMES, such as frequency, pulse width, intensity, waveform, plateau time, on:off-time and ramp-up/ramp-down time (Figure 1).

Pulse width, frequency, and intensity

Overall, research has shown that increasing each of pulse width, frequency, and/or intensity leads to recruitment of more muscle fibers, resulting in higher force production (7–10). However, these parameters also affect the comfort of stimulation.

Frequency correlates directly with muscle torque production, even when using textile electrodes (12). Longer pulse widths, such as between 400 and 600 μ s, selectively target motor fibers, while shorter pulse widths target sensory fibers to a higher extent. Consequently, longer pulse widths positively influences muscle torque production. Studies on quadriceps NMES suggest that a pulse width of 400–600 μ s and frequency between 30 and 50 Hz provide optimal muscle recruitment without inducing excessive muscle fatigue and metabolic demands (3).

On: off-time and ramp-up/ramp-down time

The on: off-time and ramp-up/ramp-down time are believed to mainly affect comfort. The optimal on: off time is not well defined, but if the off-time is too short, the risk of fatigue increases due to insufficient muscle recovery (3). Prior research has demonstrated that an on: off time of 1:5 (e.g., 10 s on and 50 s off) allows the muscle to recover between stimulations (3).

High- and low-intensity NMES

Most research has focused on high-intensity NMES, aiming to mimic the muscle contractions during maximal exercise, which is desirable for muscle strengthening effects (13, 14). However, high intensity NMES can be quite painful. In contrast, low-intensity (LI)-NMES results in minimal pain (15) while still producing muscle contractions, an outcome which significantly increases both venous and arterial blood flow. LI-NMES has therefore been demonstrated as a promising method to prevent venous thromboembolism in both calf and quadriceps muscles (12, 16–18).

Differences between NMES and voluntary muscle contractions

While NMES aims to mimic voluntary muscle contraction, it differs from the contractions induced via the central nervous system in a number of ways. NMES activates muscle units simultaneously between the position of the electrodes, often

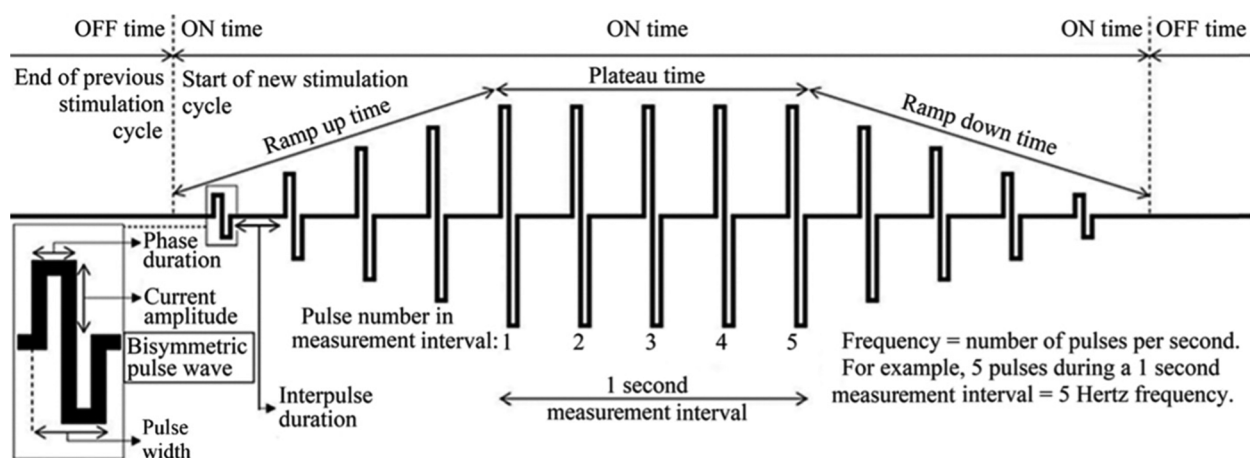


FIGURE 1

Examples of parameters that may be adjusted for optimal treatment effects and comfort during neuromuscular electrical stimulation (NMES). Image adapted from Juthberg et al. (10).

targeting superficial muscles, and recruits them repetitively in a fixed spatial pattern, which leads to quicker fatigue compared to voluntary contractions (3, 7–9). In contrast, voluntary muscle contractions disperse the recruitment of motor units and vary their activation in numbers and across changing locations. NMES also primarily targets fast-twitch muscle fibers, which contribute to quicker fatigue but on the other hand is advantageous for rehabilitation, as these are the fibers predominantly weakened following injury or surgery (3).

Side effects of NMES

In recent years, an increasing number of studies have indicated that improper electrical stimulation can have harmful effects (19). In addition to common muscle soreness lasting one to four days after treatment, over-treatment can result in muscle fiber damage, increased secretion of creatine kinase, and muscle breakdown (rhabdomyolysis). This can potentially lead to acute kidney failure, especially in individuals whose kidney function already is reduced (20). These injuries have been particularly noted with excessive muscle training in suits, i.e., whole-body electromyostimulation, containing many electrodes stimulating several muscle groups simultaneously (20). However, whole-body electromyostimulation has in recent reviews of controlled trials shown significant, moderate to large effect sizes on sarcopenia, muscle mass and strength parameters (21).

Other side effects or drawbacks of current NMES treatments are that many patients experience discomfort or pain during stimulation (3, 4), and difficulties in correctly setting up the NMES device without assistance, leading to low adherence (22, 23). Adherence to treatment is the most important factor in determining whether the treatment in clinical practice can achieve the effects shown in studies. This challenge has prompted researchers at Karolinska Institutet to focus on the development and optimization of NMES, including integrating the treatment into clothing, which has the potential to dramatically improve treatment adherence with NMES (Figure 2) (24).

NMES electrodes

Optimal NMES usage requires adapting the size, number, and placement of electrodes (Figure 2). Studies have shown that larger electrodes are more comfortable than smaller ones, but excessively large electrodes decrease the effectiveness of the treatment (15, 25). The optimal size also depends on the muscle being stimulated, with larger muscles generally requiring larger electrodes (15, 25). Placement of electrodes on so-called motor points has been shown to provide more comfortable and effective stimulation (3, 5). The electrophysiological definition of a motor point is the location on the skin which requires the lowest intensity of electrical stimulation to cause a muscle contraction (26). However, the time-consuming manual motor point search with a motor point pen requires training, and thus poses a problem in the daily use of NMES. Therefore, anatomical maps have been developed showing where on the body motor points are most likely to be found (5, 27, 28). However, there is significant individual variation in the location of motor points and thus

normal users will experience problems in locating motor points, which will lead to a compliance problem with the therapy.

Multiple NMES electrodes in a matrix

To address these challenges and account for the large individual variation in motor point locations, years of development has led to an automatic motor point search procedure performed within a matrix of electrodes, which may improve NMES treatment adherence (6). Within a matrix of electrodes, multiple electrodes can be combined to form individualized electrode sizes, enhancing both compliance and treatment outcomes. Customizing electrode sizes is essential for different treatment indications and muscle groups. Additionally, varying stimulation within the electrode matrix can reduce muscle fatigue and recruit a broader range of muscle fibers. As a result, NMES within an electrode matrix offers the potential for automatic electrode placement over motor points, with individualized electrode sizes and numbers tailored to specific treatments.

Muscle strengthening effects of NMES

NMES is currently used both as a complement to training to optimize the effect in healthy individuals and by physiotherapists as part of rehabilitation, such as after surgery or injuries, to maintain muscle strength and strengthen weakened muscles (3, 4, 27–29). Most earlier studies on the training effects of NMES have focused on its use alongside voluntary muscle activation (30, 31). However, recent studies show that NMES alone can also have beneficial effects on maintaining muscle strength, rehabilitating injuries, and achieving recovery after training (3, 32).

NMES with voluntary muscle contraction

Several studies have demonstrated that combining NMES with voluntary muscle contractions yields superior training effects, both in younger and older individuals (3, 9, 29–31). For example, one study demonstrated that NMES combined with leg and gluteal strength training three times a week during for four weeks in older adults improved walking test times more than exercise alone (33). Another study in young, healthy and physically active individuals showed that a 6-week training program involving vertical jumps with added electrical stimulation increased jump height by 10% more than just jump training alone or no training at all (3). These findings suggest that NMES can stimulate parts of the muscle that regular exercise may not easily reach and/or provide a greater load than typical training. Moreover, a recent study indicated that NMES and exercise can potentiate each other even when performed on opposite extremities (34). These observations suggest involvement of either systemic mediator mechanisms and/or effects mediated through the central nervous system.

NMES without voluntary muscle contraction

Studies have shown that NMES alone can achieve a relatively high percentage of the maximum force generated during voluntary muscle activation, without any voluntary contraction



FIGURE 2

Image of NMES pants seen from the outside (A frontside, B backside) and inside (C frontside, D backside). On (A,B) there are connectors for stimulation. The larger electrodes are sized 5 × 9 cm (upper electrodes in C and all electrodes in D) and the smaller (lower electrodes in C) are sized 5 × 5 cm. The NMES pants are developed together with the Swedish School of Textiles at the University of Borås, Sweden. Image adapted from (12).

(3, 9, 35, 36). To measure the force generated during knee extension exercises of the thigh muscles, a dynamometer (Biodex) is used, and the maximum force generated is referred to as the “maximum voluntary contraction” (MVC) (37). The degree of muscle activation during NMES can also be measured using this device (36), and the percentage of MVC achieved is reported as a percentage of MVC.

Research suggests that a stimulation level of at least 20% of MVC is required for muscle-strengthening effects (9). Muscle contractions induced by NMES generally produce lower force output than voluntary contractions, usually less than 50% of MVC at the highest tolerable intensity (38), which is attributed to the difference between how the muscles are activated (3, 8, 9).

NMES may also activate more superficial muscle fibers, which could result in poorer training outcomes compared to regular exercise. This has led to further research aimed at improving NMES techniques (38), including optimizing the number, placement, and size of electrodes, NMES parameters, and training protocols (8, 15, 23, 39). Additionally, combining NMES with methods like blood flow restriction has shown potential for producing better training effects than NMES alone (38, 40).

The molecular effects of NMES

To better understand the effects of NMES on muscle, several studies have examined its effects at the gene and muscle fiber levels (13, 41–45). One study comparing a 30-min NMES session

at the highest tolerable intensity with regular strength training found that both methods altered the expression of genes activated by exercise in the thigh muscle 24 h post-workout (13). While regular strength exercise regulated gene expression to a greater extent than NMES, NMES remains a good alternative when regular exercise is not possible (13).

A recent study conducted by our research group demonstrated that a single NMES session at 20% MVC, using NMES pants, regulated 4,448 differentially expressed genes (DEGs), with an 80% overlap with the 2,571 DEGs regulated by regular exercise. The genes regulated by NMES included well-known exercise-related genes such as PPARGC1A, ABRA, VEGFA, and GDNF. Only eight genes were regulated in opposite directions by NMES and exercise. The three genes upregulated by NMES and downregulated by exercise included genes involved in neurite outgrowth (MYLIP), cell proliferation and regulation of mTORC1 signaling (ICK) and negative regulation of cell proliferation (JARID2) (34). It was also demonstrated that the NMES-session at 20% of MVC could be applied with an acceptable level of discomfort, e.g., VAS below 4 (34).

In other studies, the effect of multiple NMES treatments (over 5 days to 10 weeks, with 3–6 sessions per week, lasting 18 min to 2 h per session) have been shown to affect gene and muscle fiber composition in both younger (41, 43) and older adults (41, 44). These effects have also been observed in orthopedic contexts, aiding recovery of quadriceps strength after knee surgery, anterior cruciate ligament reconstruction and total knee arthroplasty (42, 46–48).

In summary, studies have concluded that NMES can preserve muscle mass, prevent muscle atrophy, and to some extent alter and improve gene expression. When compared to regular exercise, the effects of NMES are less pronounced, but it remains a valuable option for individuals unable to engage in regular exercise and as a complement to standard training for healthy individuals (41, 42).

NMES benefits during physical inactivity

Physical inactivity is a major and growing global health problem, contributing to approximately 3.2 million preventable deaths each year (49, 50). Immobilization and inactivity are closely linked to the development and progression of obesity, type 2 diabetes (50), venous blood clot development in the legs and lungs (51), and reduced muscle strength and balance, which can lead to falls, particularly in older adults (49, 50, 52). While physical activity is an effective way to counteract these negative effects, it is not always possible, especially after surgery or for older patients with underlying illnesses (53). Current treatment methods for these conditions are often insufficient, largely due to low compliance. There is a clear need for improved treatment options to mitigate the adverse effects of physical inactivity. NMES, which uses the body's own energy to create muscle contractions, is an alternative way to activate muscles during periods of immobilization (30, 54–56). This makes NMES especially beneficial for older adults, post-surgical patients, and individuals with cardiovascular risks or other co-morbidities,

such as chronic obstructive pulmonary disease, who have difficulty engaging with exercise programs.

Improved balance

For people over 65, there is a 30% risk of falling each year (57), and for those living in nursing homes, this rate increases to 50% (48). Falls in older adults can result in severe consequences, including fractures, immobilization, and even death (58). While regular physical activity reduces the risk of falls and related fractures (50), many older adults are unable to engage in such activities. NMES has, especially among older and/or untrained individuals, been shown to provide effective muscle activation, resulting in improved muscle strength and function (30, 31, 45, 54, 55, 59). For example, NMES treatment for 30 min, 2–3 times a week for 9 weeks has been shown to improve walking test time by 15%–20% (45).

Improved metabolic control

In addition to the risk of falls, physical inactivity also increases the risk of type 2 diabetes and obesity (50). Globally, one in eleven adults has diabetes, and in 2019 more than four million people died due to diabetes or its complications, equating to one death every 8 s. In addition to those already diagnosed with diabetes, even more people have pre-diabetes with the risk of developing the disease but also with a great opportunity for prevention (60). Physical activity is crucial both for prevention and treatment of type 2 diabetes, but as mentioned above, many are unable to engage in regular exercise. For these individuals, NMES presents as a valuable alternative, offering similar effects as regular physical activity on blood sugar regulation (53, 61–64). One study demonstrated that patients with type 2 diabetes who performed 40-min quadriceps NMES sessions, 5 days per week for 8 weeks, significantly improved fasting glucose levels and reduced body fat (53). A systematic review has confirmed these effects (65). Moreover, patients with type 2 diabetes often suffer from peripheral artery disease, which causes ischemic pain in the lower limbs and impairs walking. NMES has been shown to increase peripheral arterial flow, reduce ischemic pain, and enhance walking distances (66). However, systematic reviews call for more high-quality trials to draw definitive conclusions (67).

Preventing the formation of blood clots

Another significant risk posed by physical inactivity and extended immobilization is the development of blood clots in the legs or lungs (51). Between 1 and 4 out of 100 people will develop a blood clot requiring treatment during their lifetime (68). Anticoagulant treatments, while available, are not always effective (69), and for older adults who are prone to falls, they pose a bleeding risk (70). Mechanical compression therapy, such as intermittent pneumatic compression (IPC), is used in hospitals to increase blood flow, mimicking the muscle pump action that occurs during walking (71). However, IPC machines are too large and noisy for use outside of hospital environments, which is why NMES treatment, where electronics can be minimized, provides a quiet and mobile treatment option outside of hospitals. NMES treatment on the calf and quadriceps has

been shown to improve venous blood flow in the leg vessels (12, 17, 18). Adding NMES treatment to drug therapy with anticoagulants during knee replacement surgery (72) and for patients undergoing major surgeries (73) reduces the risk of blood clots in the leg. While NMES alone can lower the risk of clots compared to no treatment during immobilization, it has not yet proven as effective as anticoagulants (18, 74). More research is needed to explore NMES as a sole treatment for preventing blood clots, as studies in this area are limited (18).

Future directions

Future research should clarify the similarities and differences between the effects of NMES and regular physical exercise. One notable area of exploration is the load or impact on the cardiovascular system. Additionally, exercise has demonstrated neurobiological benefits, such as protection against cognitive disorders like dementia. A key factor released during exercise, which is brain protective, is brain-derived neurotrophic factor (BDNF). Interestingly, NMES has also been demonstrated to increase BDNF levels (75). The neurobiological effects of muscle stimulation are likely mediated via the release of myokines, which are peptide modulators of several tissue processes such as brain neuroplasticity, bone mineralization, and tissue repair (76). Notably, NMES has demonstrated the production of several myokines, which can exert beneficial effects on the pathophysiology of several conditions in patients with limited mobility (76). Future research should in more detail delineate the indications, settings and optimal dose-response relationships of NMES to induce beneficial effects.

Limitations

While NMES shows promise, certain patients may be “non-responders” to NMES, particularly those with low contractile responses. Thus, in a study of critically ill patients in an intensive care unit it was demonstrated that patients with higher severity of illness were more likely to be non-responders to NMES (77). However, NMES has shown positive effects to maintain and improve limb strength in other severely ill populations, such as those with acute exacerbation of chronic obstructive pulmonary disease (78), acute heart failure (79), chronic kidney failure on hemodialysis (80) and spinal cord injury (81). Still, the existing studies have reported a wide range of stimulation parameters. Thus, future high-quality randomized trials should focus on standardizing NMES settings for specific indications.

Conclusion

In summary, NMES offers a range of applications with positive effects for both older and younger individuals, including those who are healthy or living with health conditions. It can serve as a complement to physical activity or as an alternative when

traditional exercise is not feasible, providing similar benefits. Additionally, NMES can also be considered as a non-invasive tool to address several research questions regarding muscles and muscle function in compromised populations. Although current NMES applications remain suboptimal, recent advancements in automated electrode placement and individualized stimulation settings show promise. These developments may improve treatment adherence and deepen our understanding of how to optimize NMES for various populations.

Author contributions

PA: Conceptualization, Funding acquisition, Resources, Supervision, Writing – original draft, Writing – review & editing. RJ: Conceptualization, Writing – original draft, Writing – review & editing. JF: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

PA and RJ declare a potential conflict of interest. They have a granted patent related to neuromuscular electrical stimulation. UK Patent, publication number GB2601757. A system comprising a controller and an electrical stimulation system.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY

David Arthur Hart,
University of Calgary, Canada

REVIEWED BY

Russell Coppack,
Defence Medical Rehabilitation Centre,
United Kingdom

*CORRESPONDENCE

Melissa J. Tinney
✉ majugo@med.umich.edu

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Supporting a lifetime of fitness for the military veteran athlete: a narrative review

Melissa J. Tinney^{1,2*} and Chantal Nguyen³

¹Department of Physical Medicine & Rehabilitation, University of Michigan Medical School, Ann Arbor, MI, United States, ²Department of Physical Medicine & Rehabilitation, Lieutenant Colonel Charles S. Kettles VA Medical Center, Ann Arbor, MI, United States, ³Department of Orthopaedic Surgery—Division of Physical Medicine & Rehabilitation, Stanford University, Redwood City, CA, United States

The military veteran starts their career at peak physical fitness. Once injured or retired, physical activity for the veteran is integral to rehabilitation, recovery, and ongoing wellness. This may require adaptation for continued participation in physical activity. The military veteran, in the United States, has access to resources which can facilitate ongoing physical activity, engagement in competitive and recreational sports, no matter what age or ability. Reviewing the current literature will help understand the scope of programs available, their outcomes, and strategies employed to support a lifetime of fitness that may be applied to other populations and health care systems.

KEYWORDS

military veteran, physical activity, fitness, adaptive sports, inclusive sports

1 Introduction

Optimal physical fitness is inherent to the job in the military. Once injured or retired, physical activity can decline for the military veteran. The need to stay active is important, given the multiple comorbidities in this population. Veteran populations have shown to be less healthy than non-veteran populations, self-reporting higher incidence of multiple diseases (1). Veterans in 2019 were estimated to have higher rates of morbidity for obesity/overweight status, heart disease, stroke, cancer, lung disease, arthritis, and diabetes. This has been attributed to stressors of multiple deployments in recent decades (1). According to the National Center for Post-Traumatic Stress Disorder (PTSD), veterans are more likely to have PTSD during their lifetime at a rate of 7%, compared to civilians and veterans receiving care within the United States (2).

A multitude of VA programs for physical activity have been developed. Because of the inclusivity and national reach of these programs, outcomes are studied at a large scale over a diverse population. This literature review aims to identify components of these programs and strategies that are implemented and what areas of health outcomes they impact, which is applicable to the general, non-veteran population interested in maintaining a lifetime of fitness.

2 Materials and methods

A literature search was conducted in 3 databases ([PubMed.gov](#), CINAHL via EbscoHost, and [Scopus.com](#)) to identify studies regarding physical activity and the military veteran. The search strategies utilized controlled vocabulary and keywords for veterans; keywords for specific programs including GeroFit, Whole Health, VA MOVE!, Golden Age Games, and Wheelchair Games; adjacency searching for exercise across the

lifespan, lifetime fitness adaptive physical activity, continuum of fitness, geriatric physical activity, and integrated exercises; and keywords for adaptive sport, inclusive sport, adaptive athletes, winter sports clinic, and summer sports clinic. The searches were not restricted by publication year or language, but were limited to articles published in the United States.

3 Results

Searching 3 bibliographic databases and utilizing Covidence software, 316 references were imported and 140 duplicates were removed. Of the 176 studies for title and abstract screening, 126 studies were excluded. 50 studies were assessed for full-text eligibility and 40 articles were included.

The majority of studies ranged from publication years of 2007–2024. Of the 40 included articles, there were 19 on adaptive athletes, 9 on older athletes, 3 on mental health in athletes, 2 on novice athletes, and 7 pilot studies. The majority of studies were either cross-sectional (14/40), qualitative analyses (4/40), retrospective analyses (3/40), or cohort analyses (3/40). Funding was primarily from VA offices and programs, with 25/40 government-funded studies included.

4 Programs

As part of the VA's approach to care that supports a veteran's health and well-being, there are a variety of cited VA programs in the literature that facilitate participation in physical activity

inclusive of the new, older and/or disabled athlete. Programs include the National Veterans Wheelchair Games (NVWG) (3), National Veterans Golden Age Games (NVGAG) (4), Gerofit (5), National Disabled Veterans Winter Sports Clinic (NDVWSC) (6), National Disabled Veterans Golf Clinic (NDVGC) (7), VA MOVE! program (8), National Veterans Summer Sports Clinic (NVSSC) (Table 1).

For the individual veteran, the VA covers prescription of different types of adaptive sports equipment with a qualifying impairment and appropriate medical justification. Other VA grants provide a stipend for those training with a Paralympic or Olympic team to facilitate participation at the national/international level (10). There is also a VA Adaptive Sports Grant Program that provides funds for qualifying organizations to organize and sustain longitudinal adaptive sports opportunities for veterans with disabilities (11). One study looking specifically at the characteristics of community programs showed 76% of programs reviewed have VA medical center affiliation (12).

In addition to these large, national organized events, the VA has offered smaller local adaptive sports events. One example in the literature is, Heroes on the Hudson, an annual one-day adaptive kayaking and sailing event for those with psychological (PTSD, depression), physical (such as amputees, spinal cord injury, traumatic brain injury), and visual impairments. One pilot program was based on the framework of Gerofit, to prepare frail older veterans for surgery, as part of a prehabilitation program (13). One pilot program was based on the framework of Gerofit, to prepare frail older veterans for surgery, as part of a prehabilitation program (14). Another pilot program was created at the

TABLE 1 National VA programs facilitating organized participation in physical activity for all veteran athletes, organized by year of inception.

| Event | Inception | Location | Qualifying diagnoses | Number of participants (average) | Sports/activities |
|--|-----------|---|---|----------------------------------|--|
| National Veterans Wheelchair Games (NVWG) (3) | 1981 | United States (different location each year) | SCI, TBI, amputation, central nervous system (CNS) pathology necessitating use of wheelchair (i.e., multiple sclerosis, cerebral palsy) | 550 | Wheelchair basketball, quad rugby, power soccer, throwing events, cornhole, disc golf, handcycling, swimming, adaptive fitness, 9-ball, softball, table tennis, wheelchair slalom, motor rally, boccia, pickleball, bowling, air pistol, air rifle, bass fishing |
| National Veterans Golden Age Games (NVGAG) (4) | 1985 | United States (different location each year) | Age ≥50 years old | >900 | Basketball, cycling, pickleball, power walking, swimming, track & field, badminton, bowling, disc golf, table tennis, pistol, air rifle, basketball free-throw, boccia, cornhole, nine ball, shuffleboard |
| Gerofit (5) | 1986 | Founded in Durham, North Carolina, but now in 33 VA systems | Age >65 years old, stable medical condition and independent with ADLs | Thousands | Individual and group supervised exercise sessions, including core strengthening, balance, tai chi, dance, treadmills, ellipticals, stair climbers, cycling |
| National Disabled Veterans Winter Sports Clinic (NDVWSC) (6) | 1987 | Snowmass, Colorado | SCI, TBI, amputation, visual impairment | 400 | Adaptive sled hockey, adaptive Alpine/Nordic skiing, snowmobiling, fly fishing, curling, scuba diving, rock climbing |
| National Disabled Veterans Golf Clinic (NDVGC) (7) | 1994 | Riverside, Iowa | SCI, TBI, amputation, CNS pathology, visual impairment | 200 | Adaptive golf, air rifle, bicycling, bowling, and kayaking |
| VA MOVE! Program (8) | 2008 | Nationwide | BMI of 30 kg/m ² or BMI 25–30 kg/m ² with metabolic syndrome | >35,000 | 150–300 min of physical activity per week |
| National Veterans Summer Sports Clinic (NVSSC) (9) | 2008 | San Diego, California | SCI, TBI, amputation, visual impairment, burns, MS, stroke, depression, PTSD | 150 | Cycling, surfing, sailing, adaptive fitness, yoga, kayaking, archery, and pickleball |

War-Related Illness and Injury Study Center at the VA New Jersey Health Care System to address Gulf War Illness. The study's authors note "this is the first clinical program that has piloted an intensive interdisciplinary and integrative functional medicine-based virtually delivered Whole Health coaching program in Veterans with complex post-deployment chronic multi-symptom illness from deployment-related exposures". It was described as a 6-month video-to-home telehealth program including: functional medicine assessments, individual and group nutritional and adaptive exercise coaching with portable exercise equipment, group mindfulness meditation and yoga, guest health lectures, character strength evaluation and coaching, and targeted nutritional supplementation that were tailored to each Veteran (15).

Because of the known comorbidity of PTSD, other pilot studies focused on providing exercise and physical activity to improve mental health. One pilot program studied the use of group integrative exercise to reduce symptoms of PTSD. Weekly 1-h exercise sessions included aerobic exercise, strength training with weights and resistance bands, and yoga movements and poses presented within a framework of mindfulness principles, with one principle presented in each session as the focus of the week (16). Another pilot study looked at ways to improve health and wellness for veterans in the Mental Health Intensive Case Management Program, a community-based intensive program for veterans (involving walking intervention as modified from the MOVE! program, weekly in-person sessions with trained mental health providers) with severe mental illness (SMI) who are at risk for decompensation and frequent hospitalizations (17).

There are many non-VA programs that promote physical activity for veterans (11), but few were found in this literature review. The U.S. Paralympic Military Sport Camp (USPMSC) and Higher Ground, an adaptive outdoor recreation program are noted (18, 19). At the international level, the annual Invictus Games involves disabled veterans from around the world, including the United States, to compete in various sports over the course of one week (20).

5 Outcomes

For the veteran athlete, participation in organized programs for physical activity and adaptive sports has led to comprehensive improvements in physical health, psychological health, and overall quality of life (QOL)/well-being.

5.1 Health parameters outcomes

Veteran participation in the VA MOVE! program has led to increased overall weight loss, presumably with improvements in both diet and physical activity parameters (21). Another study looked at medication prescriptions. After 1-year of participation in GeroFit, participants showed when comparing prescriptions filled in the pre-GeroFit baseline to the post-12-month period, 55% of patients had a decrease in their overall number of fills of medications for multiple comorbidities, which included opiates,

cardiac, mental health, diabetes, and lipid lowering medications (22). Blood pressure (BP) and weight were also studied in community-based programs and within 2 months of participation BP and average weight decreased in one study. The data reported in that study showed the mean weight of participants decreased by 9 lbs, percent of controlled BP increased by 24, and percent of uncontrolled BP decreased from 40% to 16% of participants (21). BP and weight improvements were also seen in community-based programs and within 2 months of participation blood pressure and average weight decreased. The mean weight of participants decreased by 9 lbs, percent of controlled blood pressures increased by 24, and percent of uncontrolled blood pressures decreased from 40% to 16% of participants (23).

5.2 Fitness and mobility outcomes

One study of obese individuals demonstrated they make improvements and show clinically significant changes in performance measures of mobility compared with overweight and normal-weight individuals (24). Similarly, veterans with SMI, participating in GeroFit, also make improvements in mobility, as well as strength and endurance, similar to veterans without SMI, showing the capacity for improvement with complex comorbidities (25). In frail elderly veterans, a pre-surgical exercise program demonstrated improvement in fitness outcomes: gait velocity, chair stands, 6-minute walk, 8 foot up and go, and arm curls (14).

Partaking in the NVWG significantly increased veterans' wheelchair mobility when compared to mobility at home or in their local communities, with increased distance traveled (4,466.2 vs. 1,367.4 m), wheelchair propulsion velocity (0.76 vs. 0.64 m per second), and continuous drive time (5.2 vs. 2.5 min). Furthermore, wheelchair users at the NVWG had fewer stops every 500 m while at the NVWG when compared to being at home. This included improvements in the same movement parameters for power wheelchair users during the NVWG (26).

5.3 Psychological health outcomes

Physical activity has been incorporated into treatment of PTSD, as shown in a VA pilot study. In one particular study, the integrated exercise group demonstrated greater improvement in PTSD symptom severity and psychological QOL compared with participants randomized to the wait list control group (16). One group assessed GeroFit data and noted significant improvement in their overall PTSD symptoms as well as each of the four PTSD symptom clusters (intrusion, avoidance, negative cognitions/mood, hyperarousal) after three months (27). A randomized control trial of a 12-week integrative exercise program for war veterans with PTSD saw significant improvements in mindfulness, interoceptive bodily awareness, and positive states of mind compared to a wait list control. These changes in secondary outcomes may be partial mechanisms of action for how integrative exercise creates the observed improvements in PTSD symptoms and QoL (28). In a specific non-VA program, Higher Ground, they performed a

non-randomized experimental trial to study the impact of a sports and recreation program on veterans with PTSD symptoms. Participants showed reduction in PTSD symptoms after participants completed the program (29). After participation in Higher Ground events, veterans noted decreased rates of anger and depression, instead highlighting a newfound sense of energy and motivation to participate in the sport and within the community (19). These same improvements are seen on the local and international level with the Invictus Games (20). Even with a 1-week event, the NVSSC, one study showed depression, anxiety, social functioning, and positive and negative affect significantly improved from pre-to post program, but returned to baseline levels at 3-month follow-up (30). In a secondary analysis of the same group, there were significant improvements in depression, generalized anxiety, insomnia, positive affect, and negative affect immediately following the NVSSC, as well as improvements in depression anxiety and positive affect immediately following a singular session activity. Veterans with probable PTSD also reported significant reductions in PTSD symptom severity over the course of the program, which were reliable and statistically significant (30).

5.4 Quality of life and social outcomes

From a QOL perspective, veterans participating in wheelchair sports report increased overall life satisfaction with a predominant increase in social network or number of friends, which was highlighted by 98% of 132 participants at the 26th NVWG and 20th NDVWSC (31). Longer duration of participation in physical activity (at least ten years) led to overall higher self-esteem scores when compared to more novice veterans participating in physical activity for less than 5 years, in addition to improvements in self-efficacy/ability to independently perform activities of daily living (32). In general, veterans participating in the NVWG report a higher quality of life and improvements in relationships with the community, as formally noted with documented higher Sports Participation Outcome Research Tool and Comprehensive Uniform Surve (SPORTACUS) and Functional Mobility Assessment (FMA) scores (33). These psychological benefits and improved social support have yielded further communal benefits, with increases in employment rates, after participation in the NVWG. Of note, there is a correlation of increased employment rates with additional years of adaptive sports participation; veterans attending at least 3–4 NVWG's noted positive improvement in ability to obtain employment (34). In a similar light, participation in the USPMC led to improvements in perception of a veteran's disability, thus helping him/her focus on optimism, autonomy, inspiration to pursue other organized recreational adaptive sports, and desire to engage in pre-injury interests (18).

Veterans' perspectives on participation in GeroFit identified factors that could be viewed as facilitators. Amongst participants (less than 3 months gap in exercise) and non-participants (more than 3 months gap in exercise), camaraderie was uniformly noted as a valuable part of the GeroFit program (35). Social

connectedness was rated as high by all GeroFit participants, with the majority endorsing positive social support and relatedness with their exercise companions. In those veterans with PTSD that reported symptom improvement, positive feelings of social connection were significantly related, accounting for approximately 20% of the gain (27). Morey and colleagues did a 5-year retrospective analysis of GeroFit and noted it has several components that particularly enhance the psychosocial aspects of the program, particularly the program is for veterans who share a strong common bond (36). In a study looking at older veterans with SMI, participating in GeroFit, those who were retained at 6 months had better health-related QOL (25).

6 Discussion

The VA has built a uniquely robust and inclusive infrastructure to support physical activity for all ages and abilities and has established a framework to analyze the efficacy of such wide-reaching programs. The individualized, whole health approach has demonstrated positive outcomes, with proven success utilizing key strategies across these programs. These key strategies include camaraderie, defined goals and objectives, personalized guidance, virtual platform options, and measurable outcomes (Figure 1).

Despite positive outcomes from these key strategies, veteran athletes still face known barriers to participation in exercise and sports, including transportation and travel distance (37). To address this barrier, the VA has created pilot programs to explore increased telehealth services or implementation of modified virtual programs, such as the GeroFit program. Changes in the program, including modifying performance measures adjusted to a smaller space and using only mobile equipment and plyometric (weight-bearing) exercises made programs like GeroFit accessible to rural populations (37). A systematic review was also conducted specifically looking at telehealth or virtual delivery of the GeroFit program and found several studies showing similar gains in physical health outcomes from virtual vs. in-person exercise (38).

VA programs emphasize an individualized approach, from the novice to elite athletes and provide outcomes in populations that would normally be excluded from exercise intervention trials (24). As referenced from Browne and colleagues, goal setting and motivational strategies, with examination of mechanisms of change within multicompartamental exercise programs like GeroFit, can specifically yield beneficial physical activity outcomes (39). This demonstrates that veterans, even with complex conditions, can benefit from supported and strategic ongoing physical activity. Furthermore, veterans who find difficulty integrating into their communities or sustaining a job due to their medical history or impairments have found improvement in social connection with increased participation in physical activity, which extends to improvements in self-efficacy and higher rates of sustaining employment (34).

This review demonstrates a limited amount of published information across all outcomes for both VA and non-VA programs. Research on these programs are mostly pilot studies or



FIGURE 1
Physical activity strategies for the veteran athlete..

singular year outcome analyses, which limits generalizability of results and determination of long-term effectiveness of each program. Future research may examine longitudinal health outcomes given the longevity of these programs over all military service eras. There is an opportunity to cumulatively study at least tens of thousands of veterans participating in these programs in a strategic, systematic way via fellowships, quality improvement programs, and/or research centers.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY

David Arthur Hart,
University of Calgary, Canada

REVIEWED BY

Nadhir Hammami,
University of Jendouba, Tunisia
Delphine Labbé,
University of Illinois Chicago, United States

*CORRESPONDENCE

Annika Kruse
✉ annika.kruse@uni-graz.at

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The impact of cycling on the physical and mental health, and quality of life of people with disabilities: a scoping review

Nina Mosser¹, Glen Norcliffe² and Annika Kruse^{1*}

¹Department of Human Movement Science, Sport and Health, University of Graz, Graz, Austria, ²Faculty of Environmental and Urban Change, York University, Toronto, ON, Canada

Adaptive cycling holds potential for promoting physical and mental health among individuals with disabilities, who often face barriers to traditional cycling and other forms of exercise. This scoping review systematically examines existing scientific literature to assess the effects of adaptive cycling on the physical and mental health of individuals with disabilities. Following a widely recognized methodological scoping review framework, 35 qualitative and quantitative studies were identified through comprehensive database searches and manual screenings. The review highlights the positive impacts of adaptive cycling on cardiovascular fitness, muscle strength, and overall physical well-being, as well as improvements in mental health and quality of life. Despite these benefits, significant research gaps remain, particularly concerning adaptive cycling modalities, such as sociable cycles, chair transporters, and power-assisted bikes, which were underrepresented in the existing literature. This review underscores the need for further studies to provide a comprehensive understanding on the effects of different adaptive cycling modalities. Such studies are essential to improve accessibility and ultimately support the health and social inclusion of individuals with disabilities.

KEYWORDS

impairment, disability, adaptive cycles, bicycling, health, mobility

1 Introduction

Cycling is widely acknowledged to have numerous health benefits including the enhancement of cardiovascular fitness, muscle strength, joint mobility, proprioception and mental health (1, 2). Regular participation in cycling can significantly reduce the risk of chronic diseases including cardiovascular diseases, metabolic diseases, and certain cancers (1, 2). Moreover, cycling supports weight management, usually reduces stress levels, and contributes to overall well-being. Its low-impact nature makes it an ideal form of exercise for individuals across various age groups and fitness levels, further solidifying its role as a valuable health-promoting activity (1, 2).

Despite the well-documented benefits of cycling, not everyone can engage in this form of activity. Individuals with certain disabilities may face significant barriers that limit their ability to participate in traditional cycling (3). As stated by the World Health Organization, about 1.3 billion people, or approximately 16% of the world's population, live with some form of disability (4). According to the United Nations, persons with disabilities "include those who have long-term physical, mental, intellectual, or sensory impairments which in interaction with various barriers may hinder their full and effective participation in society on an equal basis with others" [(5), p. 4]. This

definition includes physical, sensory, cognitive, and developmental disabilities, affecting individuals across all age groups (4). The prevalence of disabilities is expected to increase as the population ages, with elderly individuals experiencing higher rates of physical impairment (6).

For people with disabilities, an inability to engage in regular physical activity, such as cycling, can lead to a range of health risks (7). High levels of sedentary behavior are common among this population, which can result in secondary health conditions including obesity, cardiovascular disease, and mental health issues such as depression and anxiety (8, 9). These risks underscore the importance of promoting accessible forms of physical activity to maintain health and prevent disease in individuals with disabilities.

Adaptive cycling plays a crucial role in addressing these challenges. By incorporating various technical adaptations—such as hand cycles for those with lower limb impairments, tricycles for enhanced stability and hemiplegia, tandem bicycles for individuals with visual impairments, specially adapted cycles for persons with skeletal dysplasia, and electrical-assisted features to accommodate varying levels of physical capability—adaptive cycling makes it possible for individuals with a wide range of disabilities to participate (3, 10). These innovations enable people with disabilities to enjoy the physical and psychological benefits of cycling, while promoting inclusion and active living (3, 10). Given these considerations, adaptive cycles present a distinctive opportunity to promote physical activity among individuals with disabilities, helping to mitigate sedentary behavior and the associated health risks.

While various forms of adaptive physical activity have been reviewed in the literature (11, 12), adaptive cycling has not yet received the same level of attention. This form of exercise may offer distinct benefits due to its low-impact nature, its potential for fostering social inclusion, and assumed adaptability to a wide range of impairments. A scoping review focused on adaptive cycling is thus necessary to address the specific needs, outcomes and possibilities associated with this activity. This review will not only summarize the current body of research but will also highlight critical gaps in knowledge and suggest directions for future research in this underexplored area.

The purpose of this scoping review is to systematically investigate the existing scientific literature. The guiding research question is: “Is there scientific information available about the effects of adaptive cycling on the physical and mental health of individuals with disabilities?” By synthesizing the available evidence, this review seeks to (1) highlight the potential benefits and limitations of adaptive cycling, (2) identify research gaps, and (3) suggest directions for future studies. The findings will provide valuable insights for healthcare providers, policymakers, and individuals with disabilities.

2 Methods

We adhered to the methodological framework for scoping reviews outlined by Arksey and O'Malley (13), which consists of

five key stages: (1) identifying the research question; (2) identifying relevant studies; (3) study selection; (4) charting the data; and (5) collating, summarizing, and reporting the results. We note that steps 4 and 5 were combined for efficacy, without compromising the quality of the analysis.

In addition, we adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines (14) throughout the review process, ensuring transparency and methodological rigor.

2.1 Identifying the research question

As outlined above, this scoping review is guided by the following research question: “Is there scientific information available about the effects of adaptive cycling on physical and mental health of individuals with disabilities?” Thus, the aim of the following steps is to synthesize existing research to understand the influence of adaptive cycling on the health of individuals with disabilities and to identify any research gaps.

2.2 Identifying relevant studies

To identify relevant studies, we conducted a literature search in April 2024 using three databases: PubMed, Scopus, and Web of Science. We performed a spot-check of two other databases (Cochrane and ScienceDirect) which resulted in no further identification of new, significant literature. No publication date restrictions were applied to ensure a comprehensive search, capturing all studies written in English or German available up to the search date. The search terms were developed based on the PICO framework (15), focusing on Population, Intervention, and Outcome, while the Comparison component was excluded to maximize the inclusion of all potential studies. The search was conducted in a two-step process:

1. Initially, we conducted searches in each of the three databases using a primary search term based on the research question of our study, focusing on the Title/Abstract fields, as shown in Table 1.
2. Subsequently, we conducted a further search using a secondary search term, also outlined in Table 1. This secondary term was developed based on the articles identified in the initial search. Specifically, we revisited the search using terms related to adaptive cycles that had already been identified. This step was taken to ensure that we did not overlook any specific designations or variations of adaptive cycles. The aim was to further refine the search results.

In addition to this two-step process, we conducted supplementary searches by reviewing the reference lists of identified articles and utilizing Google Scholar to identify any additional relevant sources. The final search terms, which were adjusted according to the requirements of each respective database, are presented in Table 1. For more information on the results, please refer to Figure 1.

TABLE 1 Final primary and secondary search term used for the identification of relevant studies.

| Primary search term (title/abstract) |
|---|
| (cycling OR bike*OR biking OR bicycl* OR "adaptive cycling") AND (disabilit* OR amputee* OR wheelchair* OR para-* OR impairment*) AND (physical OR mental OR physiological OR psychological OR health OR "quality of life") NOT (animal* OR menstr* OR "life cycle") |
| Secondary search term (title/abstract) |
| (framerun* OR racerun* OR "frame running" OR "race running" OR "frame runner" OR "race runner" OR handbik* OR handcycl* OR (hand AND (bicycle OR bike OR cycl*)) OR (tandem AND (bicycle OR bike OR cycl*)) OR tricycle OR quadricycl* OR (stationary AND (bicycle OR bike OR cycle)) OR e-bike OR "power-assisted bike") AND (disabilit* OR amputee* OR wheelchair* OR para-* OR impairment*) AND (physical OR mental OR physiological OR psychological OR health OR "quality of life") NOT (animal* OR menstr* OR "life cycle") |

examined for additional relevant literature. Additionally, Google Scholar was screened for further relevant articles. The study selection was initially conducted by one primary reviewer based on the inclusion and exclusion criteria defined beforehand by all authors. For the final selection, all authors were involved in reviewing the articles to ensure consensus. Any conflicts or disagreements that arose during the process were resolved through discussion among the authors. Only articles that met the inclusion criteria after thorough examination were included into the analysis. After agreement among the authors on the final selection of studies, one reviewer processed the findings. The final selection of articles then underwent the steps outlined in Chapter 2.4.

2.3 Study selection

The study selection process was based on the PRISMA flow chart model (16). Following primary and secondary searches, a manual preselection of relevant studies was conducted based on their title and abstract. Subsequently, duplicates were removed, and another screening of the remaining articles was performed using the inclusion and exclusion criteria outlined in Table 2. During the review of these articles, reference lists were also

2.4 Charting data and collating, summarizing and reporting results

The previously selected studies were systematically organized in a table (see Table 3), wherein various characteristics of each study were collated. These characteristics included the reference (main author and publication year), study design, study participants, number of participants, type of adaptive cycle used, intervention employed, intervention groups, and identified health outcomes.

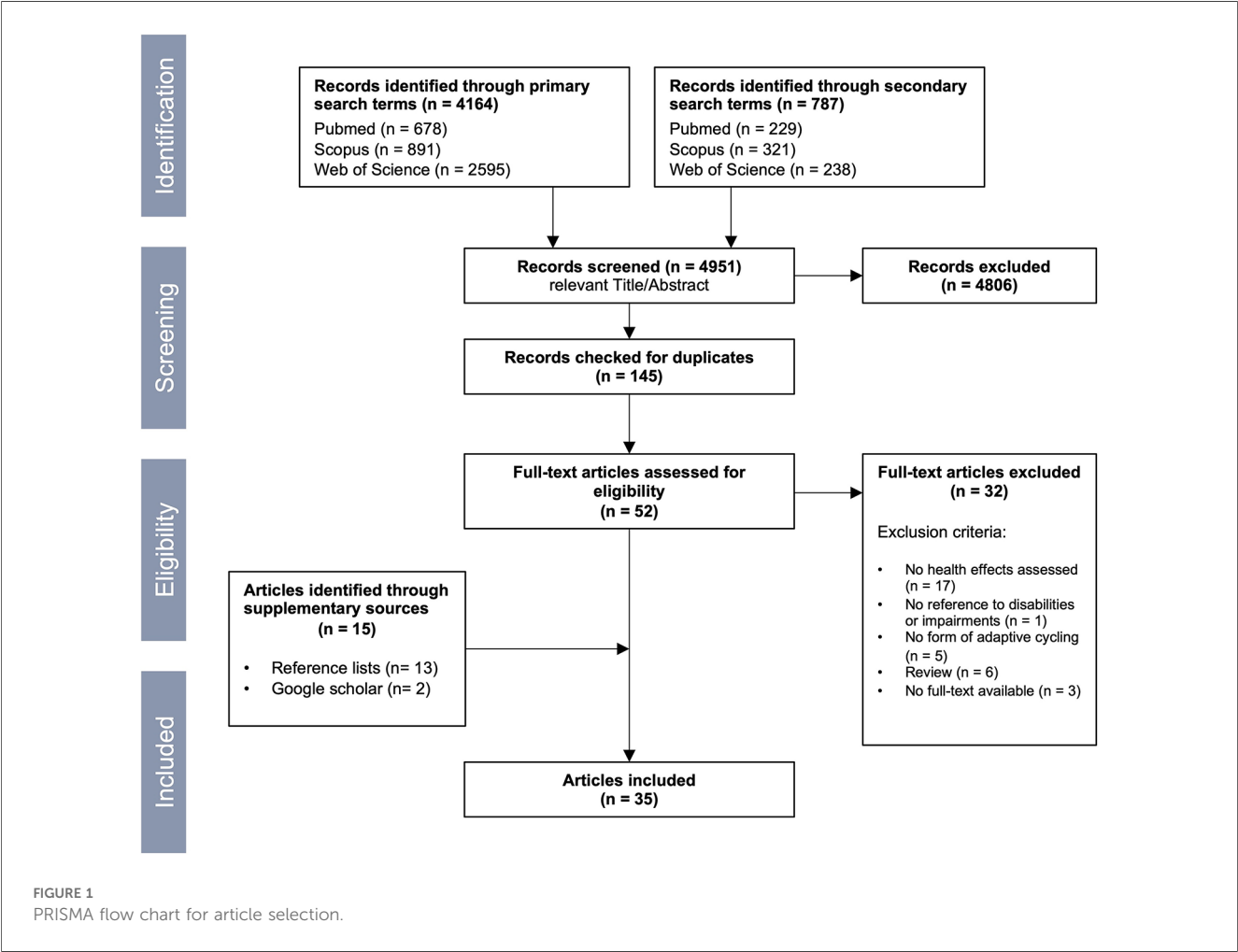


TABLE 2 Overview of inclusion and exclusion criteria applied during the manual preselection and subsequent screening of articles identified in the primary and secondary literature searches.

| Inclusion criteria | Exclusion criteria |
|--|---|
| <ul style="list-style-type: none">• Health effects assessed• Any kind of disability or impairment• All forms of adaptive cycling• Empirical studies• Full-text available (except conference papers)• Full-text in English or German• Grey literature if relevant | <ul style="list-style-type: none">• No health effects assessed• No reference to disability or impairment• No form of adaptive cycling• Review (direct inclusion of relevant studies)• No full-text available (except conference papers) |

Subsequently, an overview was generated based on this table, reflecting the current body of literature along with its gaps. Afterwards, a synthesis of the compiled data was conducted to provide a cohesive summary of the findings. This synthesis aimed to elucidate the significance and implications of the identified research outcomes, shedding light on major trends, patterns, and areas that require further investigation. In addition, particular attention was paid to placing the results into the broader context of adaptive cycling research in order to gain valuable insights for practitioners and researchers in this field.

2.4.1 Definition of health categories

To ensure clarity in the presentation and interpretation of results, it is important to define the categories of health outcomes discussed in this review. In the following, physical health refers to improvements in physiological functions such as cardiovascular fitness, strength, and endurance (52), while mental health is conceptualized as changes in cognitive function, mood, and emotional well-being (53). Quality of Life (QoL) was included as an additional category due to its significant role in complementing overall health outcomes in the analyzed population. It encompasses broader dimensions of well-being, including life satisfaction, social participation, and general happiness (54). To avoid confusion, a clear distinction is made between these categories, acknowledging that some outcomes (e.g., life satisfaction) may overlap with both mental health and QoL. This distinction is made to more accurately capture the specific impacts of adaptive cycling interventions on different aspects of health and well-being, allowing for a more comprehensive understanding of their effects.

3 Results

Altogether 35 studies were identified, including 34 quantitative and 1 qualitative study, that have investigated the physical and mental health effects of adaptive cycling in individuals with disabilities. The selection process is illustrated in Figure 1 following an adapted form of the PRISMA flow chart (16). All of the studies included in this review concentrate on structured interventions with adaptive cycling, examining the effects of specific cycling interventions on health outcomes in controlled settings.

3.1 Overview of the study characteristics

3.1.1 Study characteristics

The following table (Table 4) provides a summary of key variables extracted from the reviewed literature, including sample size, study design, and intervention characteristics. The distribution of studies and their percentages within each variable category is presented. Notably, a wide variance in sample size is evident. The identified literature was categorized into three clusters of study designs: experimental (57.14%), observational (40.00%), and descriptive studies (2.86%). Additionally, the type of intervention was classified to better contextualize the health outcomes of the reviewed studies. This involved categorization into acute interventions (a single session of adaptive cycling), short-term interventions lasting less than 6 months, long-term interventions exceeding 6 months, and investigations examining follow-up effects. The relative share of each intervention type among the 35 articles is as follows: 17.14% for acute interventions, 62.86% for short-term interventions, 17.14% for long-term interventions, and 2.86% for follow-up studies.

Moreover, based on the analysis, the majority of experimental studies focused on short-term interventions (16 studies), followed by acute interventions (2 studies) and long-term interventions (2 studies). Observational studies were predominantly short-term (6 studies), with fewer focusing on acute (4 studies), long-term (3 studies), and follow-up interventions (1 study). Descriptive studies primarily addressed long-term interventions (1 study).

3.1.2 Adaptive cycles

The variety of adapted cycles was categorized using the classification suggested by Norcliffe et al. (10). The proposed categories effectively cover the existing types of adaptive cycles and thus allowed for an examination of the available literature. As shown in Figure 2, the highest number of articles were found for stability machines ($n = 14$: 20, 21, 25, 26, 32, 34, 37, 39, 40, 43, 48–51) and handcycles ($n = 13$: 17, 18, 24, 27–29, 33, 35, 36, 44–47). Additionally, three articles were found for pedal (23, 29, 38) and tandem bicycles (30, 31, 41). Two articles could not be assigned to a specific cycle type attributed as undefined (21, 42) and one article was found for power-assisted bikes (19). It is noteworthy that the article of Inckle (29) focused on different types of adaptive cycles, making it assignable to multiple categories. As shown on the right side of Figure 2, no articles were found regarding the mental and physical health impacts of adaptive cycling among individuals with disabilities for the categories sociables (side-by-side), power-assisted bikes, and chair transporters.

For clarity, the identified cycles were categorized as follows: handcycles encompassed all cycles propelled by hand, including arm cycles, indoor handcycles, and traditional handcycles. Stability machines included cycles such as frame runners, stationary bikes, and hip-extensor tricycles. Pedal cycles comprised all adapted cycles with pedals not classified under stability machines, such as recumbent bicycles and tricycles, cycling wheelchairs, trikes, and standard bicycles. Additionally,

TABLE 3 Key characteristics of the selected studies.

| Reference | Study design | Participants | Number of participants | Groups | Adapted bicycle | Intervention | Health outcomes |
|-------------------------|---------------------|--|------------------------|--|--|---|---|
| Abel et al. (17) | Observational study | Spinal cord injury, amputation of both legs | 27 | Wheelchair racing ($n = 10$) handbiking ($n = 17$) | Handbikes and wheelchair racer | Basal metabolism evaluation, incremental exercise test, endurance test | Energy expenditure high enough to maintain fitness, may prevent cardiovascular diseases |
| Bakkum et al. (18) | Experimental study | Inactive people with long-term spinal cord injury | 20 | Hybrid cycling ($n = 10$) handbiking ($n = 10$) | Hybrid cycle, handbike | 30 min per day, 2×/week for 16 weeks | Improvement in cardiovascular fitness |
| Blumenstein et al. (19) | Experimental study | Healthy subject | 1 | – | Adapted e-bike | Single bouts of exercise | Improvement in space orientation and allows tuning of the electric motor's power to meet individual physical needs |
| Bryant et al. (20) | Experimental study | Children with cerebral palsy | 15 | Spastic bilateral CP ($n = 11$) dyskinetic CP ($n = 4$) | Frame runner | 3×/week for 12 weeks | Enjoyment, increased standing ability, no change in the CP QoL-Child questionnaire scores, significant improvement of bone density |
| Daly et al. (21) | Experimental study | Children with cerebral palsy | 3 | – | Adaptive bicycles | 30 min daily | Significant improvement on the energy expenditure index, improvement in gross motor function (all subjects) |
| Fowler et al. (22) | Experimental study | Children with cerebral palsy | 62 | Cycling ($n = 31$) control ($n = 31$) | Stationary bicycle | 30 sessions over 12 weeks | Significant improvements in locomotor endurance, gross motor function, and some measures of strength |
| Fu et al. (23) | Observational study | Elderly with physical disability | 41 | – | Cycling wheelchair | 30 min per day, 5×/week for 4 weeks | Improvement in quality of life and aerobic capacity |
| Gervasoni et al. (24) | Experimental study | People with multiple sclerosis | 20 | Crossover: group A ($n = 10$) group B ($n = 10$) | Arm cycling and tailored task-oriented exercise | 20 sessions over 8 weeks | Reduction in fatigue and motor fatigability, increase in finger movement rate |
| Grecco et al. (25) | Experimental study | Unilateral transtibial amputees | 34 | Non-athlete untrained ($n = 17$) Paralympic athletes ($n = 17$) | Stationary bicycle and resistance training | 3×/week for 8 weeks | Improvement in general functional condition, muscle strength, and cardiorespiratory performance |
| Hjalmarsson et al. (26) | Experimental study | Adolescents and young adults with cerebral palsy | 15 | – | Frame runner | 2×/week for 12 weeks | Increase in cardiorespiratory endurance, increase in thickness of medial gastrocnemius muscle and decreased ankle dorsiflexion on more-affected side, increase in passive hip flexion on less-affected side |
| Hoekstra et al. (27) | Observational study | Wheelchair users | 59 | – | Handbike | 4 months free-living condition | POpeak, VO2peak and waist circumference improved significantly |
| Hussein et al. (28) | Experimental study | Children with hemiplegic cerebral palsy | 48 | Study ($n = 24$) control ($n = 24$) | Arm cycling | 30 min arm cycling and 60 min gait training exercises over a 6 month period | Significant improvement in arm swing, significant increase in flexion angular displacements of the hip and ankle joints during gait cycle |
| Inckle (29) | Descriptive study | People with physical disability, impairment or mobility impairment | 7 | – | Standard two-wheeled bicycle, handbike, trike, recumbent | Experience of cycling from ten to more than 50 years | Experience of mobility, independence, and freedom, huge benefits for mental and physical health and wellbeing |
| Kamelska et al. (30) | Observational study | Visually impaired and properly sighted people | 26 | Visually impaired ($n = 13$) properly sighted ($n = 13$) | Tandem bicycle | 1.5–2.5 h per day, 3–5×/week for 7 months | Statistically significant increases in VO2max and Pmax, no time × visual impairment interaction effect was found |
| Kamelska et al. (31) | Observational study | Visually impaired and properly sighted people | 26 | Visually impaired ($n = 13$) | Tandem bicycle | 1.5–2.5 h per day, 3–5×/week for 7 months | Similar improvement in majority of hemodynamic variables, visual impairment did not limit health benefits of regular physical activity |

(Continued)

TABLE 3 Continued

| Reference | Study design | Participants | Number of participants | Groups | Adapted bicycle | Intervention | Health outcomes |
|------------------------|---------------------|--|------------------------|---|-----------------------|--|---|
| | | | | properly sighted ($n = 13$) | | | |
| Kim et al. (32) | Experimental study | Chronic stroke patients | 32 | Experimental ($n = 16$) control ($n = 16$) | Stationary bicycle | 30 min per day, 5×/week for 6 weeks | Significant improvements in balance and gait abilities, improvements in balance, 10-m walking test score (gait) significantly greater in cycling group |
| Kim et al. (33) | Experimental study | People with a spinal cord injury | 15 | Exercise ($n = 8$) control ($n = 7$) | Indoor handbike | 60 min per day, 3×/week for 6 weeks | Compared to control group significantly decreased BMI, fasting insulin, and HOMA-IR levels, and significantly increase in Vo2peak and strength in shoulder abduction, adduction, flexion, and extension and elbow flexion and extension |
| King et al. (34) | Experimental study | Children with cerebral palsy | 7 | – | Hip-extensor tricycle | 10 weeks daily | Visually analysed gait improved, but hip extensor strength did not, childrens and parental reports on use and enjoyment were positive |
| Kouwijzer et al. (35) | Observational study | People with health conditions such as spinal cord injury, amputation, or multiple trauma history | 136 | – | Handbike | 5 months training | Life satisfaction increased, mental health showed no change over time, improvement in cardiorespiratory fitness was associated with an increase in life satisfaction |
| Kouwijzer et al. (36) | Observational study | People with health conditions like spinal cord injury | 143 | – | Handbike | 5 months training and 1 year follow-up | Body satisfaction significantly increased during training period and decreased at follow-up, improvements in physical capacity and waist circumference significantly associated with improvements in body satisfaction |
| Lauhoff et al. (37) | Experimental study | People with Parkinson's disease | 23 | – | Stationary bicycle | 30 min per day, 1x/week for 6 weeks | Statistically significant improvements noted in balance, activities of daily living and mobility, trend towards improvement for exercise tolerance, no significant effect on QoL |
| Leblanc et al. (38) | Experimental study | Children with cerebral palsy | 7 | – | Bicycle, tricycle | 10 sessions over 5 weeks | No significant difference in gross motor function and locomotor endurance, significant improvement of locomotor performances of lying and reversal motor capacities, significant improvement in the locomotor performance in daily life reported by parents |
| Lousada et al. (39) | Observational study | People with cerebral palsy | 5 | – | Frame runner | 3 different sprint training sessions | Frame running at a sufficient intensity to promote health and fitness adaptations possible |
| Mayo et al. (40) | Experimental study | people within 12 months of acute Stroke who were able to walk >10 m independently | 87 | Cycling ($n = 43$) exercise ($n = 44$) | Stationary bicycle | 15–30 min cycling per day vs. disability-targeted exercises for 12 months | Both programs were equally effective in maintaining walking capacity after discharge from stroke rehabilitation |
| McGough et al. (41) | Experimental study | People with mild to moderate Parkinson's disease | 41 | – | Tandem bicycle | 3×/week for 10 weeks | Statistically significant physical performance improvement across domains of gait, balance, and mobility |
| Pickering et al. (42) | Observational study | Children with cerebral palsy | 25 | – | Adaptive bicycles | 6 weeks of adaptive cycling | Enjoyment of this experience, improved sense of well-being |
| Shafizadeh et al. (43) | Observational study | Racerunning athletes | 8 | – | Frame runner | Series of 100 m sprints on frame runner | Racerunning athletes with neurological motor disorders absorb the impact shock of framerunning through strategy that mimics able-bodied runners |
| Stone et al. (44) | Observational study | Competitive and recreational handcyclists | 13 | Competitive ($n = 7$) recreational ($n = 6$) | Handbike | Bouts of exercise at training (50% POpeak), competition (70% POpeak), and sprint intensity | Greater flexibility in the thorax, shoulders, and scapula in the competitive group, indicating that kinematic adaptations attributable to technical training potentially optimize muscle recruitment and force generation of the arm |

(Continued)

TABLE 3 Continued

| Reference | Study design | Participants | Number of participants | Groups | Adapted bicycle | Intervention | Health outcomes |
|----------------------------|---------------------|--|------------------------|---|------------------------|---|---|
| Valent et al. (45) | Observational study | People with a recent spinal cord injury | 162 | Handcycling ($n = 55$) non-handcycling ($n = 82$) not recorded ($n = 25$) | Handbike | Regular rehabilitation program | Significantly larger increase in Vo(2)peak, POpeak, and elbow extension strength in subjects with paraplegia, no influence on any outcome measures in postrehabilitation period |
| Valent et al. (46) | Experimental study | People with tetraplegia | 22 | – | Handbike | 24 sessions within 8–12 weeks | Significant improvements in POpeak, Vo(2)peak, mechanical efficiency, and shoulder abduction strength |
| Valent et al. (47) | Experimental study | People with a spinal cord injury | 40 | Experimental ($n = 20$) control ($n = 20$) | Handbike | 30–45 min per day, 2×/week for 9–39 weeks | Strong tendencies for improvement in wheelchair capacity (POpeak and oxygen pulse), significant effects on shoulder exo- and endo-rotation and unilateral elbow flexion strength, no improvements on pulmonary function |
| van der Linden et al. (48) | Observational study | Frame running athletes | 115 | – | Frame runner | 3 months of frame running | Subjects felt increased muscle stretch and self-confidence, some had extreme fatigue or sore muscles after training, less out of breath during mobility tasks and felt improved functional mobility, some reported increased muscle tightness and some a Frame Running-related injury lasting more than 4 weeks |
| van Schie et al. (49) | Observational study | Young athletes with mobility limitations | 62 | – | Frame runner | Minimum of 3 months of frame running | Significant positive change on all three subscales of the PIADS questionnaire, most change experienced in performance, the ability to participate, happiness and self-confidence, increased QoL |
| Vogt et al. (50) | Experimental study | Adolescents with intellectual and developmental disabilities | 11 | Crossover | Stationary bicycle | 10 min moderate cycling | Temporarily enhances neuronal activity in relation to cognitive performance |
| Williams and Pountney (51) | Experimental study | Non-ambulant children with CP | 11 | ABA design with participants acting as their own controls | Adapted static bicycle | 3×/week for 6 weeks | Improvements in functional ability |

adaptive cycles were labeled as undefined if the articles did not specify the type of cycle being used.

3.1.3 Population

Within this scoping review, various groups of individuals with disabilities who participated in adaptive cycling interventions were identified. These subject groups encompassed individuals with medical conditions such as spinal cord injuries (17, 18, 33, 35, 36, 45, 47), cerebral palsy (20–22, 26, 28, 34, 38, 39, 42, 51), multiple sclerosis (24), Parkinson’s disease (37, 41), and those recovering from acute and chronic strokes (32, 40). Additionally, participants with conditions such as amputations, physical disabilities, impairments, or mobility restrictions, tetraplegia, paraplegia, intellectual and developmental disabilities, multiple trauma histories, and visual impairments (17, 23, 25, 29–31, 35, 46, 49, 50), as reported by the original authors, were also included. Furthermore, other groups of individuals with disabilities were identified that were not clearly categorized by the authors under a specific condition but were described as wheelchair users, frame running athletes, and competitive and recreational handcyclists (27, 43, 44, 48).

3.2 Health outcomes of adapted cycling on individuals with disabilities

This section provides an overview of the health effects examined in the selected studies. The outcomes are categorized into physical and mental health effects, and effects on QoL. Within each of the categories, the impact of interventions is

discussed based on the duration of the interventions as well as the adaptive cycle used.

3.2.1 Physical health effects

From the examined articles, 27 focused on the physical health effects of adaptive cycling, encompassing various aspects and dimensions of physical performance and health. The acute physical effects of adaptive cycling activities were investigated through handcycling, power-assisted cycling and frame running. Handcycling demonstrated high energy expenditure levels, sufficient to maintain fitness levels and potentially prevent cardiovascular diseases, even when performed at moderate intensity corresponding to 2 mmol/L lactate (17). Similar effects promoting health and fitness adaptations were observed with frame running (39). Moreover, competitive handcyclists exhibited greater flexibility in the thorax (~5°, $p < 0.05$) and extended their shoulder (~10°, $p < 0.01$), and posteriorly tilted their scapular (~15°, $p < 0.05$) more compared to recreational handcyclists suggesting kinematic adaptations attributable to technical training that may optimize muscle recruitment and force generation of the arm (44). Additionally, frame running athletes with neurological motor disorders employed strategies akin to able-bodied runners to absorb impact shock during frame running, positively influencing their movement behavior (43). The use of adapted E-bikes, as shown by Blumenstein et al. (19), can enhance space orientation for individuals with perceptual disorders and allow for the tuning of the electric motor’s power to meet individual physical needs, offering tailored support during physical activity.

Regarding the short-term effects of adaptive cycling on physical health, as defined by studies with intervention durations of less than 6 months, a variety of cycles were examined, including handcycles, stability machines, pedal cycles, and tandem cycles. Handcycling interventions, as demonstrated by Bakkum et al. (18) and Gervasoni et al. (24), have shown positive effects on cardiovascular fitness and reductions in fatigue and motor fatigability. Valent et al. (46) and Valent et al. (47) highlighted significant improvements in peak oxygen uptake, mechanical efficiency, and wheelchair capacity associated with handcycle use, including enhancements in arm and shoulder strength and mobility. Similarly, Hoekstra et al. (27) and Kim et al. (33) reported significant improvements in peak oxygen uptake, power output, strength in various muscle groups and body composition parameters following handcycle interventions. These findings collectively underscore the effectiveness of handcycle interventions in promoting both cardiovascular health and muscular strength and suggest their potential in enhancing overall physical well-being.

Using short-term interventions involving stability machines, similar findings were observed. frame running, described by Hjalmarsson et al. (26), contributed to an average increase in cardiorespiratory endurance, accompanied by enhancements in muscle thickness and passive hip flexion, although it was associated with decreased ankle dorsiflexion. As highlighted by Bryant et al. (20), frame running interventions also led to improvements in standing ability and significant improvements of bone quality index scores. Van der Linden et al. (48) highlighted the multiple effects of frame running, including

TABLE 4 Summary of key variables extracted from the reviewed literature, including sample size, study design, and intervention characteristics.

| Variable | | |
|-------------------------------------|--------------------|-----------------------|
| Sample size | Number of subjects | |
| Minimum | 1 | |
| Median | 25 | |
| Maximum | 162 | |
| | Number of studies | Percentage of studies |
| Study design | | |
| Experimental studies | 20 | 57.14 |
| Observational studies | 14 | 40.00 |
| Descriptive studies | 1 | 2.86 |
| Intervention | | |
| Acute intervention (single session) | 6 | 17.14 |
| Short-term intervention (<6months) | 22 | 62.86 |
| Long-term intervention (>6months) | 6 | 17.14 |
| Follow-up effect | 1 | 2.86 |

The table presents the minimum, median, and maximum sample sizes, (number of subjects), as well as the distribution and percentages of studies within the categories of study design and intervention characteristics, based on a total of 35 articles.



FIGURE 2

Adaptive cycling modalities identified in the literature search. The figure shows the types of cycling studied for their impact on the physical and mental health of individuals with disabilities, as well as areas lacking research.

improved muscle stretching, increased self-confidence, and improved functional mobility, although they reported fatigue and muscle soreness. Nevertheless, the latter is a common training adaption of the muscle which improves its strength in the long-term. An intervention with a hip-extensor tricycle by King et al. (34), yielded improvements in gait analysis, although no significant changes were observed in hip extensor strength. Using stationary bicycles, Grecco et al. (25) demonstrated enhancements in overall functional condition, muscle strength, and cardiorespiratory performance. This was further underscored by Fowler et al. (22), who reported substantial improvements in locomotor endurance, gross motor function, and strength. Additionally, individuals with disabilities using stationary bicycles were observed to experience additional enhancements in balance, mobility, and gait abilities, along with improvements in activities of daily living (32, 37). Overall, these findings emphasize the positive impact of short-term interventions involving stability machines in enhancing cardiorespiratory endurance, strength and functional mobility, thereby supporting improvements in overall physical health.

Pedal cycles, including cycling wheelchairs, bicycles, and tricycles, have also demonstrated substantial benefits in various physical health aspects, particularly through short-term interventions. Interventions with cycling wheelchairs resulted in improvements in aerobic capacity (23), while interventions involving bicycles and tricycles significantly enhanced locomotor performance, lying, and reversal motor capacities (38). Following a tandem cycling intervention, McGough et al. (41) observed statistically significant improvements in physical performance across gait, balance, and mobility domains.

In addition, two short-term interventions with undefined adaptive cycles found that significant improvements in the energy expenditure index as well as gross motor function can be achieved (21) and improvements in functional ability were associated with adapted cycles (51).

While the findings of short-term interventions collectively underscore the diverse and significant positive impacts of adaptive cycling on physical health and function, it is equally important to consider the long-term effects of interventions lasting more than 6 months to fully understand the potential of adaptive cycling on physical health for individuals with disabilities. Altogether five studies were found that investigated the long-term effects including handcycles, tandem cycles and

stability machines. Handcycling led to significant improvements in arm swing and flexion angles during the gait cycle (28), with a notable increase in physiological parameters among paraplegic individuals, while its influence post-rehabilitation was inconclusive (45). Tandem cycling resulted in statistically significant increases in VO_{2max} and P_{max} , with elite cyclists exhibiting significantly higher VO_{2max} compared to sub-elite cyclists (30); additionally, it demonstrated similar improvements in hemodynamic variables (e.g., heart rate, stroke volume, cardiac output, ejection fraction, systemic vascular resistance), suggesting that severe visual impairment does not impede the health benefits of regular physical activity (31). Following a long-term intervention with stationary bicycles, Mayo et al. (40), found that stationary cycling was equally effective in maintaining walking capacity after discharge from stroke rehabilitation as were mobility exercises and brisk walking.

3.2.2 Mental health effects

Seven articles addressed the mental health effects of adaptive cycling among individuals with disabilities. Vogt et al. (50) found that acute stationary bicycle use temporarily enhances neuronal activity, particularly in relation to cognitive performance in individuals with intellectual and developmental disabilities. Short-term effects were observed across a restricted range of cycling modalities. Frame runner and hip-extensor tricycle interventions were associated with increased enjoyment (20, 34) and increased self-confidence (48), while adaptive bicycle use was associated with an improved sense of well-being (42). Handcycling was linked to increased life satisfaction during the training period, although no significant changes in mental health were noted over time (35). When examining the long-term effects studied by Inckle (29), a perceived enhancement in the experience of mobility, independence, and freedom, along with significant benefits for mental and physical health and wellbeing of the individuals involved, can be observed.

3.2.3 Effects on quality of life

In addition to the physical and mental health benefits, five studies also examined changes in QoL among individuals with disabilities throughout adaptive cycling interventions. Fu et al. (23) reported enhancements in QoL using cycling wheelchairs among elderly with physical disability. Similarly, frame running interventions have been associated with positive changes in

various aspects of QoL, as reported by parents of participating children. These changes were particularly evident in performance, participation ability, happiness, and self-confidence, suggesting an overall increase in QoL (49). In contrast, Bryant et al. (20) found an increase in enjoyment using frame runner but no changes in QoL. Lauhoff et al. (37) supported those findings, observing no significant impact on QoL following a stationary bicycle use.

Follow-up examinations of handcycle interventions conversely revealed significant changes in body satisfaction. Body satisfaction significantly increased during the training period but decreased back to pre-training levels at follow-up, whereby individuals with more severe impairments exhibited a larger decrease in body satisfaction. Additionally, improvements in physical capacity and waist circumference were significantly associated with improvements in body satisfaction (36).

4 Discussion

The present scoping review aimed to comprehensively examine the existing literature on the physical and mental health effects of adaptive cycling in individuals with disabilities. While the review identified a substantial body of research investigating the effects of various adaptive cycling interventions, several noteworthy gaps and future research directions emerged from the analysis.

Adaptive cycling interventions demonstrated significant potential for enhancing physical health outcomes, including improvements in cardiovascular fitness, muscle strength, mobility, and functional capacity. Specifically, interventions involving handcycles, stability machines, pedal cycles, and tandem cycles were associated with positive changes in physical fitness parameters such as peak oxygen uptake, power output, and muscle strength. Moreover, adaptive cycling activities promoted cardiovascular health, with studies indicating improvements in cardiorespiratory endurance and energy expenditure levels. In terms of mental health, a limited number of studies addressed this aspect, but those available found positive effects. Short-term effects on mental well-being were observed across various cycling modalities, including increased enjoyment and a sense of well-being. However, the evidence base for mental health outcomes was less extensive compared to physical health outcomes, indicating a need for further research in this area.

Controversies and inconsistencies were also observed, particularly regarding QoL outcomes. While some studies reported significant enhancements in QoL domains, such as performance, participation ability, happiness, and self-confidence, others found no effects of adaptive cycling on QoL. These discrepancies underscore the need for further research to elucidate the true impact of adaptive cycling on QoL outcomes and to address potential confounding factors that may influence individual perceptions.

Furthermore, there was variability in the quantity and quality of evidence across different categories of adaptive cycling modalities. While certain modalities, such as handcycles and stability machines, were supported by a relatively robust body of evidence, others, such as sociable cycles, chair transporters, and power-assisted bikes, were underrepresented or lacked sufficient empirical support. This underscores the necessity for further research to

investigate the diverse array of adaptive cycling options and their effects on health outcomes among individuals with disabilities, particularly as those alternative cycling modalities show potential but have not been adequately studied. Future research should explore their potential benefits and feasibility to provide a more comprehensive understanding of adaptive cycling options.

Moreover, it is essential to consider the broader context of adaptive physical activity. Research on other forms of physical activity, such as adapted sports and exercise interventions for individuals with disabilities, has shown similar benefits in terms of physical and mental health, as well as QoL (55–57). This review's findings align with the broader literature on adaptive physical activity, underscoring the importance of structured and inclusive physical exercise for individuals with disabilities. Future studies should explore how adaptive cycling may complement or differ from other adaptive physical activities, contributing to a more comprehensive understanding of the role of physical activity in improving overall health outcomes.

Another significant issue in the existing literature is the inconsistency in how populations are defined and categorized. While various groups of individuals with disabilities have participated in adaptive cycling interventions, the studies often lack clear and standardized definitions of these populations. For instance, some studies include individuals with spinal cord injuries, cerebral palsy, multiple sclerosis, and other specific conditions, while others broadly categorize participants as wheelchair users or individuals with physical disabilities. This lack of uniformity in population categorization limits the ability to compare and generalize findings across studies. Moreover, some disability groups, such as those with intellectual and developmental disabilities or sensory impairments, remain underrepresented. Additionally, gaps remain in assessing health outcomes related to the community usage of adaptive cycling, which could provide valuable insights into its real-world impact and broader applicability. Future research should aim to standardize the categorization of disability populations and ensure inclusivity, also in relation to community settings, to better capture the diverse needs and experiences of individuals with disabilities.

The studies reviewed in this scoping review varied considerably in terms of sample size, study design, and intervention duration, highlighting challenges in interpreting the findings. The wide variance in sample sizes, with some studies involving very small participant groups, may impact the reliability and generalizability of the results. Additionally, while adaptive cycling shows potential for improving physical and mental health, the predominance of short-term interventions limits our understanding of its long-term effects, underscoring the need for further research with larger sample sizes and extended intervention and follow-up periods.

4.1 Limitations

While every effort was made to conduct a comprehensive search of the literature, it is always possible that some studies were not captured by the search terms. Despite trying alternative search criteria, it is always possible that mis-specified keywords

and inaccurate abstracts led to the exclusion of certain studies that could have provided further insights into the topic. This review included studies published in English and German to reflect the authors' linguistic abilities; studies in other languages were therefore not included, which may have limited representation from regions where research is predominantly published in other languages. Furthermore, the quality and heterogeneity of the included studies may have influenced the synthesis and interpretation of the findings. Although we did not develop a formal protocol or conduct a critical appraisal—given that our aim was to map the breadth of the existing literature rather than evaluate study quality—we adhered to the remaining PRISMA-ScR guidelines to ensure a comprehensive and transparent report of our methods and findings.

5 Conclusion

In summary, this scoping review consolidates the current evidence on the physical and mental health effects of adaptive cycling for individuals with disabilities, and emphasises significant gaps in the literature. The findings demonstrate the potential of adaptive cycling to enhance physical health, mental health, and quality of life. However, inconsistencies in the evidence, especially concerning quality-of-life outcomes, highlight the need for further investigation.

Beyond summarizing existing evidence, this review underscores the importance of expanding research to include underrepresented populations and modalities, such as sociable cycles and chair transporters. Future research should also explore the long-term effects of adaptive cycling interventions and consider the broader spectrum of health outcomes associated with various cycling modalities over different time periods. Such efforts could provide a more comprehensive understanding of adaptive cycling's benefits and ensure its accessibility for diverse disability groups.

Ultimately, this review serves as a foundation for future research and practice in the field of adaptive cycling for individuals with disabilities. Its findings have the potential to inform clinical decision-making, guide future research endeavors, and thereby foster improved health and well-being of individuals with disabilities.

Data availability statement

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

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Author contributions

NM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. GN: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing. AK: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY

Hassane Zouhal,
University of Rennes 2, France

REVIEWED BY

Akshata R. Naik,
Oakland University, United States
Jose Manuel Salum Tome,
Temuco Catholic University, Chile

*CORRESPONDENCE

Rebecca E. Hasson,
✉ hassonr@umich.edu

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Enhancing home-based physical activity for neurodivergent children: adapting the *InPACT at Home* program with AI and universal design

Tania Sapre¹, Haylie L. Miller¹, Anna Schwartz¹,
Leah R. Ketcheson², Alanna Price³, Kerry Winkelseth¹,
Jeanne M. Barcelona², Ronald F. Zernicke^{1,4} and
Rebecca E. Hasson^{1*}

¹School of Kinesiology, University of Michigan, Ann Arbor, MI, United States, ²College of Education, Wayne State University, Detroit, MI, United States, ³Detroit Public School Community District, Detroit, MI, United States, ⁴Department of Orthopaedic Surgery, School of Medicine, University of Michigan, Ann Arbor, MI, United States

Purpose: While it is common practice for schools across the United States to include neurodivergent children in physical education classes, many programs outside of school—such as those at home or in the community—are not effectively tailored to meet their support needs. This gap contributes to lower levels of physical activity among neurodivergent children. Our objective was to address this issue by systematically adapting the *InPACT (Interrupting Prolonged sitting with ACTivity) at Home* program to enable neurodivergent children to safely engage in physical activity at home.

Methods: The rapid-cycle research adaptation process involved several key steps: (1) sorting and grouping video content based on different types of skills and exercises (*problem exploration*); (2) assembling an expert team to guide the development of the instructions (*knowledge exploration*); and (3) using generative artificial intelligence (AI) to create concise instructions and cue words for each skill/exercise (*solution development*). These outputs were then fine-tuned by the expert team. The refinements were guided by the Universal Design for Learning (UDL) principle of “Representation,” which acknowledges that learners perceive and understand information in diverse ways.

Results: From the 132 *InPACT at Home* videos, over 500 activities were identified and categorized into main skill groups: jumping, core, lateral, sport, upper body, lower body, and compound movements. Expert meetings emphasized the importance of the “Three C’s”—consistency, conciseness, and clarity—in crafting instructions, along with the use of simple, elementary sight words. AI was employed to generate and refine prompts like “Provide simplified step-by-step instructions for a jumping jack, suitable for a neurodivergent child” and “Condense the step-by-step instructions for a jumping jack, suitable for a neurodivergent child”.

Discussion: The adaptation of the existing *InPACT at Home* program was guided by dissemination and implementation science frameworks, aiming to increase equitable access to structured youth physical activity opportunities for

neurodivergent children. By incorporating AI and UDL principles, we aim to further enhance the program's accessibility. Our next steps include evaluating the effectiveness of our program adaptations in encouraging participation in the *InPACT at Home* program and subsequently increasing physical activity levels among neurodivergent children.

KEYWORDS

generative AI, universal design for learning (UDL), adolescent and youth, exercise, implementation science

Introduction

The role of physical activity in child development

Physical activity plays a critical role in shaping children's physical health, social development, and cognitive abilities. For neurotypical children, participation in physical activity is associated with improved physical health, higher self-esteem, and the development of a strong social identity through sports (Logan et al., 2019; Piercy and Troiano, 2018). Similarly, children with intellectual and developmental disabilities experience comparable benefits. For instance, neurodivergent children (e.g., those diagnosed with autism, developmental delay, intellectual disability, or similar) who participate in programs like Special Olympics show greater fitness, strength, aerobic capacity, self-esteem, confidence, social competence, and friendships compared to their peers who are not involved in such activities (Logan et al., 2019). Autistic children can also benefit from physical activity and exercise (Ceccarelli et al., 2020; Monteiro et al., 2022; Ruggeri et al., 2020), specifically experiencing positive changes in communication, social interaction, social cognition, social motivation, regulation of repetitive behaviors and awareness (Huang et al., 2020; Koh, 2024; Liang et al., 2022; Rafie et al., 2017). Physical activities like sports can also expose children to varied external stimuli, engaging multiple senses—sight, hearing, touch, and smell—and promoting sensory integration through nervous system activation and neural development (Rafie et al., 2017). Exercise further supports motor skill development, executive function, and overall quality of life for neurodivergent children (Bremer et al., 2016; St John et al., 2020; Sun et al., 2022). Collectively, this evidence underscores the profound impact of physical activity in fostering the development and wellbeing of all children, with especially significant benefits for neurodivergent children.

Current challenges in youth physical activity participation

Despite these benefits, few children and youth are regularly physically active (Piercy and Troiano, 2018). According to the 2024 United States Report Card on Physical Activity for Children and Youth, only 20%–28% of children aged 6 to 17 meet the recommended 60 min of daily physical activity (Alliance, 2024). These data, drawn from the National Survey of Children's Health and National Health and Nutrition Examination Survey, show even lower levels of activity among neurodivergent children, with just

19% meeting the recommended amount (Alliance, 2024; Case et al., 2020). These findings are consistent with previous research using large datasets (McCoy et al., 2016) or objective measurements (Liang et al., 2020) and highlight the urgent need for targeted interventions to increase physical activity levels, particularly among neurodivergent children.

Low motor competence plays a significant role in these low physical activity levels. Research shows that neurotypical children with motor competence below an “average” threshold are unlikely to meet recommended physical activity guidelines (De Meester et al., 2018). Additionally, many neurodivergent children exhibit fundamental motor skill differences, such as delays or challenges in balance, aiming, catching, and strength (Staples and Reid, 2010). However, findings in the neurodivergent population are mixed (Taylor et al., 2024). Some studies show only a weak association between low motor competence and physical activity levels, with motor competence varying across specific domains (e.g., upper limb coordination versus running speed). These domain-specific difficulties may influence participation in certain types of activities.

Perceived motor competence is particularly important for motivating autistic youth to engage in physical activity (Wong et al., 2024) but appears less influential for children with intellectual disabilities or ADHD. This highlights the need for programs that address not only motor skills but also the diverse psychological needs of neurodivergent children to support their engagement in physical activity.

Although person-centered factors like motor competence affect participation, features of the social and physical environment also exacerbate disparities in physical activity participation among neurodivergent children (Wong et al., 2024; King et al., 2003). One major issue is the limited understanding among instructors and coaches about neurodivergent children's abilities. Caregivers, instructors, and physical educators may not be comfortable modifying exercise instructions for a person with high communication or cognitive support needs (McDermott et al., 2022; Parsons et al., 2024). Playground design poses another barrier, since most fail to accommodate the needs of neurodivergent children (Johnson et al., 2021). Key features such as wayfinding systems, stable surfacing, flush transitions, and sensory elements are often missing, making spontaneous physical activity less safe, engaging, and accessible. Finally, there is a notable shortage of evidence-based, free resources, including specialized curricula and community programs, to support parents in addressing their children's physical activity needs (Rimmer and Rowland, 2008). These gaps further exacerbate the barriers to physical activity faced by neurodivergent children.

Strategies for inclusive physical activity

Addressing these challenges requires developing targeted strategies to promote inclusive physical activity for neurodivergent children (Lakowski and Long, 2011; Murphy and Carbone, 2008). However, creating new interventions from scratch can be time-consuming and resource-intensive, making it more efficient to adapt existing evidence-based interventions (Wang et al., 2018). Adapting interventions involves modifying evidence-based interventions while maintaining their core components to ensure effectiveness (Baumann et al., 2018). This process has previously involved consideration of factors such as race, ethnicity, service setting, location, and organizational characteristics (Wiltsey Stirman et al., 2015). Yet, few researchers have applied adaptation frameworks to enhance equity and inclusion in physical activity interventions (Hasson et al., 2022; Scott-Andrews et al., 2021).

The current project: *InPACT for Everyone*

The main objective of the current project was to systematically adapt the *Interrupting Prolonged sitting with ACTivity (InPACT) at Home* program to enable neurodivergent children to engage in physical activity at home safely. This adaptation effort, named *InPACT for Everyone*, was guided by two key principles: rapid-cycle research and the Universal Design for Learning (UDL) principle of Representation (Johnson et al., 2015; Meyer et al., 2014). Rapid-cycle research is a systematic process where research teams identify barriers and address them using practice-based evidence, facilitating a swift transition from concept development to implementation in practice (Johnson et al., 2015). We previously used this approach to adapt a classroom-based physical activity intervention for delivery in the home (Hasson et al., 2022). The UDL principle of Representation emphasizes the need to represent information in multiple ways (e.g., through differing modalities such as text, images, and audio) to maximize accessibility of instructional content for learners with diverse backgrounds and support needs (Lieberman et al., 2021; Lieberman and Houston-Wilson, 2018). Multiple means of representation should also be provided in the assessment process, so that learners have a variety of opportunities to demonstrate skills.

The current paper describes key steps in the systematic adaptation of the *InPACT at Home* program, leveraging these frameworks to increase access to health-enhancing physical activity for neurodivergent children. By enhancing flexibility while maintaining fidelity, *InPACT for Everyone* seeks to address health equity and foster inclusive environments for physical activity.

Methods

The *InPACT at Home* program was chosen for adaptation due to its extensive reach across the state of Michigan. Specifically, when the program launched, website reach included all 83 counties and the daily viewership on public television ranged from 15,000–20,000 (Hasson et al., 2022). The *InPACT at Home* program was developed during the COVID-19 pandemic to provide equitable opportunities for physical activity in the home environment and address growing

concerns of inactivity and obesity during the shelter-in-place restriction. Adapted from an existing classroom-based physical activity intervention, the *InPACT at Home* program retained key elements such as use of exercise videos, maintenance of intervention dose, and instructor-led physical activities (Hasson et al., 2021). The program features 132, 8-min exercise videos created by physical education teachers, pediatric exercise physiologists, athletes, and other fitness professionals. These videos focus on four main types of exercise: cardio, strength, sports skills, and mindfulness. The videos have been evaluated as high quality regarding their production (Beemer et al., 2023). Children have rated the program as enjoyable and can feasibly complete two videos at home (Beemer et al., 2022; Beemer et al., 2024).

Rapid adaptation of the *InPACT at Home* program

In June 2023, an expert in neurodivergent movement (H.L.M.) reached out to the program director of the *InPACT at Home* program (R.E.H.) to discuss increasing inclusive physical activity opportunities for youth. The principal investigator agreed and formed an interdisciplinary team of researchers and practitioners with expertise in motor development, pediatric exercise physiology, inclusive physical activity practices, and adapted physical education to address this issue (see Table 1). The *InPACT* program director contacted each team member via email to confirm their involvement in the adaptation team. Approximately 55% of the team members identified as women of color (including African American, Asian, Hispanic, and Middle East and North Africa [MENA]), and the entire team was composed of women. In addition, one of the team members identified as neurodivergent and had a neurodivergent immediate family member.

This diversity played a pivotal role in shaping the adaptation process by bringing together multiple cultural and experiential perspectives. The team's varied social backgrounds and professional expertise ensured the adapted intervention would be inclusive and accessible to a wide range of neurodivergent children. With women of color from diverse cultural and neurodivergent backgrounds on the team, the adaptations were crafted with an enhanced sensitivity to how social, cultural, and cognitive factors affect engagement, comprehension, and comfort for children from different backgrounds. This inclusivity, paired with interdisciplinary expertise, enabled the team to create a nuanced, culturally sensitive adapted intervention to meet the unique needs of neurodivergent children.

Rapid adaptation of the *InPACT at Home* program

The six steps of rapid-cycle research provide a structured approach to developing, testing, and scaling solutions. These steps are based on the Framework for Rapid-Cycle Research developed by the Agency for Healthcare Research and Quality, which outlines the phases of the adaptation and research process from conceptualization to implementation (Johnson et al., 2015). The process begins with *preparation*, where partner organizations

TABLE 1 Team member expertise. The specific expertise of each member of the video review team and expert team.

| Team member name | Expertise |
|---|--|
| Video reviewer 1 | A research assistant with a B.S. in Biopsychology, Cognition, and Neuroscience from the University of Michigan, with experience in developmental psychology and fitness app development for neurodivergent children |
| Video reviewer 2 | An undergraduate research assistant at the University of Michigan specializing in Biology, Health, and Society, with experience as a dance instructor |
| Video reviewer 3 | An undergraduate research assistant at the University of Michigan specializing in Biology, Health, and Society, with experience in pediatric exercise physiology |
| Video reviewer 4 | An undergraduate research assistant at the University of Michigan specializing in Applied Exercise Science, with practical experience in sports |
| Video reviewer 5 | An undergraduate research assistant at the University of Michigan specializing in Movement Science, with practical experience in sports |
| Video coder 1 | A research assistant with a B.S. in Applied Exercise Science from the University of Michigan, with experience in strength training and fitness instruction |
| Video coder 2 | A research assistant with a B.S. in Movement Science from the University of Michigan, with experience working with kids with ASD, Down syndrome, and other processing disorders |
| Neurodivergent movement expert researcher (H.L.M.) | A researcher specializing in neurodivergent movement, with 12 years of experience developing and implementing physical activity interventions in pediatric populations affected by ASD. |
| Adapted physical education expert researcher (L.R.K.) | A researcher specializing in adapted physical education, with 15 years of experience in developing and promoting early motor and physical activity interventions for special populations |
| Adapted physical education practitioner (A.P.) | An experienced practitioner specializing in kinesiology with over 20 years of teaching adapted physical education in public schools |
| Physical education researcher and practitioner (K.W.) | An experienced researcher and practitioner specializing in physical education, with 38 years teaching Physical education and 25 years managing community-based physical activity programs for both typically developing and neurodivergent youth |
| Video script development expert (J.M.B) | A researcher and general educator with 11 years' experience developing interventions that support health behaviors across communities and lifespans |

are identified, along with individuals within those organizations who will champion the program. This is followed by *problem exploration*, which involves understanding key problems that need to be solved. This stage emphasizes dialogue and sharing diverse perspectives to deepen the understanding of the issue. Next is *knowledge exploration*, which examines the problem from multiple angles. This includes characterizing the problem, identifying industries that face similar challenges, pinpointing organizations within those industries that have successfully addressed the problem, and analyzing the processes or activities that set these organizations apart.

Solution development then focuses on identifying the simplest, least invasive, and most scalable solutions that can be applied. Once potential solutions are developed, the *solution testing* phase evaluates their effectiveness. Project team members assess the importance of and progress on various evaluation dimensions (Reach, Effectiveness, Adoption, Implementation, Maintenance or RE-AIM). Based on these assessments, teams prioritize one or two RE-AIM dimensions, set proximal goals, and implement strategies to improve their progress. This step follows an iterative process to refine the solutions. Finally, the *dissemination* phase ensures the findings and effective solutions are shared, facilitating broader adoption and scaling.

This project specifically focused on the second through fourth phases: *problem exploration*, *knowledge exploration*, and *solution development*. Each of these three steps of rapid-cycle research and their associated activities are described in Table 2. The fifth and sixth

phases (*solution testing* and *dissemination*) were beyond the scope of this project and the *preparation* phase was accomplished prior to the adoption of the rapid cycle framework through the formation of the adaptation team.

Problem exploration-understanding the problems that were important to solve

The adaptation team identified that the difficulty level of the *InPACT at Home* exercises posed a barrier to engagement for both neurotypical and neurodivergent children. Previous research found that the skill level needed to complete the exercises was a challenge for neurotypical children (Beemer et al., 2022). This suggested that skill level may also be a barrier for neurodivergent children. To improve program engagement for both neurotypical and neurodivergent children, it became necessary to identify which exercises featured in the videos required additional instructions, cues, and demonstrations to support participation. The following sections outline the activities conducted during the *problem exploration* phase.

Activity 1: assemble a video review team

During the *problem exploration* phase, the adaptation team formed a video review team to identify and categorize exercises in the *InPACT at Home* videos that required additional instructions, cues, and demonstrations (see Table 1). For this project, an exercise

TABLE 2 Key cycle steps to adapt the *InPACT at Home* program for use in neurodivergent pediatric populations.

| Rapid cycle steps | Description | Activities | Outcome |
|---|---|--|--|
| Problem exploration <i>Understanding key problems that need to be solved</i> | Identified problem: motor skill level required to complete <i>InPACT at Home</i> exercise videos was a barrier to for both neurotypical and neurodivergent children | 1. Assembled a video review team and coders 2. Identified exercises in videos 3. Standardized names of exercises 4. Categorized exercises based on muscle group/motor skill | 1. Video review team composed of research assistants with expertise in pediatric exercise physiology and motor development 2. 500+ unique activities identified 3. 260 standardized exercises cataloged 4. 7 motor skill categories developed |
| Knowledge exploration <i>Examining the problem from multiple perspectives</i> | Questions asked: <ul style="list-style-type: none">• How many activities need step-by-step instructions?• What, if any, free resources are available?• How would the instructions be developed? | 1. Assembled an expert team to review the list and categories of exercises 2. Expert team searched for free resources that offered step-by-step instructions for basic movements 3. Expert team provided recommendations on how to develop and refine step-by-step instructions from AI-generated output, if free resources were not available | 1. Experts included practitioners and researchers 2. Expert team identified no available resources that met the needs of this project 3. Recommendations for refining instructions included: <ul style="list-style-type: none">• Step-by-step instructions for all exercises• Tailoring ChatGPT prompts• Applying UDL principles• Avoiding figurative language• The Three C's• Cognitive Load Management• Standardized Starting Positions• Encouraging Continuation |
| Solution development <i>Identifying the simplest least invasive, and most scalable solutions that can be applied</i> | Solution: Use Generative AI to develop prompts to create instructions with expert team refinement Expert team development of cue words and videos | 1. Novice AI prompt developer recruited 2. ChatGPT used to develop prompts through an iterative process 3. Generated prompts used to develop exercise instructions and cues 4. Expert team modified the ChatGPT instructional output for content and style 5. Experts identified exercises that were “complex” 6. Instructional videos were developed | 1. Novice developer with 100 h of experience using ChatGPT was selected 2. Two prompts were created 3. Review team extracted important information from the Chat-GPT instructions 4. Expert team reviewed instructions and cues for instructional content validity 5. A “burpee” was identified as a highly complex movement 6. 24, 2-min instruction videos were created to scaffold learning to complete a “burpee” |

was defined as “a series of skills or movements performed to strengthen one or more muscle groups”.

The video review team had two distinct roles: “video reviewers”, who systematically documented exercise names in the videos, and “coders”, who standardized these names by grouping similar exercises under a single term. Standardizing exercise names aimed to reduce variations in terminology and concepts, minimizing the cognitive load on the learner’s working memory (van Merriënboer and Sweller, 2010). As a result, children could focus more on performing the movements rather than processing different terms or ideas.

Activity 2: identify exercises in videos

Each *InPACT at Home* video was reviewed to identify the exercises included. Each reviewers watched a subsection of the video catalog, noting every exercise taught and any unique exercise names that needed standardization. This process produced a comprehensive list of movements and exercises found in all *InPACT at Home* videos.

Activity 3: standardize exercise names

The coders then assigned each unique exercise a more standardized name (e.g., “stand-up sit-downs” were grouped under “squats”). To accomplish this, the coders examined each uniquely named exercise, watched the corresponding video segments, and identified its key movements. If those movements

matched an exercise already on the standardized list, the coders grouped the activity under the appropriate name, eliminating the unique names from the final list.

Activity 4: categorize standardized exercises by muscle group or motor skill

After standardizing the exercise names, exercises were categorized based on the muscle group or movement skill they primarily targeted. The team coded the standardized list of exercises from the *InPACT at Home* videos, focusing on the main body parts and skills activated during the movements. Recognizing that no exercise exclusively targets a single body part or skill, the video review team determined which body part was most activated or which skill was most integral to each movement.

Knowledge exploration—Exploring the problem from different perspectives

The following sections outline the activities conducted during the *knowledge exploration* phase.

Activity 1: assemble an expert team

Drawing from insights gained during the problem exploration phase, the adaptation team brought together a group of experts—comprising researchers and practitioners from within

the team—during the *knowledge exploration* phase. This team (A.P., H.L.M., K.W., and L.K.) reviewed the list and categories of exercises and provided guidance on developing step-by-step movement instructions tailored to meet the needs of neurodivergent children.

Activity 2: expert consultations to identify existing free resources

Members of the adaptation team (A.S., T.S., and R.E.H.) conducted a series of meetings with practitioners (A.P. and K.W.) from the expert team to explore the availability of free resources offering step-by-step instructions for fundamental movement skills. These discussions also addressed potential strategies for developing such instructions if free resources were not available. The team specifically considered the utility of generative artificial intelligence (AI) for creating tailored resources for neurodivergent children.

ChatGPT 3.5, a free AI chatbot developed by OpenAI, emerged from the discussions as a promising tool due to its ability to quickly provide accurate information and enable customization through interactive prompts (Ray, 2023). This capability allows users to tailor outputs to specific needs, making it a valuable resource for developing inclusive instructional materials. Additionally, using generative AI software would enable the adaptation team to efficiently develop and refine instructions for hundreds of activities—a task that would have otherwise taken months to complete.

In reviewing the literature, the adaptation team confirmed that generative AI had already been successfully used in fitness and medicine to instruct and inform users. For example, researchers in Finland used ChatGPT 4.0 to generate personalized workout plans that participants found to be high quality, engaging, and useful (Logacheva et al., 2014). Another study showed that medical students in Canada were more successful at learning surgical skills in simulations when tutored and given feedback by an AI tutor rather than an expert instructor (Fazlollahi et al., 2022).

While AI technologies are not yet recommended as replacements for personalized, progressive, and health condition-specific guidance from healthcare and fitness professionals, they can serve as valuable supplementary tools. In their current form, AI technologies enhance accessibility, particularly for individuals who cannot afford professional advice. Consequently, the practitioners discussed using generative AI alongside expert feedback to develop step-by-step instructions for inclusive physical activity.

Activity 3: expert recommendations for developing and refining instructions and cue words

If new resources needed to be developed, the expert team agreed to provide recommendations on how to develop and refine instructions and cue words from AI-generated output.

Solution development—identifying the simplest possible solution to be applied

The following sections outline the activities conducted during the *solution development* phase.

Activity 1: novice AI prompt developer recruitment

To assist in developing new instructions and cue words, a novice AI prompt developer was recruited. The decision to use a novice

developer instead of a professional prompt engineer was intentional, aimed at simulating the experience of an average user with limited or no experience using ChatGPT. This approach ensured that generating instructions would be feasible for parents and families.

Activity 2: ChatGPT prompt development

The process of developing ChatGPT prompts was iterative. Initially, the bot was asked to provide instructions for a sample exercise (lateral lunge), and the outputs were then refined to match the desired content and format. For instance, if ChatGPT produced lengthy instructions (more than 10 steps), it was prompted to condense them. If the language used was not straightforward (e.g., using metaphors or elaborate sentences to describe the step) or was too verbose, it was instructed to simplify the wording. Subsequently, ChatGPT was asked, “What prompt should I use to get this output?” The returned output would then be used as a template prompt for each exercise on the standardized list by substituting “lateral lunge” for the exercise of interest (Prompt 1).

A similar process was used to develop a prompt that further shortened the length of the instructions, helping the content become more digestible (Prompt 2). The combination of both prompts allowed for the instructional content to be accurate (Prompt 1) and concise (Prompt 2). Figure 1 displays the series of ChatGPT inputs used in the form of a decision tree to generate prompts for creating inclusive step-by-step instructions. Supplementary Appendix S1 provides an example of the iterative process used to generate and refine exercise instructions from ChatGPT.

Step 1: Development of step-by-step instructions and cue words

After finalizing the two template ChatGPT prompts, the AI prompt developer used the prompts to generate step-by-step exercise instructions for each activity on the standardized list of exercises.

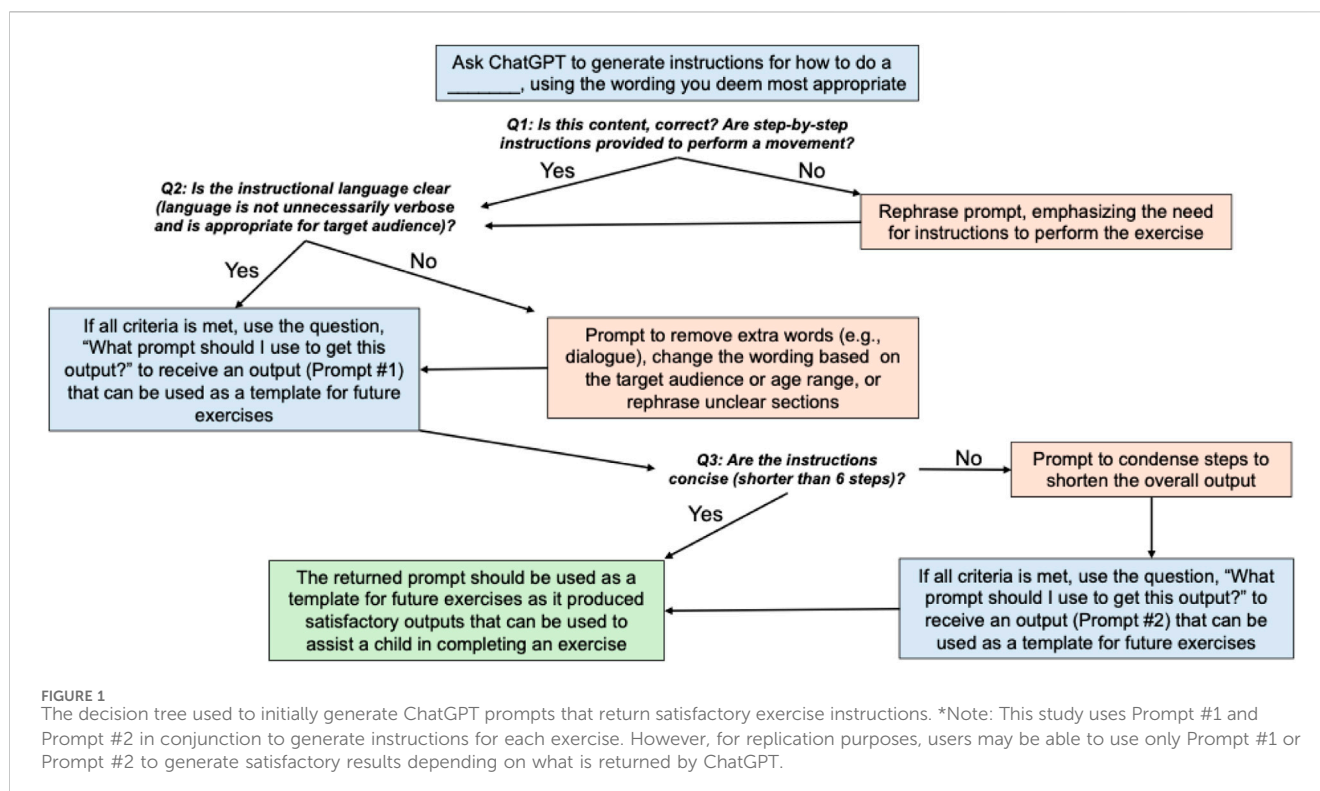
Step 2: Refinement of step-by-step instructions

Once the AI-generated exercise instructions were created, members of the expert team reviewed and approved them for both content validity and style consistency. Based on this review, a set of expert recommendations was compiled to assist parents and families in using generative AI to develop their own instructions for additional exercises beyond those included in the *InPACT at Home* program.

Step 3: Cue word development and refinement

After the expert team reviewed and approved the AI-generated instructions for content and style, the video review team began developing short cue words (2–3 words) to reinforce key concepts from the instructions. The focus was on content validity, ensuring that the cue words were derived directly from the longer instructions.

The video review team assessed the instructions to identify critical words related to physical form or specific body movements. For example, the AI-generated instructions for a squat exercise might read:



Starting Position: 1) Stand with feet hip-width apart. 2) Bend Knees: Slowly bend knees, like sitting in a chair. 3) Keep Back Straight: Maintain a straight back. 4) Go Down Comfortably: Lower body as far as comfortable. 5) Push Up: Push through heels to stand straight.

From this, the expert feedback led to refined instructions: 1) Stand with feet hip width apart; 2) Pretend you're sitting in a chair; 3) Push through heels to stand.

The corresponding cue words, developed by the review team, would then be: 1. Feet apart; 2. Pretend chair sit; 3. Push to stand.

The expert team then verified that each cue word reinforced essential information for completing the movement. By combining AI-generated instructions with expert feedback to refine the cues, the new resources were reviewed at multiple levels—iteratively refined by AI, the video review team, and the expert team—to ensure the content was accurate and beneficial for both neurotypical and neurodivergent children.

Step 4: Expert identification of “complex” exercises

After developing the step-by-step exercise instructions and cue words, the expert team identified which exercises were “complex”. These exercises were deemed particularly challenging for children due to the involvement of multiple compound movements. For these exercises it was recommended that children would benefit from demonstration videos to better understand these movements. This aligned with the UDL principle of Representation, which emphasizes presenting information in multiple formats to support diverse ways of learning and engaging with instructional content (Meyer et al., 2014).

The expert team identified specific complex exercises in the *InPACT at Home* videos that could be broken down into individual movements and then scaffolded into a video series teaching comprehensive whole-body complex movements. Additionally, it was determined that these step-by-step instructional videos could serve as introductory videos for both neurodivergent and neurotypical youth who are new to the *InPACT at Home* program. This approach ensured that all participants, regardless of their developmental background, could effectively learn and engage with the *InPACT at Home* exercises.

Step 5: Video development

A member of the expert team, A.P., was chosen to appear in the instructional videos due to her previous experience in exercise video production. An expert in video script development (J.B.) was recruited to join the expert team to create the video content, while R.E.H., the *InPACT* program director, served as the scientific advisor to ensure the accuracy of the video content. All videos were filmed at a community location using professional equipment and staff.

Results

Problem exploration

Outcome 1: composition of the video review team

The video review team consisted of graduate and undergraduate research assistants from the adaptation team with expertise in pediatric exercise physiology and motor development. Five

TABLE 3 *InPACT at Home* Exercise Categories. This table displays each category of exercise present in the *InPACT at Home* program. Each category includes distinct key features that help determine which category each exercise belongs in. The table also provides examples of exercises in each category.

| Category | Key features | Example |
|-------------------|---|---------------------------------------|
| Jumping | Jumping as the predominant movement | Jump rope, star jumps |
| Lateral movement | Moving side to side | Lateral foot taps, lateral line jumps |
| Core | Exercises that predominantly engage core muscle groups | Crunches, heel taps |
| Upper body | Focused movement above the torso, including arms, shoulders, and upper back | Arm circles, jabs |
| Lower body | Focused movement below the torso, including glutes, quads, hamstrings, and calves | Squats, butt kicks |
| Sports skills | Activities that simulate skills needed to play a sport | Overhand throw, soccer dribbles |
| Compound movement | Exercises that involve two or more major categories | Burpees, planks |

assistants were assigned as video reviewers, while the other two served as video coders.

Outcome 2: identification of unique exercises

From the 132 videos in the *InPACT at Home* program, more than 500 unique exercises were identified.

Outcome 3: standardization of exercises

The 500+ unique exercises were consolidated into a list of 259 standardized exercises.

Outcome 4: standardized exercises categorized by muscle group or motor skill

The list of standardized exercises was then coded into one of seven fundamental motor skill categories based on the skill that was performed: jumping, lateral movement, core, upper body, lower body, sports skills, and compound movement. Table 3 describes the key features and examples of each category. For example, the “squat” exercise was initially identified to target glutes and quadriceps muscles. This was then coded into the lower body category, as the muscles predominantly involved were part of lower body muscle groups. This coding process helped the team visualize the distribution of exercises across motor skills categories. From this analysis, there were 11 jumping exercises, 4 lateral movement exercises, 28 core exercises, 61 upper body exercises, 68 lower body exercises, 48 sports skill movements, and 39 compound movement exercises.

Knowledge exploration

Outcome 1: expert team assembled

The expert team consisted of four researchers and/or practitioners with expertise in neurodivergent movement, adapted physical education, and physical education. This team reviewed a subset of the compiled list of activities and developed a strategy for creating a glossary of exercise instructions.

Outcome 2: expert identification of available resources

Consultations with the practitioners on the expert team revealed that while validated adapted physical activity resources exist, many come with associated costs and are not freely accessible to the public.

The free resources that are available do not include step-by-step instructions for teaching fundamental motor skills. As a result, the decision was made to use ChatGPT to generate step-by-step instructions.

Outcome 3: expert recommendations for developing and refining instructions from AI-generated output

Throughout the project, nine meetings with the expert team were conducted, leading to several key recommendations for developing and refining the AI-generated exercise instructions:

Step-by-Step instructions for all exercises

Early discussions with researchers H.L.M. and L.R.K. led to the recommendation that all exercises, regardless of complexity, should include step-by-step instructions. This approach was chosen due to the lack of a clear definition for complex exercises and the need to address individual differences, particularly for neurodivergent children.

Tailoring ChatGPT prompts for neurodivergent children

The team emphasized the importance of adjusting ChatGPT prompts to meet the unique needs of neurodivergent children, who often have different body awareness compared to neurotypical peers (Fears et al., 2023). The researchers highlighted that any movement is beneficial, even if it does not perfectly match the cue words and instructions.

Applying UDL principles

A strong focus was placed on UDL principles. The team stressed the need to include both written descriptions and visual aids (e.g., pictures and videos) to accommodate diverse learning preferences and enhancing accessibility. Accordingly, the expert team recommended presenting instructional content in three formats: detailed instructions, short cues, and videos. This variety allows children to learn in the format that best suits their needs, whether through text or visual aids, and helps ensure accessibility for all learners (Meyer et al., 2014).

Avoiding figurative language

Practitioners A.P. and K.W. advised against using figurative language (e.g., metaphors like “keep your eyes on the target”) in the instructions (Holt and Ratliffe, 2004), as neurodivergent children

TABLE 4 A sample of exercises, the ChatGPT outputs, the corresponding instructions, and their cues. Short instructions and cue words were developed by the review team with expert input.

| Exercise name | Category | ChatGPT output | Short instructions | Cue words |
|-------------------|------------|--|---|---|
| Star jumps | Jumping | 1. Stand straight, arms down 2. Jump out wide, arms and legs out 3. Jump in, arms and legs down 4. Repeat, breathing steadily 5. Enjoy! | 1. Stand at the ready position 2. Jump out, stretching your arms and legs out wide like a star 3. Jump in, bringing your arms back down and legs together 4. Keep going! | 1. Ready position 2. Jump out 3. Jump in 4. Keep going! |
| Heel taps | Core | 1. Lie on back with knees bent 2. Lift shoulders slightly 3. Tap right heel with right hand 4. Tap left heel with left hand 5. Repeat 6. Breathe steady 7. Have fun! | 1. Lie down, with your back touching the floor 2. Bend your knees, with your feet flat on the floor 3. Squeeze your stomach muscles 4. Reach your right hand to tap your right heel 5. Reach your left hand to tap your left heel 6. Keep going, alternating your taps! | 1. Lie down 2. Tap heel 3. Tap other heel 4. Keep going! |
| Lateral line jump | Lateral | 1. Stand with feet together 2. Jump sideways 3. Jump back 4. Repeat at your own pace 5. Breathe steady 6. Have fun! | 1. Stand at the ready position 2. Jump to one side 3. Jump back 3. Keep going! | 1. Ready position 2. Jump sideways 3. Jump back 4. Keep going! |
| Small arm circles | Upper body | 1. Stand with feet apart 2. Raise arms to sides 3. Make small circles forward 4. Repeat 5. Breathe steady 6. Have fun! | 1. Stand at the ready position 2. Raise arms out like a “T” 3. Make small circles with your arms, like stirring the air 4. Change directions, stirring the air the other way 5. Keep going! | 1. Stand comfortably 2. Make a “T” 2. Small circles 3. Change directions 4. Keep going! |
| Butt kicks | Lower body | 1. Stand with feet apart 2. Lift heels towards buttocks 3. Switch legs 4. Repeat 5. Breathe steady 6. Have fun! | 1. Stand at the ready position 2. Bring one heel to your butt 3. Bring the other heel to your butt 4. Hop faster from foot to foot 5. Keep going! | 1. Stand comfortably 2. Heel to butt 3. Other heel 4. Faster 5. Keep going! |
| Overhand throw | Sport | 1. Stand with feet apart 2. Hold the ball 3. Step forward with opposite foot 4. Raise arm back 5. Throw the ball forward 6. Follow through with arm 7. Repeat 8. Breathe steady 9. Have fun! | 1. Find something to throw (ball, rolled socks, etc.) 2. Stand at the ready position 3. Hold item in hand 4. Raise arm, bending at elbow to make an ‘L’ shape 5. Step forward with opposite foot (right hand, left foot) 6. Twist upper body towards ‘L’ shape side 7. Throw item | 1. Hold item 2. Make an ‘L’ 3. Step and twist 4. Throw |

often struggle with figurative language. Instead, they recommended clear, straightforward language to improve understanding (Kalandadze et al., 2018).

The three C’s

The expert team recommended focusing on the 3 C’s for instructional content—conciseness, clarity, and consistency—to reduce cognitive load and improve comprehension (Sweller et al., 2011). Conciseness refers to using as few words as possible, clarity involves using simple and unambiguous language, and consistency requires using the same terminology for each activity.

Cognitive load management

The team recommended limiting each exercise to three-to-five cues, with each cue being two-to-three words long. This helps prevent cognitive overload, as research indicates that working memory typically holds only three-to-four pieces of information (Farrington, 2011).

Standardized starting positions

To reduce unnecessary wording, the expert team established four standardized starting position names: “ready position” (stand upright, feet together), “stand comfortably” (stand upright, feet shoulder-width apart), “lie down” (lie on back with body parts flat on the ground), and “bend knees” (feet shoulder-width apart, in a half-squat position).

Encouraging continuation

The expert team also recommended adding the phrase “Keep Going!” at the end of instructions to signal that the movement should be repeated until the child feels comfortable.

Solution development

Outcome 1: novice AI prompt developer identified

A member of the adaptation team with approximately 100 h of experience using ChatGPT 3.5 was selected to create concise instructions and supplementary cue words for each exercise.

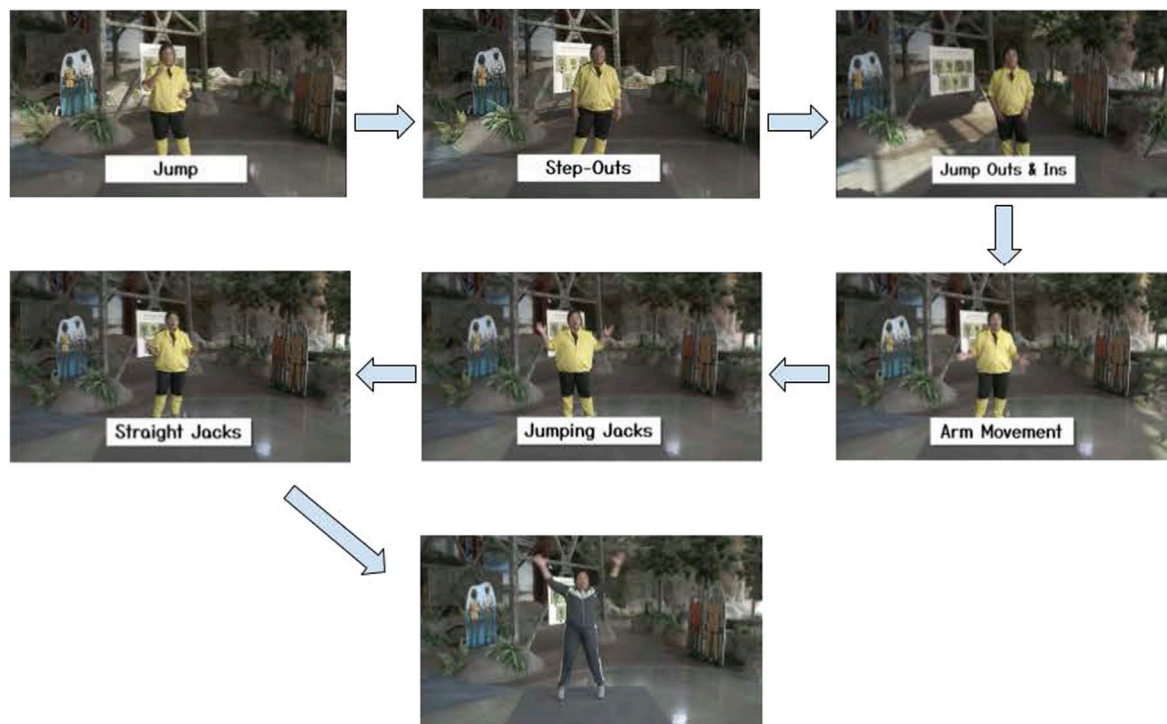


FIGURE 2
Screenshots from each of the videos in unit 1, leading up to straight jacks (a scaled-up version of jumping jacks). The last image shows the basic foundational exercise from unit 1, jumping jacks, serving as the warmup for unit 2 videos.

Outcome 2: ChatGPT prompts

Through the iterative process of developing ChatGPT prompts, the team identified two complementary prompts that, when used together, offered consistent and effective instructions. These two prompts were, “Provide simplified step-by-step instructions for a [insert exercise name here] suitable for a neurodivergent child” and “Condense the step-by-step instructions for a [insert exercise name here] suitable for a neurodivergent child.”

Outcome 3: step-by-step instruction and cue word development

These AI-generated prompts were inserted into ChatGPT one after the other, substituting the blank for an exercise name, to result in a set of instructions to perform the movement. The review team then extracted the important information from the ChatGPT-generated instructions to develop cue words. **Table 4** displays a sample of the developed instructions and cue words.

Outcome 4: step-by-step instruction and cue word refinement

After the initial development of cues and instructions, the expert team reviewed them for instructional content validity. They ensured that the wording for starting positions, signals for repetitions, and instructions for general movements remained consistent across each set of instructions and thoroughly covered all the necessary information to correctly perform the movement. This qualitative process helped to ensure the accuracy of the instructions and cues.

Outcome 5: expert identification of “complex” exercises

The burpee was identified as a highly complex movement due to its combination of multiple motor skills (e.g., jumping and balancing), compound movements (e.g., engaging the core, lower body, and jumping), and the need for precise coordination across nearly every muscle group. Given its complexity, the burpee was selected as an example for a demonstration video to guide participants in mastering the movement effectively.

Outcome 6: video development

Figure 2 shows a visual representation of several videos designed to teach children how to perform complex exercises by breaking the movements down into manageable steps. A total of 24 videos, each 2 minutes long, was created for this purpose. These videos were organized into four units, with each unit named after the specific complex exercise covered in its series of six videos. Within every unit, exercises were ordered so that each new skill could be scaffolded onto the next, ensuring that the fundamental skills needed to complete the complex exercise were mastered before moving on to the next component. For example, completing unit 1 meant that the child would be able to perform a straight arm jack, a complex version of a jumping jack. To do this, they are taught how to jump in video 1, how to move their legs side to side in video 2, how to jump in and out in video 3, how to move their arms in video 4, how to put everything together to perform a jumping jack in video 5, and then finally how to perform a straight jack in video 6.

Each of the first three units focused on teaching different complex exercises that were about the same difficulty. Because the expert team determined that one of the most complex exercises present in the *InPACT at Home* videos was the burpee, exercises in units 1-3 focused on skills that would help perform a burpee in unit 4. These foundational skills were reinforced through each unit by making moves from the previous unit serve as the warm-up in the following unit (e.g., jumping jacks from unit 1 were the warm-up for exercises in unit 2).

To ensure equitable access, the videos are broadcast on the Michigan Learning Channel as part of their “Read, Write, ROAR!” program (<https://www.michiganlearning.org>). They are now also a complementary component of the *InPACT at Home* program (inpactathome.umich.edu). The instructions for all these exercises are also being compiled into a glossary and will be made available to families on the program website.

Discussion

Systematic adaptation process

To enhance the accessibility of the *InPACT at Home* program for neurodivergent children, a systematic adaptation approach was utilized. The process began with a video review team identifying and categorizing exercises by muscle group or skill (*problem exploration*). Following this, a series of meetings with an expert team established the criteria for creating step-by-step instructions (*knowledge exploration*). Generative AI was then used to generate initial instructions, which were reviewed, refined, and supplemented with short cues by the expert team. For exercises that were particularly complex, additional instructional videos were produced to offer further guidance (*solution development*).

This approach addressed a fundamental shortcoming of many at-home physical activity programs, which often lack options for children with diverse cognitive needs and may require financial resources or prior exercise knowledge (Rimmer and Rowland, 2008). By integrating generative AI with expert feedback, this adaptation process rapidly provided step-by-step instructions, ensuring that neurodivergent children have equitable opportunities to participate in physical activity at home. *InPACT for Everyone* includes prompts and guidelines that parents can use to generate instructions, sample instructions and cues for activities, and videos to further support participation. The outcome of this systematic process of adaptation provides families with the tools to support their children in completing virtual exercise routines without financial constraints or access barriers.

Collaborative expertise and adaptation

Similar to the initial adaptation of the *InPACT* program from the classroom to the home environment, the *InPACT at Home* program’s adaptation relied on collaboration with researchers and practitioners specializing in motor development, pediatric exercise physiology, inclusive physical activity practices, and adapted physical education. These experts were considered “physically educated” (Decorby et al., 2005), and contributed essential

expertise to teach basic movement skills, apply UDL principles, and model a range of inclusive physical activities that promote lifelong participation in physical activity.

Role of generative AI in adaptation

In this study, ChatGPT was used to create step-by-step instructions for physical activities, leveraging a free and accessible platform to support neurodivergent children. While several programs offer evidence-based resources, their cost limits accessibility for many families. For example, Sports, Play, and Active Recreation for Kids (SPARK) is an evidence-based program that offers physical education resources and curricula to promote physical activity and healthy lifestyles in schools (McKenzie et al., 2016). SPARK is particularly useful as it breaks exercises down into manageable steps and includes inclusive physical education options. Similarly, the Effective Physical Education Curriculum (EPEC) program aims to create inclusive physical education environments and ensure accessibility for all children, including those with disabilities, by providing progressive exercises to reinforce new skills and apply them in various contexts (Michigan’s Exemplary Physical Education Curriculum Project, 2000). However, both SPARK and EPEC are behind paywalls, limiting their accessibility for parents who want to guide their children in exercises.

OPEN (<https://openphysed.org>) provides high quality free curriculum resources to schools but this curriculum lacks specific instructor prompts for teaching fundamental motor skills. The National Center on Health, Physical Activity and Disability (<https://www.nchpad.org>) offers free information and exercise videos for people with physical, sensory, and cognitive disabilities, but provides limited guidance on teaching motor skills and complex movements to neurodivergent children who need additional support. Finally, resources like Steps to Inclusion (Tristani et al., 2019) provide theoretical guidance on making physical activity inclusive but can be challenging for parents without practical experience. By utilizing ChatGPT and integrating expert feedback, the current study demonstrated how AI can bridge these gaps, offering accessible and practical tools for parents and families.

Observations on AI output and inclusivity

An interesting observation made during the project was ChatGPT’s tendency to include motivational language when prompted to develop tailored instructions for neurodivergent children. This extra content was not consistently included when ChatGPT was asked to provide instructions alone or when the target audience was specified as “kids”. Although this motivational content was removed from the instructional materials for this project due to its lack of direct relevance to the movements, it is noteworthy that ChatGPT tends to add extra information based on assumptions about the needs of neurodivergent children.

That phenomenon highlights the importance of training AI models with diverse, inclusive datasets, as an AI model’s

effectiveness depends on the training data it was developed with. Research on developing inclusive AI systems highlights that the problem-solving frameworks used for training often represent a single viewpoint, which can lead to homogenization and perpetuate stereotypes or biases (Hutson, 2024). For example, the above-mentioned scenario with ChatGPT implies that neurotypical children do not require additional motivation to complete exercises, whereas neurodivergent children do. Motivation levels vary among all individuals, regardless of whether they are neurodivergent or neurotypical. Thus, a neurotypical child who needs extra motivational content might not receive it, while a neurodivergent child with strong intrinsic motivation might receive unnecessary motivational content that could detract from the specific exercise. Hutson suggests that AI models like ChatGPT should be trained with broader, more diverse data sets, including those reflecting the viewpoints of neurodivergent individuals, to enhance inclusivity and expand the model's utility in diverse contexts (Hutson, 2024). Future research should explore strategies for optimizing AI training to better reflect the nuanced needs of all users, ensuring equitable and accurate outputs.

UDL framework

UDL, a framework developed by the Center for Applied Special Technology (CAST), aims to enhance and optimize teaching and learning for everyone, drawing on scientific insights into how humans learn (CAST, 2024). UDL has been successfully applied in various contexts to enhance instructional content accessibility. For instance, UDL, combined with the inclusion spectrum, has helped general physical education teachers align learning goals with activities that enable neurodivergent children to interact with their peers while staying physically active (Grenier et al., 2017). Additionally, UDL, together with the Planning for All Learners (PAL) procedures, has improved the accessibility of high school reading comprehension programs (Meo, 2008). The PAL process provides a practical four-step approach for implementing UDL: (1) setting goals, (2) analyzing the current status of the curriculum and classroom, (3) applying the UDL framework to lesson and unit development, and (4) teaching these UDL-aligned lessons and units (Israel et al., 2014).

As generative AI becomes increasingly popular, more programs are beginning to combine AI with UDL to enhance inclusivity. For example, one initiative used AI to optimize UDL implementation in an online graduate course, enabling personalized learning and customized assessments and course content (Morgan et al., 2024). Another project employed AI to develop K-12 health education lesson plans incorporating UDL principles, allowing teachers with no prior experience in health education to effectively teach the content (Conrad and Rees, 2024). While generative AI has been used in education to enhance UDL applications, its combination with UDL principles for creating inclusive physical activity resources at home remains underexplored. This project addresses that gap by providing a model for integrating UDL and AI to enhance accessibility and inclusivity.

Strengths and limitations

This study highlights several key strengths. First, it utilized implementation and dissemination science frameworks along with universal design to systematically adapt the *InPACT at Home* program. The involvement of a diverse adaptation team was another major strength, ensuring that multiple perspectives were integrated into the resource development process, thereby enhancing the accessibility of the resources for the pediatric population in Michigan. Additionally, the innovative use of ChatGPT to create inclusive instructional content was validated by incorporating expert feedback, which further strengthened the content.

However, the study also has some limitations. Previous research has highlighted AI's tendency to "confabulate" (i.e., to make up something without malicious intent), which may have affected the accuracy of ChatGPT's output (Alkaissi and McFarlane, 2023). That limitation was mitigated by refining the AI-generated content through expert team feedback. Another limitation is that the effectiveness of the *InPACT at Home* adaptation—specifically its step-by-step instructions, cue words, and demonstration videos—in improving program participation among neurodivergent children has not yet been rigorously tested. Additionally, the current study focuses solely on children, creating a gap in research on how these adaptations might apply to other age groups. Furthermore, the adaptation focused exclusively on the UDL principle of "Representation." Future research should explore how the UDL principles of "Engagement" and "Action and Expression" could be employed to further optimize inclusion within the *InPACT at Home* program. Finally, since the goal of *InPACT for Everyone* is to make the program accessible to all children, further testing is needed to determine whether this approach is effective for individuals with physical or cognitive disabilities beyond neurodivergence. It is our hope that the flexibility of this approach can be adapted to benefit a broader and more diverse community.

Conclusions

In conclusion, this study provides valuable insights into the rapid adaptation of the *InPACT at Home* program for neurodivergent children by integrating generative AI with expert feedback and grounding the process in dissemination and implementation science frameworks. That systematic approach not only addressed barriers to accessibility that often limit participation in at-home physical activity programs but also offers a replicable model for families to create their own physical activity resources.

By following specific guidelines—such as using ChatGPT prompts to generate detailed instructions, ensuring the content is concise, clear, and consistent, and presenting the instructions in various forms—families can effectively support their children's physical activity at home. While the study highlights promising outcomes, further research is needed to rigorously test the effectiveness of these adaptations and explore additional UDL principles to enhance inclusivity. Ultimately, this work sets a precedent for promoting health equity through the systematic and inclusive design of physical activity interventions, helping to reduce physical activity disparities and foster healthy habits among *all* children.

Data availability statement

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

Author contributions

TS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Writing—original draft, Writing—review and editing. HM: Conceptualization, Methodology, Supervision, Writing—review and editing. AS: Data curation, Investigation, Methodology, Writing—review and editing. LK: Formal Analysis, Investigation, Methodology, Supervision, Writing—review and editing. AP: Data curation, Investigation, Methodology, Writing—review and editing. KW: Methodology, Supervision, Writing—review and editing. JB: Data curation, Writing—review and editing. RZ: Funding acquisition, Writing—review and editing. RH: Funding acquisition, Project administration, Supervision, Writing—original draft, Writing—review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fphys.2024.1496114/full#supplementary-material>

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EDITED BY

Ronald F. Zernicke,
University of Michigan, United States

REVIEWED BY

Eduardo Carballeira,
University of La Laguna, Spain
Hugo Vieira Pereira,
Lusofona University, Portugal

*CORRESPONDENCE

Nuno Domingos Garrido
✉ ndgarrido@gmail.com

[†]These authors have contributed equally to
this work and share first authorship

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Impact of tele-exercise on quality of life, physical fitness, functional capacity and strength in different adult populations: a systematic review of clinical trials

Nuno Domingos Garrido^{1,2*†}, Victor Machado Reis^{1,2†},
José Manuel Vilaça-Alves^{1,2†}, Gabriela Chaves Lucas¹,
Ismael Lima Godinho¹, Rafael Peixoto¹, Alberto Fucarino³,
Manuela Cantoia³, Enzo Iuliano³, Andrea De Giorgio³,
Antonio Fabbri-
zioso M, Zimatore G, Baldari C and Macaluso F⁴

¹Research Center in Sports Sciences, Health Sciences and Human Development (CIDESD), Vila Real, Portugal, ²Sports Science, Exercise and Health Department, University of Trás-os-Montes & Alto Douro, Vila Real, Portugal, ³Department of Theoretical and Applied Sciences, eCampus University, Novedrate, Italy, ⁴Department of Biomedicine, Neuroscience and Advanced Diagnostics (BIND), University of Palermo, Palermo, Italy

Introduction: This study aimed to review the impact of tele-exercise on different adult populations, comparing synchronous and asynchronous interventions and their effects on outcomes such as quality of life, physical fitness, functional capacity, strength, and pain.

Methods: Randomised clinical trials and quasi-experimental studies published between 2014 and 2024 were included, totalling 16 studies with 1,416 participants. The interventions varied between synchronous teleexercise (via videoconference) and asynchronous (via apps and recorded videos). The review followed the PRISMA guidelines, ensuring a systematic approach to study selection, data extraction, and bias assessment.

Results: The results indicate that tele-exercise, especially synchronous, has the potential to primarily improve physical fitness, functional capacity, and pain perception, being effective for the elderly and individuals with specific conditions such as multiple sclerosis and obesity.

Discussion: However, the methodological heterogeneity of the studies and the lack of consistent data limit the generalisation of the findings, highlighting the need for more high-quality research.

Systematic Review Registration: https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42024563241, PROSPERO (CRD42024563241).

KEYWORDS

physical exercise, elderly, technology, health, tele-exercise

1 Introduction

Recent advances in technology and artificial intelligence, along with the COVID-19 era, have driven the development and popularisation of various online telehealth tools (1). Telehealth, including the adaptable concept of tele-exercise, has emerged to meet the need to incorporate physical exercise into current demands, empowering individuals to take control of their health (2, 3).

Physical exercise can be defined as a structured activity aimed at improving and maintaining physical fitness (4). Tele-exercise, in turn, is an online exercise prescription methodology that can be performed synchronously or asynchronously. Among the tools that comprise tele-exercise are training apps for smartphones with personalised programs, synchronous training via videoconference or mobile calls, apps with recorded videos to guide into workouts, activity monitoring via smartwatches and smart homes, and virtual assistants that suggest and monitor activities (2, 3, 5, 6). The advancement of these tools can be a resource for exercise training and adherence for individuals with mobility restrictions, health issues, and even people with limited access to in-person exercise environments, such as many elderly or individuals with limitations and comorbidities (7–9).

Given the global trend of low physical activity levels, it is concerning that 31% of adults and 80% of adolescents do not meet the World Health Organization's recommendations for physical activity (10), representing a significant public health challenge.

Given the trend towards sedentary lifestyles, tele-exercise has been introduced as a potential tool for expanding physical exercise (9). A basic tele-exercise program consists of a central database using web services to connect healthcare providers to patients' devices virtually. With technological advancements, tele-exercise using high-speed internet, videoconferencing, and smartphone apps can allow individuals to engage in physical activities remotely under the supervision of experienced and trained professionals. Importantly, these tools can enable participants to choose their preferred exercise regimes, especially those requiring minimal supervision (6, 11), thereby catering to their individual fitness needs and making them feel considered in their fitness journey.

These regimes help maintain regularity while minimising costs. Webcams provide communication between healthcare professionals and are a method for monitoring patients' activity (12). As one of the most recent branches of telemedicine, the theoretical data on its effectiveness lacks sufficient practical data to support it.

During the COVID-19 pandemic, the importance of tele-exercise as a health alternative was put into perspective (1, 13). Although some systematic reviews have addressed the topic of tele-exercise, its role in health, particularly regarding improvements in quality of life, physical fitness, and sub-groups such as functional capacity and strength in adult populations, is not yet well defined. Thus, this study primarily aims to understand the impact of tele-exercise on different population groups. Secondly, it seeks to compare synchronous vs. asynchronous tele-exercise and tele-exercise vs. in-person exercise, assessing whether there are differences in impact on quality of life, physical fitness, functional capacity, and strength across different adult populations based on the exercise method

used. Therefore, our focus is primarily on randomised clinical trials, recognising the importance of systematic reviews that include such studies. However, acknowledging that the current literature on the topic is recent, this work also accepts quasi-experimental studies that meet the eligibility criteria to make the review more comprehensive.

2 Methods

2.1 Registration protocol

The protocol was registered with the International Prospective Register of Systematic Reviews—PROSPERO (registration number CRD42024563241) prior to the start of this review, which was drafted in accordance with the PRISMA 2020 statement (14).

2.2 Eligibility criteria

2.2.1 Inclusion criteria

The selection process was meticulous and thorough. Initially, it was considered various study designs, but upon discovering a substantial number of clinical trials and quasi-experimental studies, it was chosen to focus on these two designs. Whether randomised or not, or included control groups, it was sought study designs that most effectively address the research question while rigorously accounting for their methodological limitations through stringent risk of bias criteria. Studies published between 2014 and 2024 with no language restrictions were included. The criteria was stringent, requiring at least one tele-exercise intervention, either synchronous or asynchronous, with a minimum duration of 6 weeks.

The present review encompasses a diverse range of adult populations. Adults aged between 18 and 99 who were not hospitalised or undergoing cardiac rehabilitation or physiotherapy programs were included. There were no restrictions regarding the population, resulting in a rich heterogeneity. The population categories included elderly individuals, elderly individuals in cancer remission, pregnant women with obesity or overweight, obese adults, adults with Parkinson, adults with multiple sclerosis (MS), adults with Down syndrome, adults with recent COVID-19, and healthy adults.

Accommodating a wide range of tele-exercise interventions, it were considered studies with synchronous and/or asynchronous tele-exercise interventions of any structured training method (e.g., resistance training or yoga). Synchronous interventions were required to be conducted via live videoconferencing, either in groups or individually, using smartphones, tablets, or computers. Asynchronous interventions could utilise technologies such as recorded videos, remote training apps, or traditional methods like prescription and supervision via phone calls. Asynchronous interventions could involve either one-time or ongoing interactions.

The main outcomes of this review included data assessing changes from baseline over time by group or between groups. Studies were included if they assessed at least one outcome

related to physical fitness, quality of life, functional capacity, strength, and pain, evaluated using a validated assessment tool. The presence of a control condition was not a mandatory inclusion criterion.

Studies with synchronous and/or asynchronous tele-exercise interventions of any structured training method (e.g., resistance training or yoga) were included. However, synchronous interventions needed to be conducted via live videoconferencing, either in groups or individually, using smartphones, tablets, or computers. Asynchronous interventions could utilise technologies such as recorded videos, remote training apps, or traditional methods like prescription and supervision via phone calls. Asynchronous interventions could involve either one-time or ongoing interactions.

2.2.2 Exclusion criteria

Studies were excluded if they addressed telemedicine or telerehabilitation in the context of physiotherapy or post-surgical recovery, as well as those related to virtual reality environments and e-sports. Studies without a structured tele-exercise program were also excluded. Articles published before 2014 were disregarded. Given the rapid technological advancements, we chose to prioritise more recent publications that reflect current technological tools.

2.3 Search strategy

On July 6, 2024, and July 10, 2024, searches were conducted in four databases: PUBMED (74 articles), SCOPUS (59 articles), WEB

OF SCIENCE (54 articles), and SCIENCE DIRECT (53 articles), totalling initially 240 articles. The search terms used (Table 1) were “Tele-exercise,” “Remote exercise,” “Remote training,” “Tele-exercise programs,” “Synchronous exercise,” and “Asynchronous exercise,” separated by the boolean operator OR, with a filter for “Title/Abstract” and coverage from 2014 to the present. A “snowball” search was also performed in the reference lists of the full texts, identifying two studies of interest. The entire process was conducted independently by two investigators. Table 1 presents the search strategy used for PUBMED.

2.3.1 Permission to reuse and copyright

No permission was necessary for the use of copyrighted content.

2.4 Study selection process

The initial reference screening was conducted using the reference management software ZOTERO 6.6.27. A total of 240 studies were initially identified (the flow diagram is provided in Figure 1 in Section 3). Duplicate records were identified using software, reviewed manually, and removed accordingly. Two reviewers independently assessed the “Title and Abstract,” and any discrepancies were discussed until a consensus was reached. The same reviewers applied the inclusion and exclusion criteria during the full-text selection process and cross-checked the results. Discrepancies were resolved by consensus without needing a third reviewer (more details in Section 3.1).

2.5 Data extraction

After applying all exclusion criteria and finalising the list of studies, data from each study were extracted by two independent reviewers using a data extraction sheet adapted from the Critical Appraisal Skills Programme (CASP) for randomised clinical trials. Two other reviewers focused on extracting general data and study characteristics for a descriptive assessment of each study (Table 2). Discrepancies were resolved through discussion or with the assistance of a third reviewer.

Data was collected on:

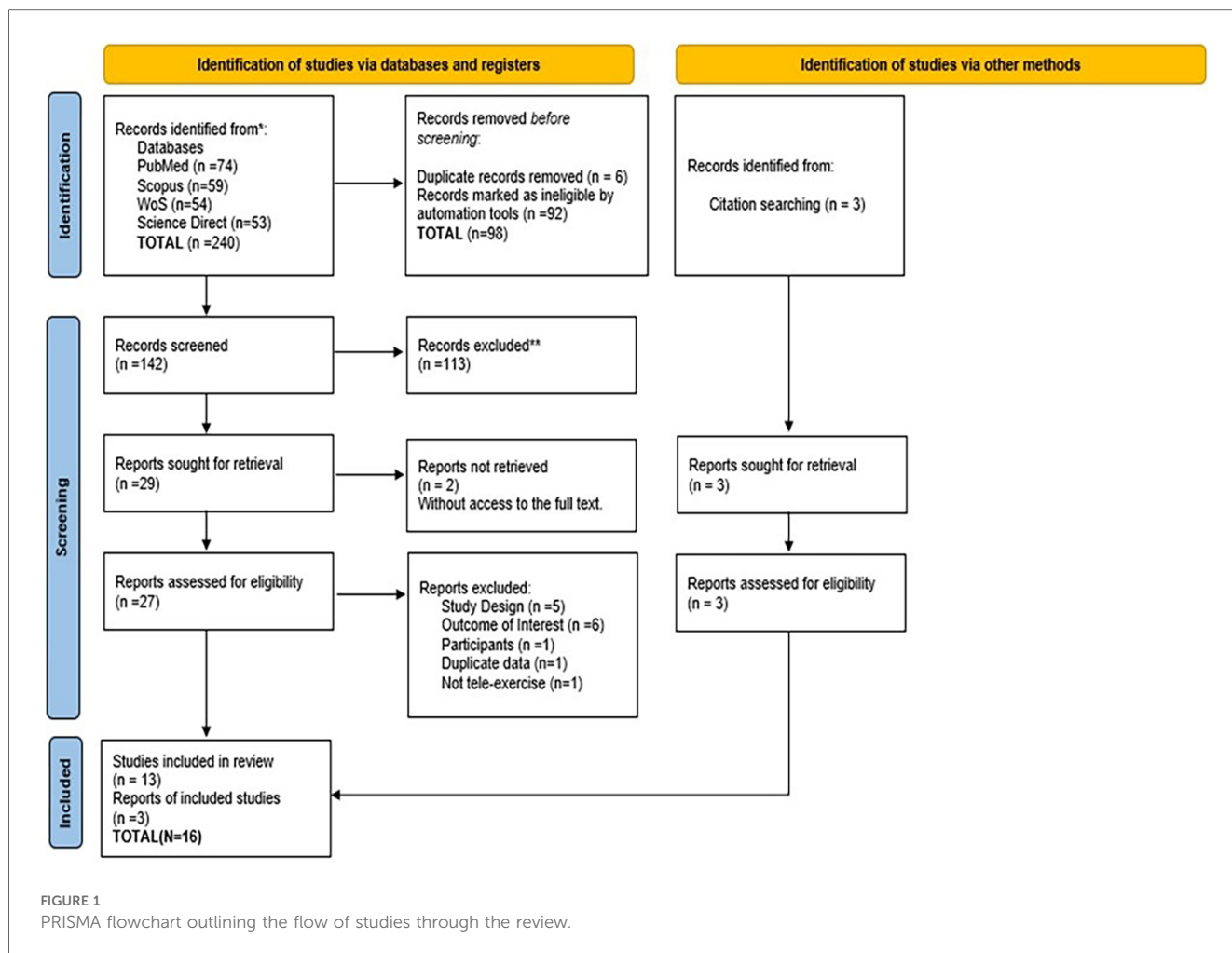
- Report: Author and year of publication.
- Study: Type of study and research question.
- Participants: Characteristics of the population.
- Intervention: Type, duration, and FITT characteristics whenever available.
- Research design or characteristics: Outcome of interest, methodology, results, and effect size.

2.6 Quality criteria of primary studies

Two reviewers independently assessed the quality of the studies. In cases of disagreement that could not be resolved

Table 1 Search strategy.

| NUMBER OF SEARCH TERMS OR COMBINATIONS USED (PUBMED) |
|--|
| #1 “Synchronous exercise” |
| #2 “Asynchronous exercise” |
| #3 “Synchronous exercise” |
| #4 “Tele-exercise programs” |
| #5 “Remote training” |
| #6 “Remote exercise” |
| #7 Teleexercise |
| #8 Tele-exercise |
| #9 OR/1-8 |
| #10 “Randomized Controlled Trial” |
| #11 “Clinical Trial” |
| #12 “Randomized Clinical Trial” |
| #13 “Randomised Controlled Trial” |
| #14 “Trial” |
| #15 “Clinical study” |
| #16 “Comparative study” |
| #17 “Observational study” |
| #18 “Cohort study” |
| #19 “Case-control study” |
| #20 “Cross-sectional study” |
| #19 “Prospective study” |
| #20 OR/10-19 |
| #21 9 AND 20 |
| FILTERS |
| NOT REVIEWS |
| FROM 2014 ON |



through mutual reconciliation, a third reviewer was consulted. The quality scale used was the ROB.2 Cochrane Risk-of-Bias Tool for Randomized Trials, given that randomised clinical trials are the primary focus of this study. The studies were assessed as having low, unclear, or high risk of bias (Figures 1, 2).

The risk of bias was assessed across five key domains: the randomization process (D1), deviations from the intended interventions (D2), missing outcome data (D3), measurement of the outcome (D4), and selection of the reported results (D5). Each domain includes subdomains designed to provide a detailed scope of each main domain.

2.7 Effect measures and data synthesis

The studies included in this systematic review exhibit heterogeneous samples, instruments, designs, and interventions, preventing the statistical precision required for a meta-analysis. Due to the heterogeneity in intervention methods and reported outcomes for different populations, we chose to present the data in tabular format, highlighting the characteristics of the interventions, population, and effect size of each article.

Additionally, we summarise and present the data in a narrative synthesis in the text, by outcome in population subgroups, detailing the main characteristics of each article, results for all outcomes, and statistical significance.

The results were organised into main categories: quality of life, physical fitness, functional capacity, and strength. The secondary outcome of pain was also described within the main category of quality of life.

3 Results

3.1 Study selection

As mentioned earlier, a total of 240 studies were initially identified during the first screening in the databases. Ninety-eight duplicates were identified and removed. The “Title and Abstract” of 142 studies were examined, and 29 were selected for full-text screening. The full text of two studies could not be accessed. An email was sent to the corresponding authors, but no response was received. Of the 27 analysed studies, 5 were excluded for not being randomised or quasi-experimental trials, 6 did not have

TABLE 2 Study characteristics.

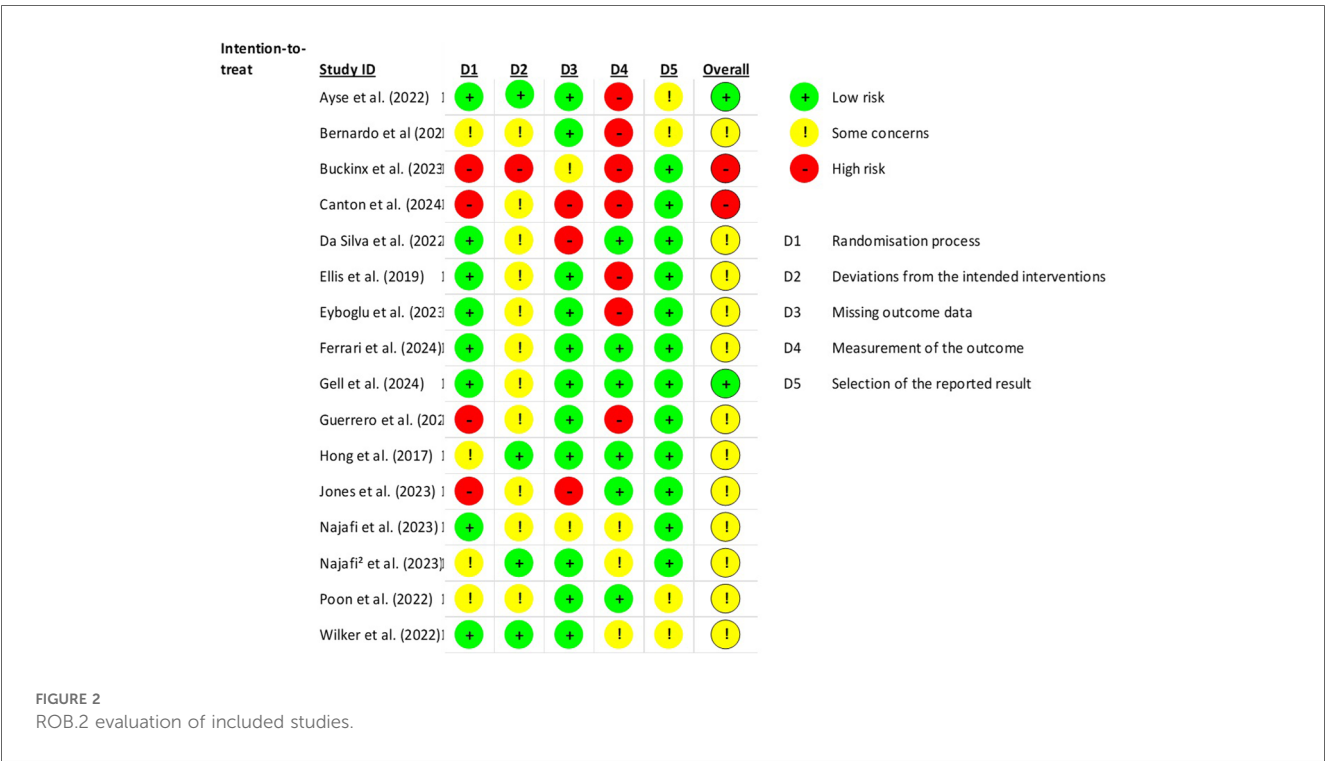
| Study | Study Desing | Intervention Type | Population | Outcome | Results |
|------------------------------|-------------------------------|--|--|--|--|
| Ayse et al., (15) | Randomised clinical trial | 6 weeks of tele-exercise synchronous IG vs. control | Isolated elderly ($n = 30$) | Physical Fitness (SFT) Quality of life (NHP) | IG \times CG: There was a significant improvement in all outcomes of the Senior Fitness Test (SFT), including strength and quality of life. |
| Bernardo et al., (7) | Randomised Clinical trial | 8 weeks of tele-exercise asynchronous IG vs. CG (control) | Obese and overweight pregnant woman ($n = 24$) | Physical fitness (PPAQ) Pain (ODI) | IG \times CG: There was a significant difference in light and moderate physical activity levels, and a reduction in pain markers. |
| Buckinx et al., (26) | Non-randomised clinical trial | 12 weeks of tele-exercise synchronous and asynchronous versys control. | Pre-independent elderly ($n = 72$) | Physical fitness (SPPB) and Tapa 1 e 2 Functional Status (OARS) | IG \times CG: There were no significant differences between groups for any outcome. Moment \times Group: The intervention group showed significant improvements in all outcomes. |
| Canton-martinez et al., (16) | Non-randomised clinical trial | 6 weeks of tele-exercise synchronous IG vs. Control | Isolated elderly ($n = 30$) | Physical fitness (SFT) | IG \times CG: There was a significant difference between groups for some of the SFT tests, namely sit-to-stand, 4-meter walk, TUG, and arm curl. |
| Da silva et al., (17) | Randomised clinical trial | 8 weeks of synchronous group tele-exercise for both groups. The IG received nutrition coaching. | Obese and overweight women ($n = 31$) | Physical fitness (VO2) | IG \times CG: There were no significant differences between groups. Group \times Moment: Both groups showed significant improvements from baseline to the last week of intervention. |
| Ellis et al., (18) | Randomised clinical trial | 12 months of asynchronous tele-exercise vs. an active control group | Adults with Parkinson's disease ($n = 51$) | Physical activity level (Pedometer) Quality of life (PDQ-39) Functional capacity (6-minute walk test, TC6) | IG \times CG: There were no significant differences between groups; however, the "sedentary" subgroup showed significant improvements in quality of life and functional capacity. |
| Eyuboglu et al., (19) | Randomised clinical trial | Intervention group (IG) received 12 weeks of tele-yoga, while the control group (CG) engaged in chest expansion exercises. | Adults with sleep apnea syndrome. ($n = 44$) | Physical fitness (VO2máx) Functional capacity (TC6) | Group vs. Control Group: No significant difference between groups. Group \times Moment: Significant difference was observed only for functional capacity. |
| Ferrari et al., (8) | Randomised clinical trial | 6 months of tele-exercise asynchronous vs. control | Healthy elderly ($n = 37$) | Balance (30 s of static balance), Functional capacity (10TC e 5-sit to stand) | IG \times CG: No significant difference was observed for any of the outcomes between the groups. Group \times Moment: The intervention group showed significant improvement in functional capacity and strength over time. |
| Gell et al., (25) | Randomised clinical trial | 16 weeks of synchronous tele-exercise vs. control. | Older adults in remission from different types of cancer. ($n = 37$) | Physical fitness (Level of de PA), quality of life (PROMIS-29), balance and strength (Sit to Stand). | IG \times CG: There was a significant difference between groups only for physical activity level. Group \times Moment: Over time, there was a significant difference for the outcomes of strength and quality of life. |
| Guerrero et al., (27) | Quasi-experimental | 12 weeks of synchronous tele-exercise. | Down syndrome adults ($n = 18$) | Balance (FICSIT-4), agility/coordination (TUG) and strength (5-sit to stand e 30s CS) | There was a significant difference for all outcomes. |
| Hong et al., (20) | Randomised clinical trial | The IG participated in 12 weeks of synchronous tele-exercise vs. a control group. | Elderly ($n = 23$) | Physical fitness (SFT) | IG \times CG: There was no significant difference between groups for physical fitness in the SFT tests. Group \times Moment: There was a time effect for some specific tests within the SFT, including the 2-minute steps, Sit and Reach, and Sit-to-Stand tests. |
| Jones et al., (21) | Quasi-experimental | 16 weeks of synchronous tele-exercise Tai-Chi | Elderly ($n = 52$) | Balance (FSST), Agility/Coordination (TUG), Strength (5-Sit to Stand), and Functional Capacity (TC5 m) | There was a significant difference for all outcomes. |

(Continued)

TABLE 2 Continued

| Study | Study Desing | Intervention Type | Population | Outcome | Results |
|-----------------------------------|---------------------------|---|--|---|--|
| Najafi et al., (22) | Randomised clinical trial | IG 8 weeks of tele-yoga and tele-exercise vs. control | Adults with Multiple sclerosis (n = 82) | Physical fitness, quality of life and pain (ovQV), functional capacity (T25FW). | IG × CG: There were significant differences for all outcomes. |
| Najafi et al. ² , (23) | Randomised clinical trial | IG 8 weeks of tele-yoga and tele-pilates vs. | Women with Multiple Sclerosis (n = 45) | Physical fitness level (IPAQ), Quality of life (MSQol-54), and Functional capacity (T25FW) | IG × CG: There was a significant difference between groups for all outcomes. |
| Poon et al., (28) | Randomised clinical trial | The intervention group underwent 8 weeks of synchronous and asynchronous tele-exercise vs. control. | Adults with recent COVID infection. (n = 41) | Physical fitness (treadmil test), Quality of life (HRQol), Strength (Handgrip e Sit to Stand) | IG × CG: There was a significant difference in quality of life between the groups. Group × Moment: There was a significant group-time effect for the outcomes in strength (handgrip e sit to stand) |
| Wilke et al., (6) | Randomised clinical trial | IG Participated in 8 weeks of tele-exercise, with 4 weeks of synchronous tele-exercise and 4 weeks of asynchronous tele-exercise vs. Control for 4 weeks and Asynchronous Control for the last 4 weeks. | Adultos saudáveis (n = 763) | Aptidão física (NPAQ-Short) e Dor (Chronic Pain Grade) | IG × CG (4s) There was a significant difference in quality of life in the intention-to-treat analysis and CAGE. For pain, there was a difference between groups only in the CAGE analysis. |

IG, intervention group; CG, Control Group.

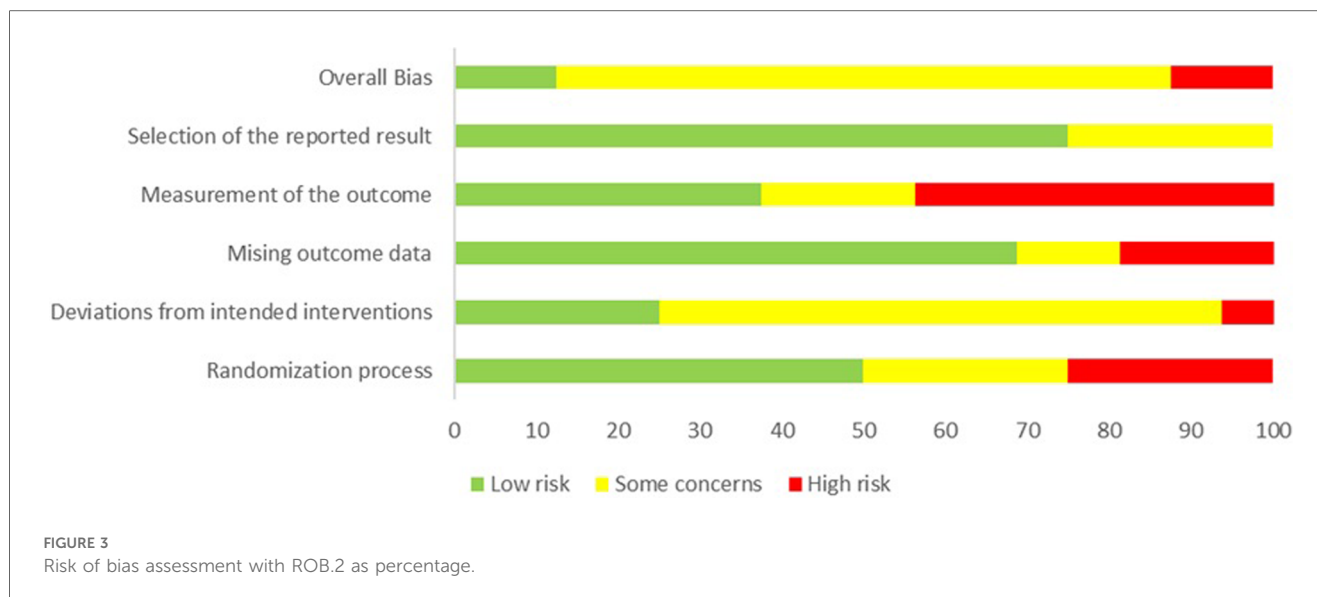


outcomes of interest, 1 did not involve an adult population, and 1 was considered not to have characteristics of structured tele-exercise. The study conducted by Jones in 2023 (24) reported results included in his other study published in 2024 (21). Only this latest was included and will be cited. Thus, 14 studies were excluded. From the full-text article list, 3 new studies were found (snowball effect). In total, we screened 242 studies, resulting in 16 eligible studies.

3.2 Characteristics of the studies

3.2.1 Tele-exercise approach

Eleven of the sixteen studies were randomised clinical trials (6–8, 15, 17–20, 22, 23, 25). Five were non-randomised clinical trials or quasi-experimental studies. Two studies used a pragmatic approach to participant allocation due to restrictions during the COVID-19 pandemic (16, 26). Two studies were



quasi-experimental with a single-group pre-post design (21, 27), and the fourth study did not report a specific reason for not being randomised (28).

Three studies presented the exclusively asynchronous approach. In the study by Ferrari et al. (2024), wearable technology with inertial sensors was used, featuring an interface that allowed the trainer to remotely prescribe workouts and provide movement feedback to the trainer. Participants received workouts via the web, including videos and demonstrations. Ellis et al. (2019) used a model based on remote monitoring, where all participants received tablets with personalised workouts.

The synchronous approach studies used various videoconferencing platforms such as Skype, Zoom, and Google Meet. All of them were conducted as group training sessions, with workouts ranging from tele-Pilates, tele-Yoga, and tele-Tai Chi to exercises incorporating strength, endurance, aerobic, flexibility, and balance components (7, 15–17, 19–23, 25, 27).

3.2.2 Population

The population of the eligible studies was heterogeneous, totalling 1,416 participants. Six studies focused exclusively on the elderly. One study evaluated pre-dependent elderly individuals, four studies assessed healthy elderly individuals, one study evaluated elderly individuals with sub-groups for comorbidities (hypertension and diabetes), and one study evaluated elderly individuals in remission from various types of cancer (8, 15, 16, 20, 21, 25, 26). Ellis et al. (2019) assessed adults and elderly individuals with Parkinson's disease, with the majority being elderly (18). Two studies focused on individuals with obesity and overweight, with one study including pregnant women (7) and the other including the general obese population (17). Four studies examined the adult population, including adults with Down syndrome (27), adults with sleep apnea syndrome (19), adults with recent COVID-19 (28), and healthy adults (6).

A summary of the characteristics, intervention types and outcomes is shown in Table 2.

3.3 Quality of evidence and strength of recommendations

Two researchers independently assessed the evidence using GRADE (Grading of Recommendations, Assessment, Development and Evaluation) criteria (29) with the assistance of the GRADE PRO GDT software, available at <http://gdt.gradeepro.org/>. The quality of evidence and strength of recommendations can be seen below (Table 3).

3.4 Results by outcomes

Different assessment tools, training methodologies, and statistical models were used to present the results of the eligible studies. In this section, we will synthesize these results by outcomes, specifying the population of each study and maintaining the statistical data in their original scales.

3.4.1 Physical fitness

We considered physical fitness outcomes related to the level of physical activity and/or aspects associated with physical capacity, except for strength, which will be presented separately.

All eligible studies reported results for at least one physical fitness marker. The most used marker was the level of physical activity (6, 7, 18, 22, 23, 25, 26). Bernardo et al. (2024) evaluated obese and overweight pregnant women using the Pregnancy Physical Activity Questionnaire (PPAQ) and reported significant differences for increases in light and moderate physical activity, with a moderate effect size ($p = 0.025$, $ES = 0.50$; $p = 0.005$, $ES = 0.66$). No significant difference was found in the level of vigorous physical activity.

A study evaluated the level of physical activity in the elderly. It assessed pre-dependent elderly individuals using the Telephone Assessment of Physical Activity (TAPA 1 and 2), finding no significant differences between groups (26). However, there was a

TABLE 3 Outcomes grades of evidence.

| Summary of results: | | | |
|---|--|--|-----------------------------------|
| Tele-exercise Versus Control for Different Outcomes | | | |
| Population: Different adult populations including elderly people | | | |
| Intervention: Tele-exercise synchronous and Asynchronous | | | |
| Comparison: Control/Pre-Post | | | |
| Outcomes | Impact | Participants | Certainty of the evidence |
| | | (Study design) | (GRADE) |
| Physical Fitness | Although the outcome physical fitness was affected by the downgrade, it still holds a moderate level of recommendation, especially for key target populations such as the elderly and healthy adults. The moderate rating indicates that, despite some uncertainty regarding the exact magnitude of the benefits, there is sufficient evidence to support tele-exercise interventions aimed at improving physical fitness in these populations. The strength of the recommendation is high, reflecting the potential impact of these interventions despite some methodological limitations and heterogeneity in the studies. | 1,416 (11 ECRs) (2 not Randomised) (2 Quasi-experimental) | ⊕⊕⊕○ Moderate ^a |
| Quality of Life | The downgrading of the quality of life outcome was necessary due to the heterogeneous nature of the studied populations and the low methodological quality of some studies. Therefore, we consider the strength of the recommendation to be low. | 245 (5 ECRs) (1 Quasi-experimental) | ⊕⊕○○ Low ^{a,b} |
| Functional Capacity | Although the outcome functional capacity was impacted by the downgrade, it still maintains an important level of recommendation, especially for specific target populations such as the elderly and healthy adults. The moderate rating suggests that, while there is some uncertainty regarding the exact magnitude of the benefits, there is sufficient evidence to support tele-exercise interventions aimed at improving functional capacity in these populations. The strength of the recommendation is high. | 365 (5 ECRs) | ⊕⊕⊕○ Moderate ^a |
| Strength | The downgrading of the strength outcome was necessary mainly due to the small sample size, the nature of the tests used, and the methodological quality of some studies. | 127 (3 ECRs) (1 not randomized) | ⊕⊕⊕○ Moderate ^{a,b,c} |
| Pain | Although the outcome of pain was affected by the downgrade, it still holds a moderate level of recommendation, especially for the adult population and in the context of synchronous tele-exercise. The moderate rating indicates that, despite some uncertainty regarding the exact magnitude of the benefits, there is sufficient evidence to support tele-exercise interventions aimed at improving pain, with a high strength of recommendation. | 811 (3 ECRs) | ⊕⊕⊕○ Moderate ^d |
| GRADE Working Group grades of evidence | | | |
| High certainty: we are very confident that the true effect lies close to that of the estimate of the effect. | | | |
| Moderate certainty: we are moderately confident in the effect estimate: the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different. | | | |
| Low certainty: our confidence in the effect estimate is limited: the true effect may be substantially different from the estimate of the effect. | | | |
| Very low certainty: we have very little confidence in the effect estimate: the true effect is likely to be substantially different from the estimate of effect. | | | |

Explanations.

^aDue to the heterogeneity of the population and the different protocols used for tele-exercise and assessment.^bDue to the low methodological quality found in some studies.^cReduced number of studies.^dFailure in blinding of the assessor and other risks of bias.

moment effect for the intervention group on TAPA 1 and 2 ($p = 0.06$; $p = 0.007$), although the effect size (ES) for each outcome was not reported. In another study, the authors objectively evaluated the physical activity level of elderly cancer survivors using an accelerometer (25). There was a significant difference with an increase in light and moderate physical activity, accompanied by a significant increase in the number of daily steps, with large effect sizes in the intervention group (respectively, $p = 0.03$, $ES = 0.72$; $p = 0.001$, $ES = 0.81$; $p = 0.01$, $ES = 0.96$).

Adults with Parkinson's disease were evaluated for physical activity levels using a pedometer to measure step count. Still, no significant differences were found between groups, nor was there a moment effect (18). Two studies assessed physical activity levels in patients with Multiple Sclerosis, both subjectively, using

the International Physical Activity Questionnaire (IPAQ). For adults with Multiple Sclerosis, there was a significant difference between groups for moderate physical activity ($p = 0.01$, $\eta^2 = 0.20$), and for all activity levels, there was a moment effect with small effect sizes (23). In women with Multiple Sclerosis, two distinct tele-exercise models, tele-pilates ($p = 0.002$, $\eta^2 = 0.52$) and tele-yoga ($p < 0.001$, $\eta^2 = 0.68$), showed significant differences between groups when compared to the control group.

One study assessed physical activity levels in healthy adults. Wilke et al. (2022) subjectively evaluated the levels using the Nordic Physical Activity Questionnaire-short (NPAQ) after eight weeks of tele-exercise, with four weeks of synchronous and four weeks of asynchronous sessions, measured at eight time points. The greatest gains occurred during the first four weeks of

synchronous tele-exercise vs. the control group, with increases of 1.65 and 1.39 in moderate and light physical activity, respectively (6).

Two physical fitness batteries were also used to assess older adults. Buckinx et al. (2021) used the Short Physical Performance Battery (SPPB) (26). Although no group effect was observed, there was a significant moment effect in the intervention group, reflected in the increase in total SPPB score ($p = 0.004$). Hong et al. (2017) used the Senior Fitness Test (SFT), with only flexibility showing significant differences between groups ($p = 0.019$). For the moment effect, the 2 min-steps cardiorespiratory fitness test showed a significant improvement in the intervention group ($p = 0.011$). In the study conducted by Ayse et al. (2022), the authors identified significant differences in three SFT tests between groups: 2 min step test ($p \leq 0.001$), Sit and Reach Test ($p = 0.028$), and 8 Step Up and Walk Test ($p = 0.010$). Additionally, significant differences were reported between groups in the SFT for the 4-meter Gait Speed ($p = 0.011$, $\eta_p^2 = 0.20$) and 8 Foot Up and Walk ($p = 0.018$, $\eta_p^2 = 0.18$) tests, with small effect sizes (15).

Three studies specifically evaluated balance. Ferrari et al. (2024) used the 30-second static balance test to assess older adults, but no significant differences were found between groups, nor was there a moment effect (8). However, using the Four-Square Step Test, Jones et al. (2024) observed a moment effect ($p = 0.45$, $d = -0.37$) (21). A moment effect was also observed ($p = 0.019$, $ES = 0.569$) in the balance of adults with Down syndrome, assessed with the Four Stage Balance Test (FICSIT-4) (27). The Timed Up and Go test, commonly used to assess balance and agility in adults with mobility limitations, was used in two studies. In the study mentioned before, by evaluating older adults, Jones et al. (21) did not observe significant differences. However, in adults with Down syndrome, a moment effect was observed ($p = 0.043$, $ES = 0.569$) (27).

Only three studies specifically assessed cardiorespiratory capacity. One study was conducted with overweight and obese women (17), another with adults with sleep apnea (19), and the last with adults who had recently had COVID-19 (28). No significant group effects were observed in any of the populations. However, for peak VO_2 , a significant difference with a small group-moment effect size was observed in overweight and obese women ($p = 0.007$, $ES = 0.36$) (17).

3.4.2 Quality of life

Six studies assessed quality of life using different tools. Ellis et al. (2019) used the Parkinson Disease Questionnaire 39 (PDQ-39) to evaluate the effect of tele-exercise on the quality of life in people with Parkinson's disease, finding no significant differences between groups. However, a significant improvement was observed in the subgroup of sedentary individuals ($p = 0.03$). In older adults in cancer remission, assessed with the Patient-Reported Outcomes Measurement Information System-29 (PROMIS), a moment effect was observed ($p = 0.04$, $d = 0.33$) (25).

Two studies evaluated individuals with Multiple Sclerosis using two different instruments: Overall Quality of Life and Health (ovQV), which assesses general quality of life, and Multiple Sclerosis Quality of Life-54 (MSQoL-54), specific to multiple

sclerosis. Both instruments showed significant improvement with group effects ($p = 0.01$, $\eta^2 = 0.12$; $p < 0.0001$) respectively (22, 23).

Poon et al. (2024) used the Health-Related Quality of Life (HRQoL) scale to assess adults with recent COVID-19 and observed a significant difference between groups ($p = 0.04$). The last instrument used was the Nottingham Health Profile (NHP) to evaluate the quality of life related to health in isolated older adults, demonstrating significant improvement for this population ($p = 0.011$) (15).

3.4.3 Functional capacity

Three studies used the 6-Minute Walk Test (6MWT). Canton-Martínez et al. (2024) observed a significant improvement in the distance covered by the elderly in the intervention group ($p \leq 0.0001$; $\eta_p^2 = 0.39$) (16). In adults with Parkinson's disease (18), only a moment effect was observed ($p = 0.02$), as well as in adults with sleep apnea syndrome ($p = 0.003$) (19).

Two other objective tests were used to evaluate older adults. Ferrari et al. (2024) used the 10-meter Walk Test and found no significant difference between groups; however, a moment effect with a moderate effect size was observed ($p < 0.001$, $ES = 0.59$) (8). For the 5-meter Walk Test, Jones et al. (2024) observed a moment effect ($p = 0.02$, $d = 0.43$) (21).

To assess functional capacity in women with multiple sclerosis, the Timed 25-Foot Walk Test was used, showing a significant difference between groups ($p < 0.0001$). Lastly, the Older Americans Resources and Services (OARS) functional status scale was used to evaluate functional capacity in pre-dependent elderly individuals. Although no significant difference was observed between groups, a moment effect was noted for the intervention group ($p = 0.02$) (26).

3.4.4 Strength

Physical capacity in terms of strength was assessed by nine studies, with the sit-to-stand test in its various forms being the most used instrument. Only two studies found significant differences between groups, both evaluating elderly individuals: Ayse et al. (2022) and Canton-Martínez et al. (2024) (respectively $p \leq 0.001$ and $p \leq 0.0001$, $\eta_p^2 = 0.38$) (15, 16). Six studies demonstrated a moment effect in the sit-to-stand test. In the sit-to-stand test, Gell et al. (2024) observed a moment effect in elderly individuals in remission from cancer ($p < 0.0001$) (25), Ferrari et al. (2024) in healthy elderly individuals ($p = 0.009$, $ES = 0.26$) (8), along with Hong et al. (2017) also in elderly individuals ($p = 0.035$) (20). Adults with recent COVID-19 also showed a moment effect ($p = 0.003$, $d = 1.29$) with a large effect size.

For the 5-sit to stand variation, a moment effect was observed in adults with Down syndrome with a moderate effect size ($p = 0.014$, $ES = 0.55$) (27), as well as in elderly individuals ($p = 0.005$, $d = 0.51$) (21). Upper limb strength was assessed in three studies. Obese and overweight women were evaluated using handgrip, and while there was no significant difference between groups, a moment effect with a small effect size was observed ($p = 0.0006$, $ES = 0.25$) (17). Similarly, adults with recent COVID-19 were also assessed using handgrip ($p = 0.032$, $d = 0.50$) (28).

However, no group or moment effects were observed for arm curls in elderly individuals (20).

3.4.5 Pain

Three studies assessed the pain outcome. Wilke et al. (2022) used the Chronic Pain Grade Scale (CPGS) and found no significant differences between groups of healthy adults (6). For adults with multiple sclerosis, a significant difference between groups was observed with a small effect size ($p < 0.0001$, $\eta^2 = 0.22$) (23). Obese and overweight pregnant women were evaluated using the Oswestry Disability Index for low back pain, which showed significant differences between groups with a large effect size ($p = 0.001$, $ES = 0.82$) (7).

4 Discussion

Physical fitness was the most studied outcome, with the level of physical activity being the most frequently used assessment tool. Synchronous tele-exercise appears to be an effective method for improving physical activity levels in different populations, showing significant group effects and moment effects ($p < 0.05$) in various studies (6, 7, 22, 23, 25). Interaction effects between groups were highlighted in studies involving adult, elderly, and multiple sclerosis populations, indicating a specific impact of the intervention on these populations (6, 22, 23, 25). However, the study by Ellis et al. (2019), which used an asynchronous tele-exercise model, did not show any effects on physical fitness between groups or over time (18). The reviewed studies feature highly diverse populations, and this was the only study focusing on adults with Parkinson's disease. Nonetheless, in Ellis's study, when dividing the training group into active and sedentary participant subgroups, the sedentary subgroup showed significant improvements in the studied outcomes. However, it is not possible to assert that these improvements are solely attributable to the intervention.

Recent studies have correlated the level of physical activity in individuals with Parkinson's disease with walking ability and the level of disease impairment, showing that moderate to vigorous physical activity appears to have more beneficial effects in reducing this impairment (29, 30). In the study in question, participants were asked to perform 5–7 exercises for a minimum of 3 days per week, although these could be done daily for a six-month period. However, there is no report on the perceived effort level or the total weekly training volume completed by each participant. Asynchronous long-term tele-exercise programs seem to have a lower capacity for maintaining training volume (6), and intensity markers, such as perceived exertion, can be used to regulate training intensity. It is possible that the training program met the volume and intensity needs of the sedentary group but fell short of the physical capacity of the active group. Studies with more robust designs are necessary to better clarify potential intervention effects for this specific population.

For obese and overweight pregnant women, the asynchronous protocol did not appear to have a negative influence, as significant

group and moment effects were observed for improvements in light and moderate physical activity levels (7). This aligns with the current literature, where structured exercise is shown to improve overall physical activity levels in pregnant women (31). The study conducted by Bernardo et al. (2024) was short in duration, lasting eight weeks, and followed FITT (frequency, intensity, type, and time) guidelines. The intervention group consisted exclusively of nutritional modifications, which may have contributed to the absence of interaction effects, as both groups followed the same asynchronous intervention protocol.

Regarding overall physical fitness levels evaluated by two test batteries (SPPB and SFT), synchronous tele-exercise proved effective in improving general fitness components in elderly populations, particularly concerning moment effects. This finding aligns with current literature on physical exercise and fitness in this population (32–34). Only one study used an asynchronous protocol, but it employed a mixed methodology, where the same group underwent both synchronous and asynchronous protocols, making it impossible to separately evaluate the effects of each type of tele-exercise (26). However, in the study by Buckinx et al. (2021), the authors observed a moment effect across all SPPB tests, which suggests a similarity with the other results (26). It is important to highlight that the observation of the moment effect indicates a modification but not necessarily one specific to intervention. Further studies using similar test batteries are needed to better clarify this issue.

When evaluating general physical fitness in populations with Down syndrome, synchronous tele-exercise appears to provide significant improvements (27), aligning with current literature (35, 36). However, more robust research with control groups and larger sample sizes is necessary to clarify potential positive effects on the physical fitness of this population, as the only study addressing this group is quasi-experimental.

Physical fitness was also specifically assessed in terms of cardiorespiratory improvement. Only synchronous tele-exercise appears to generate significant effects on peak VO_2 , which was observed only in the sedentary population of obese and overweight women (17). Other populations evaluated for the same outcome did not show significant differences, even when the protocol involved synchronous tele-exercise (19, 28). This result may be attributed to the characteristics of the study population, obese and overweight women who had not previously engaged in physical activity, making them more responsive to the short-term beneficial effects on cardiorespiratory capacity. The different training protocols could also influence the outcome. Similarly, the study by da Silva et al. (2022) was unique among the three studies in that it established load control and progression through perceived exertion, evolving the volume and intensity of the training protocol, which may have made the applied protocol more robust (17).

Regarding quality of life, six studies evaluated this outcome using different tools. For the elderly population, only synchronous tele-exercise protocols were used. Synchronous tele-exercise appears to improve domains related to quality of life, including loneliness (15, 25). These findings may be linked to the tele-exercise protocol being conducted in groups and in real-

time, which could foster social connections between students and instructors.

Regarding synchronous tele-exercise, individuals affected by multiple sclerosis (MS) demonstrated significant interaction effects on quality of life, whether through MS-specific questionnaires or general quality of life assessments. The studies used synchronous tele-exercise protocols, specifically tele-yoga and tele-pilates (22, 23). In a recent systematic review conducted by Sánchez-Lastra et al. (2019), the authors reported significant improvements in the quality of life of people with multiple sclerosis who practised Pilates, supporting the findings of this review (37). However, only three studies evaluated quality of life improvements through Pilates, and only two reported significant differences (38, 39). For yoga, a recent systematic review (40) did not find significant differences in quality-of-life improvements for yoga practitioners, contrasting with the findings here. These cited studies have distinct methodological approaches, which may lead to conflicting results. Further research, such as high-quality randomised clinical trials, is needed to better understand the effects of these practices on the MS population.

Regarding asynchronous tele-exercise, the authors did not observe significant differences in the quality of life for people with Parkinson's (18). Nonetheless, the sedentary subgroup experienced a clinically relevant improvement in quality of life with the asynchronous tele-exercise protocol. It seems that in sedentary populations, even small doses of physical activity can lead to a noticeable improvement in perceived quality of life. The levels of motor and cognitive impairment associated with Parkinson's may contribute to the differences observed within the subgroup. Current literature suggests that physical inactivity worsens the quality of life in this population, indicating that the more inactive an individual is, the lower their quality-of-life indicators (41). However, more research is needed on the impact of both asynchronous and synchronous tele-exercise for this population.

When evaluating functional capacity, synchronous tele-exercise showed interaction effects in elderly individuals assessed with the 6 Min Walk Test (TC6) (16), and moment effect for the 10-Meter Walk Test (TC10) (21). Asynchronous tele-exercise demonstrated a moment effect for the 5-Meter Walk Test (TC5) (8), while a mixed synchronous and asynchronous tele-exercise protocol achieved a moment effect for subjective assessments (26). Despite the heterogeneity of the programs, tele-exercise appears to have the potential to improve functional capacity in the elderly, yet only one study demonstrated a significant interaction effect (16), highlighting the need for more robust studies with this population. It is important to note that current research suggests functional capacity may be influenced by the type of physical exercise program used. The literature indicates that multimodal programs may be more effective in improving the functional capacity of the elderly, which could influence the results (42, 43).

Other three different population groups showed a moment effect for synchronous tele-exercise (19, 22) and asynchronous tele-exercise (18). However, it is important to note that half of the studies addressing functional capacity are either quasi-

experimental or non-randomised. More research with robust methodologies is needed to better understand the effects of tele-exercise on functional capacity.

Regarding strength outcomes, both synchronous and asynchronous tele-exercise protocols focused on lower limb strength, which was reflected in the results. Of the nine studies that assessed strength, six evaluated lower limb strength, two assessed lower and upper limb strength, and one assessed only superior limb strength. Only synchronous tele-exercise protocols (15, 16) showed significant differences between groups with interactions effects for the elderly population, aligning with current literature on the benefits of strength training for older adults (44–46). Only one study used asynchronous tele-exercise protocols. Although it did not find a significant group effect, a significant moment effect was observed (8).

Synchronous and asynchronous tele-exercise appear promising for increasing lower limb strength in the elderly population, with synchronous tele-exercise showing better results in this group. Synchronous tele-exercise appears promising for strength gains in adults with Down syndrome, aligning with current findings on resistance training for this population (35). However, the study in question lacks a control group, which renders the strength of this finding fragile, as it may not truly represent an improvement attributable to the intervention. Controlled studies are necessary to clarify whether there is an interaction effect between groups.

Only isometric strength seems to have been benefited by tele-exercise protocols for upper body strength. Women with obesity and overweight and people with recent COVID-19 showed moment effects on strength, but only with small effect sizes (17, 28). Generally, tele-exercise is performed with low load, few implements, and a focus on upper body exercises, which may influence the results regarding strength gains, particularly for upper body strength.

Finally, synchronous and asynchronous tele-exercise protocols appear to be effective regarding pain outcomes. Asynchronous tele-exercise showed significant improvement in reducing lower back pain with a large effect size in sedentary, obese, and overweight pregnant women (7). These findings align with current guidelines for pregnant women (47, 48), where structured physical exercise can help manage and reduce lower back pain. However, the study by Bernardo et al. (2024) was the only study that used asynchronous tele-exercise for the pain outcome (7).

Other studies evaluated pain with synchronous and mixed tele-exercise protocols. For people with multiple sclerosis, both tele-yoga and tele-pilates showed significant interactions effects improvements. Pilates and yoga, in their in-person form, are commonly used for pain management (49–52), and synchronous tele-exercise appears to provide similar benefits for people with multiple sclerosis. Synchronous tele-exercise also showed greater improvements in pain scales compared to asynchronous methods in adults during lockdown without specific pain complaints. However, both types of protocols reduced average perceived pain scores. The literature does not have a consensus on which type of exercise is most beneficial for pain, whether chronic, acute, or neuropathic. However, it is well-established that well-managed physical exercise is a crucial ally in reducing pain and improving

the quality of life across various populations experiencing different types of pain (53). This seems to be reflected in the tele-exercise protocols. Currently, the methodological quality of studies on tele-exercise is low, and the heterogeneity of populations makes a robust analysis even more challenging. Nonetheless, tele-exercise emerges as a promising approach, particularly synchronous tele-exercise, which demonstrates more robust results and, typically, outcomes similar to those of in-person exercise when compared within the same population group. Thus, it offers a potential way to include various populations in physical exercise practices, particularly those with limited or no access to exercise environments. More studies with high methodological quality are needed to make a clearer view of the effects and limitations of tele-exercise.

Data availability statement

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

Author contributions

NG: Conceptualization, Formal Analysis, Investigation, Resources, Supervision, Writing – original draft. VR: Writing – review & editing, Conceptualization, Funding acquisition, Supervision. JV-A: Conceptualization, Formal Analysis, Investigation, Supervision, Writing – original draft. GL: Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft. IG: Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft. RP: Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft. AF: Conceptualization, Validation, Visualization, Writing – review & editing. MC: Conceptualization, Funding acquisition, Project administration, Validation, Visualization, Writing – review & editing. EI: Software, Validation, Visualization, Writing – review & editing. ADG: Data curation, Methodology, Conceptualization, Writing – original draft. AF: Validation,

Visualization, Writing – review & editing. MS: Validation, Visualization, Writing – review & editing. GZ: Conceptualization, Validation, Visualization, Writing – review & editing. CB: Validation, Visualization, Writing – review & editing. FM: Conceptualization, Funding acquisition, Project administration, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY

David Arthur Hart,
University of Calgary, Canada

REVIEWED BY

Jacob R. Rammer,
University of Wisconsin–Milwaukee,
United States
Melissa Tinney,
University of Michigan, United States

*CORRESPONDENCE

Jeffery W. Rankin

✉ jrankin@ranchoresearch.org

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A randomized comparative effectiveness trial to evaluate two programs for promotion of physical activity after spinal cord injury in manual wheelchair users

Jenna M. Martinez^{1,2}, Lisa L. Haubert¹, Valerie J. Eberly¹,
Walter B. Weiss¹ and Jeffery W. Rankin^{1*}

¹Pathokinesiology Laboratory, Rancho Los Amigos National Rehabilitation Center, Downey, CA, United States, ²School of Medicine, University of California, Irvine, CA, United States

Objective: The goal of this study was to determine the effectiveness of a novel whole of day activity accumulation (WODAA) physical exercise program. WODAA physical activity and physiological outcomes were compared to outcomes from individuals using a traditional planned arm crank exercise (PACE) program. Both programs included progressive exercise instruction and goal setting over a 4-month period, and utilization of a wrist-worn activity monitor (Fitbit Blaze/Versa, Fitbit Inc., San Francisco, CA).

Design: Longitudinal, randomized, comparative effectiveness trial with collaborative goal setting.

Setting: Research laboratory at a rehabilitation hospital and in participants' homes and communities.

Participants: Forty-nine manual wheelchair users with paraplegia.

Outcome measures: Physical activity measurements and cardiometabolic data were collected before, during, and after the program. The primary measures were amount of daily arm activity (Steps) and time spent in different activity and heart rate zones.

Results: Relative to baseline measures, participants in the WODAA group had significantly more daily arm movement/propulsion activity (Steps) and time spent in the Fairly and Very Active Zones and the Cardio Heart Rate Zone compared to those in the PACE group over the final month of the intervention ($p < 0.05$). Minutes spent in other Activity and Heart Rate Zones were similar between groups. At final evaluation, diastolic blood pressure after a 6-Minute Push Test was significantly lower in the WODAA group, while no differences were found in distance traveled, systolic, or pre-test diastolic blood pressures. Metabolic bloodwork and shoulder pain scores did not change and were similar between groups.

Conclusion: Depending on the measure used, these findings suggest that a WODAA approach to PA is comparable or more effective than a traditional PACE program in promoting physical activity in low-active manual wheelchair users with paraplegia.

KEYWORDS

spinal cord injury, physical activity, exercise, cardiometabolic health, paraplegia, randomized control trial

1 Introduction

Physical activity (PA), including muscle strength training and aerobic exercise, in adults with or without a disability, is critical for preventing major chronic health conditions such as Type 2 diabetes and cardiovascular disease (1). Despite the well-documented physical and psychological benefits of PA, activity levels remain low in persons with spinal cord injury (SCI) (2–5). Individuals with mobility limitations (including SCI) engage in significantly less PA than the general population and are less likely to attain recommended levels of moderate and vigorous PA (6–8). Moreover, those who use manual wheelchairs (MWCs) spend significantly more time in sedentary activities, an independent risk factor for poor health, compared to non-disabled individuals (9). In addition, inactivity in persons with SCI contributes to abnormalities in carbohydrate and lipid metabolism, higher prevalence of diabetes mellitus, and an earlier occurrence of coronary heart disease and stroke relative to the general population (10, 11). Indeed, Cragg and colleagues concluded that these consequences of inactivity point to an “exigent need for targeted interventions and prevention strategies addressing modifiable risk factors for cardiovascular disease in individuals with SCI” (11).

A dilemma for those living with SCI who use an MWC is determining how to increase PA for physical and psychological health benefits without further contributing to the largely untreated problem of shoulder pain and dysfunction that negatively impacts mobility, participation, and quality of life (12). In addition, traditional forms of aerobic exercise for these individuals such as planned arm-crank ergometry (PACE) are often associated with barriers to sustainability including lack of time, resources (transportation to gyms and cost of membership or exercise equipment), and limited availability of accessible exercise facilities and equipment (13). Thus, identifying a program for those with SCI to circumnavigate the barriers associated with traditional PACE programs is critical to increasing and sustaining PA in order to obtain the associated health benefits.

One promising alternative to traditional aerobic exercise is the use of a whole of day activity accumulation (WODAA) approach. The WODAA approach is designed to decrease sedentary time and increase overall PA by measuring and accumulating activity throughout the day (9, 14, 15). WODAA has been demonstrated as effective in improving PA in the non-disabled population (14), but its efficacy has not been clearly established in other groups (9, 15). By expanding the bounds of where, when, and how movement or PA can be performed throughout the day, this intervention could more effectively address the health needs of persons with disabilities, including individuals from traditionally underserved populations with limited financial resources, by alleviating many of the barriers to exercise for persons with SCI who use an MWC. Additionally, this approach could help alleviate concerns about increasing the incidence of shoulder pain or overuse syndromes (16–18) by dispersing rest and PA bouts throughout the day.

Commercially available activity monitors have great potential as an intervention support and data collection tool. Previous work has demonstrated that using these devices to implement feedback increased PA in an underserved nondisabled population (19), suggesting that they also could be used to improve the effectiveness of our novel WODAA PA intervention. If it can be demonstrated that these devices are able to support PA programs for MWC users with SCI, then the widespread prevalence of these devices could facilitate long term adoption and improved ability to track progress towards and achievement of daily PA goals that may better address the health needs of persons with disabilities when compared to traditional PA programs. In addition, if found to be sufficiently accurate, these devices may also be used as a research/data collection tool to support the documentation of home- and community-based PA. To this end, we pilot tested two of the activity monitors readily available at the time of data collection (Fitbit Charge, Fitbit Inc., San Francisco, CA; Garmin Vivofit, Garmin International, Inc. Olathe, KS) to evaluate their ability to accurately collect wheelchair-based activity data. Two manual wheelchair users with paraplegia wore the devices on their wrists while performing several common arm activities, with recorded Fitbit values compared to manual counts/measures. We determined that the Fitbit Charge was sufficiently accurate for recording arm movements across all three exemplary tasks: (1) a 15-min bout of arm cycling (4.4% error), (2) maneuvering indoors with slow, sporadic pushes (11.5% error), and (3) 10 repetitions each of forward arm elevation (shoulder flexion) to 90° and 180° and reaching to the side (shoulder abduction) to 90° (6.7% error). In general, the Fitbit underestimated arm activity except during arm cycling, where the device exhibited a small overestimation of cycles performed (1,341 vs. 1,285 actual or 4.4% error). Based on this pilot work, we concluded that a Fitbit (in this case the Blaze and its subsequent replacement, the Versa) was sufficiently accurate to be investigated further in our activity-based intervention and as a data collection tool.

The goal of this study was to compare the ability of a novel 16-week WODAA PA program to increase PA and improve cardiometabolic health relative to a traditional PACE program in persons living with SCI who use an MWC for mobility. We hypothesized that, relative to PACE, the WODAA program would result in (1) a greater increase in PA and (2) more substantial improvements in cardiometabolic health measures (e.g., insulin resistance). We also hypothesized that both intervention groups would not experience significant increases in shoulder pain.

2 Materials and methods

2.1 Participants

A convenience sample was recruited based on the following inclusion criteria: having paraplegia resulting from an SCI [American Spinal Injury Association Impairment Scale (AIS) A-C (20)] for at least 1 year; ≥18 years of age; uses an MWC for

community mobility; interested in increasing their PA. Participants were also asked if they were currently exercising or playing sports. Individuals that responded in the affirmative were excluded if their participation in regular aerobic exercise or sports was ≥ 3 times weekly for 30 min or more per session. Additional exclusion criteria included: history of upper extremity surgery in the past year; physician-recommended limits on PA; cardiac abnormalities found on electrocardiogram (ECG) screen precluding maximal exercise testing; shoulder pain limiting MWC propulsion; full-thickness/large rotator cuff tear; pregnancy or planning to become pregnant in near future.

Prior to participation, volunteers reviewed, signed, and received a copy of the Bill of Rights of Human Subjects and informed consent form approved by the Rancho Research Institute Institutional Review Board. Following screening for eligibility, the study was conducted over 5 in-person sessions at the Pathokinesiology Laboratory at Rancho Los Amigos National Rehabilitation Center (RLANRC): one Screening, three Assessment (Initial, Interim, and Final), and one Training/Intervention Session. In addition, participant PA and Heart Rate (HR) data were collected through remote monitoring using a

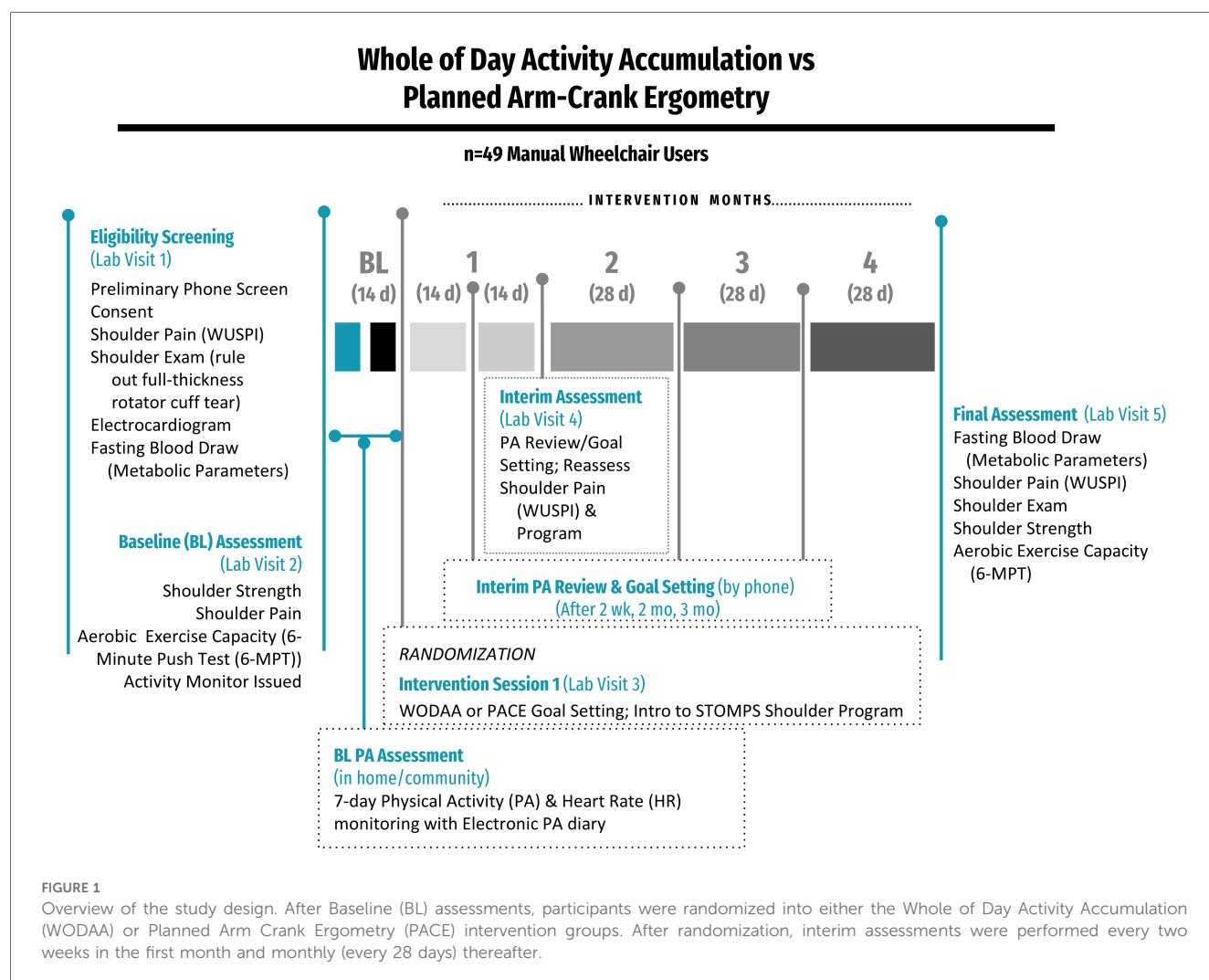
wrist-worn activity-tracking device (Fitbit Blaze/Versa, Fitbit Inc., San Francisco, CA) during home and community activity over a 7–14 day Baseline Assessment and 4-month-long intervention. Interim PA review and goal setting sessions also occurred via phone after 2 weeks, 2 months, and 3 months of the intervention (Figure 1).

2.2 Instrumentation

2.2.1 Metabolic laboratory tests

Blood samples were collected and analyzed to obtain a fasting lipid profile with its fractions as well as fasting glucose, insulin, and C-reactive protein levels. Homeostatic model assessment (HOMA-1 and HOMA-2) scores estimated beta-cell function (%B) and insulin sensitivity (%S) (21, 22). Insulin resistance (HOMA-IR) was assessed via the model index, where:

$$\text{Model Index} = \text{insulin} \left[\frac{\mu\text{IU}}{\text{mL}} \right] \times \frac{\text{fasting glucose} \left[\frac{\text{mmol}}{\text{L}} \right]}{22.5} \quad (1)$$



2.2.2 Wheelchair User's Shoulder Pain Index (WUSPI)

The Wheelchair Users Shoulder Pain Index (WUSPI) is a survey instrument consisting of 15 items that measures the amount shoulder pain the respondent experienced over the last 7 days while performing functional activities (23). The instrument has been documented to be highly reliable with repeated administration ($r = 0.9$), as well as having good internal consistency, and concurrent validity when utilized to indicate the effects of intervention on shoulder pain (23).

2.2.3 Six-Minute Push Test (6-MPT)

The 6-MPT was developed as a clinically practical test of aerobic capacity for persons with SCI. It has a high test-retest reliability [ICC of 0.97 (95% confidence interval: 0.93–0.99)] and, in persons with paraplegia, demonstrates a strong correlation with peak oxygen consumption values elicited during a maximum arm-crank ergometry test [ICC of 0.86 (0.70–0.93)] (24, 25). As a result, the 6-MPT is able to distinguish between fitness levels in those with paraplegia (24) and was utilized in this study to assess aerobic exercise capacity and fitness. Participants were instructed to push their usual MWC as many laps as possible around a track of known distance in 6 minutes and were allowed to set their own pace and permitted to take rest breaks, if needed. Participants were encouraged in their efforts at the end each minute. Blood pressure and heart rate were recorded just prior to and at the end of the 6-min period and the total distance covered during the 6-MPT was recorded. Participants also wore a heart rate monitor (Polar H10, Polar Electro Inc., Bethpage, NY) during the assessment to obtain average and peak heart rate (24).

2.2.4 Daily physical activity (PA) & heart rate (HR) data

Home and community PA data were collected using a wireless activity monitor worn on the dominant wrist (Fitbit Blaze/Versa, Fitbit Inc., San Francisco, CA). The device documented MWC propulsion/arm movement as well as continuous heart rate. Arm activity data were measured using the devices "Steps" recording feature, with our pilot data demonstrating that each wheelchair push registered approximately 2 Steps in the wrist-worn activity monitor and that a 30-min bout of arm crank ergometry exercise contributes an additional 800–1,500 Steps per day. To validate this approach, we compared the activity monitor reported propulsion cycles (Steps completed) to a direct push count obtained during the baseline 6-MPT in a subset of 11 participants. We found the validity coefficient to be 0.90 ($p = 0.000$), with the mean absolute percentage error (MAPE) of 10.5% (SD 11.4%), just slightly above the established standard acceptable MAPE of 10% (26). We additionally analyzed the accuracy of the wrist-worn activity monitor HR by comparing its HR output to a Polar HR monitor (H10, Polar Electro Inc., Bethpage, NY) during each minute of the first PACE intervention session. We found excellent validity with significant

ICCs ranging from 0.81–0.98 ($p = 0.000$) and MAPEs ranging from 1.9% to 4.9%, well below the acceptable threshold.

2.3 Procedures

2.3.1 Eligibility screening

Interested individuals were initially screened via telephone or in-person to determine preliminary eligibility (Figure 1). Potential participants were consented and the presence of shoulder pain and/or likely subacromial structure pathology was then documented using the WUSPI and performance of a clinical shoulder exam by a licensed physical therapist. The clinical shoulder exam included documentation of bilateral maximum active and passive shoulder abduction and external rotation (at 90° of shoulder abduction and elbow flexion and neutral forearm pronation/supination) range of motion and clinical test results for subacromial impingement syndrome/rotator cuff tendinopathy [Supraspinatus test (Empty Can); Hawkins-Kennedy Impingement test, External Rotator Strength test, and Codman's Drop Arm Test]. If individuals were free of shoulder pain (WUSPI score ≤ 12) and the clinical shoulder exam indicated a minimal likelihood of subacromial impingement syndrome/rotator cuff tear (27, 28), a fasting blood draw was performed for cardiometabolic analysis and an ECG was collected and interpreted by a cardiologist to ensure that the individual did not have a condition that would preclude them from increasing PA.

2.3.2 Baseline assessments

Once labs and ECG were reviewed and the participant was cleared by a cardiologist, the WUSPI was again completed and participants were asked to complete a 6-MPT. They were provided with a wrist-worn wireless activity monitor with the screen covered by an opaque black film to prevent participants from receiving device PA feedback. Participants were instructed to wear the device on their dominant wrist. The Fitbit mobile app was installed on a phone (participant's personal or a borrowed lab phone) for remote data acquisition and monitoring. Participants were instructed to not tamper with the occlusive screen cover and continue customary PA for the duration of the Baseline period. They were instructed to wear the device during waking hours (at least 8 h per day) and to charge the device while sleeping or bathing. The Baseline data collection period lasted 10–14 days, where data were collected in the participant's home and community environment. The period was selected to allow for a full 7 days of PA data acquisition with the first 7 complete days of typical activity used in the analysis.

2.3.3 Initial intervention visit

Following the Baseline home/community PA collection period, individuals returned to the lab and were randomized into either the (1) Whole of Day Activity Accumulation (WODAA) or (2) Planned Arm Crank Ergometry (PACE) intervention groups. Randomization was performed using a pre-populated chart consisting of random numbers where each entry had either a 1

or 2. Following screening, enrollment, and baseline PA assessment, participants were sequentially assigned to the next entry on the random numbers chart, with the corresponding number indicating the participant's designated intervention group (1 = WODAA; 2 = PACE). However, due to the nature of the study intervention, randomization was blocked by groups of five such that if one intervention group block became full with five participants, subsequent enrollees were forced into the opposite intervention group until it was then capped at five enrollees (29). In this case, participants were assigned the next available entry in the random numbers chart that corresponded to their forced group. Participants in the WODAA group reviewed their baseline 7-day PA and HR data with a physical therapist to understand their current PA habits. For participants in the WODAA group the occlusive activity monitor screen cover was removed, and they were educated in how to use the wrist-worn activity monitor and phone app to view and track their PA and HR. Individuals in the PACE group were provided an arm crank ergometer for home use throughout the intervention. They were asked to log each exercise session date, duration, distance, and maximum resistance upon completion into a data-logging phone app. Their opaque screen cover remained in place on their wrist-worn activity monitor, with only HR feedback displayed during arm-crank ergometry sessions on the phone app to display exertion feedback to support attainment of exertion-based arm-crank goals.

Both groups received individualized goal-setting with a physical therapist utilizing the Brief Action Planning technique for collaborative PA goal setting and plan achievement design (30, 31). Goals were tailored to either the PACE or WODAA intervention and the individual's current PA level and upper extremity health. Participants were encouraged to take the lead on goal setting, though standardized goals and associated progression metrics were suggested as needed to ensure each participant set challenging but realistic goals. Initial goals were set during the initial intervention visit and progressively updated following Week 2 and Months 1, 2, and 3 of the intervention. As part of goal setting and attainment review, participants were also asked to subjectively report their level of exertion during PA using Borg Rating of Perceive Exertion (RPE) Scale (32). The RPE is a 6-to-20-point scale that is widely used to guide exercise intensity, with higher numbers associated with higher intensity activities. Goals for the WODAA group focused on progressively increasing daily PA (Steps/arm activity) to decrease sedentary time. Depending on the participant's starting capacity, goals followed the general progression framework: (1) average at least 10,000 Steps/day, (2) increase the number of hours each day with at least 250 Steps (once 10,000 daily Steps were consistently achieved), (3) increase the amount of time spent in higher heart rate zones (i.e., the time reported by the activity monitor in the Cardio HR Zone and/or the time spent exercising at a participant reported RPE ≥ 12). Goals for the PACE group were also progressive in nature. Initially, participants were asked to perform three 15-min cycling sessions each week at a target heart rate of at least 70% of the calculated maximum rate

(typically corresponding to a participant reported RPE of 12–16). All PACE sessions included a 2-min warm-up and 1-min cool-down. PACE participants were then encouraged to progressively increase session duration from 15 to 30 min between Weeks 2 and 4 and to 33 min by Week 5. Last, participants were instructed to maintain 33–35 min sessions, but exercise at a higher intensity (target heart rate of 85% of maximum). They were encouraged, but not required, to disperse their three PACE sessions across the 7 days each week and advised to increase resistance and speed during Weeks 5–12 to meet these established goals. If participants achieved the Weeks 5–12 goal, they were encouraged to maintain that level in Weeks 12–16.

Both groups received equipment and instruction on performance of the STOMPS shoulder preservation program. Participants were encouraged to perform the STOMPS strengthening exercises three times a week, with a day of rest between resistance sessions, throughout the study. The program consists of home-based shoulder flexibility and strengthening exercises and recommendations for movement techniques that reduce shoulder demands associated with PA and daily activities after SCI (29, 33, 34).

2.3.4 Interim and final assessments

During interim assessments, participants had either an in-person or telephone appointment with the physical therapist to evaluate progress towards achieving their PA goals and, if appropriate, to progress their goals. Between assessments participants continued with either their WODAA or PACE intervention in their home and community environments. During the 2-week phone assessment, goals were set for the end of Month 1. Month 1 review and goal setting was performed in-person, where participants also received additional assistance related to study equipment and device use and progression of their shoulder strengthening program as appropriate. Shoulder pain status was also formally assessed. Two additional phone assessments, which included the review of previous goal achievement and setting new monthly goals occurred at the end of Months 2 and 3. Upon completion of the intervention (end of Month 4), a fasting blood draw was again conducted to obtain cardiometabolic variables. Participants also repeated the 6-MPT and completed the WUSPI questionnaire as well as the clinical shoulder exam, if pain was indicated on the WUSPI. Participants were permitted to keep their activity monitors upon program completion. Individuals in the PACE group were instructed in use of the wearable activity monitor and mobile app, if desired.

2.3.5 Additional contact

Outside of scheduled visits, contact between the study team and participants occurred as needed. Participants occasionally reached out for technical support/assistance with equipment and device setup. In addition, prolonged breaks in activity monitor data (≥ 3 –5 days), including identified data syncing issues, prompted the research team to contact participants.

2.4 Data management

Metabolic lab values and 6-MPT data from the Baseline and Final (Month 4) program assessments were logged for analysis. Shoulder pain (WUSPI) was evaluated at the Screening, Baseline, intervention Month 1 and Final Assessments as well as at any other time a reported change in shoulder symptoms and/or injury occurred.

Individual participant daily PA data was exported from the Fitbit website and conglomerated into averages for the Baseline period (7 days) and monthly intervention periods (Months 1–4). Heart rate (HR) data were additionally recorded from the Fitbit portal. Daily PA and HR metrics were routinely monitored and screened every 3–5 days for full days of use (≥ 8 waking hours) to ensure adequate device function and that data represented the majority of a participants' activity. Only days with ≥ 8 waking hours and only months with over half of the days (≥ 14 days) with valid data were utilized for data analysis. Activity data were binned using Activity Zones, which were defined by estimating the Metabolic Equivalent (MET) of an activity based on the commercial activity monitor's measurement of resting and current HR. Sedentary, Light, Fairly Active, and Very Active Zones were defined using the ≤ 1 , 2–3, 4–6, and > 6 METs thresholds, respectively, that are established for able-bodied individuals (35). Activity was also binned based on the recorded heart rate data, which included time spent in the Fat Burning, Cardio, and Peak Heart Rate Zones. These zones were defined as 50%–69%, 70%–84% and 85%–100% of maximum calculated heart rate. To obtain an estimation of time spent in various heart rate and activity zone levels, the maximum heart rate (HR_{max}) for each participant was entered into the activity monitor prior to participant issuance according to the equation (36):

$$HR_{max} = (208 - (0.70 \times \text{age})) \quad (2)$$

Regardless of group, participants were placed on a PA intervention hold if they experienced a health condition that affected their ability to exercise for more than 3 consecutive days or if they had a malfunctioning activity monitor. In these cases, the equivalent amount of time was added to the duration of their intervention period. Holds lasted between 3 and 17 days, except for one participant who developed an infection and was unable to exercise for 11 weeks. Placing individuals on an intervention hold may have induced detraining effects, especially for those with longer holds. However, in this study, only the secondary (cardiometabolic) measures might be influenced by detraining, as our primary metrics [activity levels (Steps), HR and Activity Zones] are instantaneous measures of activity as opposed to observations of long-term physiological changes. While previous work has found detraining effects to occur (37–39), the amount of detraining time needed before an individual living with SCI experiences physiological changes can vary greatly (from 1 to more than 16 weeks) depending on the metric measured, with most time periods greater than the holds required by the participants in this study. For example, Gurney et al. (39)

estimated that improvements in VO₂ and HR measures were partially retained even after 8 weeks of detraining, while Gorgey et al. (38) did not observe any changes in basal metabolic rate, insulin sensitivity, and resting blood pressure after 16 weeks (although they observed decreases in muscle mass and cross-sectional area).

2.5 Statistical analysis

Complete data sets were analyzed using SPSS Statistics (Version 23) software (IBM, Chicago, IL, USA). After testing for normality (Shapiro–Wilk test), differences between and within groups of normally distributed data were assessed using a two-way analysis of variance with repeated measures and Tukey's *post hoc* tests. Analyses of nonparametric data within intervention groups were performed with Wilcoxon signed-rank tests. The Independent-Samples Mann–Whitney *U*-Test was utilized for nonparametric comparisons between intervention groups. The significance level for all tests was set to $p < 0.05$. Due to multiple group and timepoint comparisons (Group: WODAA vs. PACE, and Timepoint: Baseline vs. Month or Initial vs. Final Eval) a Bonferroni correction for multiple comparisons was applied for *post hoc* statistical tests.

Primary PA outcome measures were: (1) Daily average activity monitor data (Steps, Activity Zone minutes, HR Zone minutes) at Baseline and Month 4. The difference between the daily average of the 7-day Baseline and the daily average of the final month of the intervention were used to assess long-term change. Secondary PA measures included (1) fasting metabolic bloodwork (lipid profile, calculated HOMA-IR insulin resistance, glucose) and (2) 6-Minute Push Test distance traveled and blood pressure. Changes in Wheelchair User's Shoulder Pain Index (WUSPI) scores were also assessed.

3 Results

3.1 Participants

Fifty-four (24 WODAA, 30 PACE) of 65 qualifying participants completed the entire protocol (4-month intervention and Final Assessment). Of those completing the intervention, 5 participants (3 WODAA, 2 PACE) had insufficient PA data available for analysis, resulting in 49 (21 WODAA, 28 PACE) complete data sets for the current analysis. There were no significant differences between the two groups with respect to age and time since injury (Table 1), with the average age of all participants 40.8 years (range 21.7–60.9 years) and average injury duration 16.6 years (range 1.4–38.0 years). Other baseline demographic characteristics were statistically similar between the WODAA and PACE participants, as were initial cardiometabolic laboratory test values (Table 1). Baseline PA levels including average daily Sedentary, Light, Fairly, and Very Active Zone minutes as well as Fat Burn, Cardio, and Peak HR Zone minutes were also similar between the two groups (Table 2). No

TABLE 1 Self-disclosed participant demographics.

| Variable | Participant group | | | | | |
|---|------------------------|---------------------|-------------------|-----------------------|-------------------|-------------------|
| | WODAA (<i>n</i> = 21) | | | PACE (<i>n</i> = 28) | | |
| | Total | High para (T2–T6) | Low para (T7–L3) | Total | High para (T2–T6) | Low para (T7–L3) |
| Age, years (range) | 40.9 (26.8–57.4) | 34.4 (26.8–48.3) | 44.8 (32.4–57.4) | 40.7 (21.7–60.9) | 46.6 (27.8–60.9) | 38.3 (21.7–59.7) |
| Sex, % Female | 5/21 (24%) | 1/8 (13%) | 4/13 (31%) | 5/28 (18%) | 2/8 (25%) | 3/20 (15%) |
| Duration of injury, years (range) | 14.1 (1.4–38.0) | 8.7 (1.9–17.0) | 17.4 (1.4–38.0) | 18.4 (1.4–34.0) | 24.1 (4.8–34.0) | 16.1 (1.4–32.4) |
| Level of injury | <i>n</i> = 21 | 8 (38%) | 13 (62%) | <i>n</i> = 28 | 8 (29%) | 20 (71%) |
| AIS completion score | | | | | | |
| A | 15 (72%) | 7 (88%) | 8 (62%) | 16 (57%) | 4 (50%) | 12 (60%) |
| B | 3 (14%) | 1 (12%) | 2 (15%) | 8 (29%) | 4 (50%) | 4 (20%) |
| C | 3 (14%) | 0 (0%) | 3 (23%) | 4 (14%) | 0 (0%) | 4 (20%) |
| Race/Ethnicity | | | | | | |
| American Indian | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) |
| Asian/Pacific Islander | 1 (5%) | 0 (0%) | 1 (8%) | 2 (7%) | 1 (12%) | 1 (5%) |
| Black | 3 (14%) | 1 (12%) | 2 (15%) | 6 (22%) | 3 (38%) | 3 (15%) |
| White | 14 (67%) | 6 (76%) | 8 (62%) | 13 (46%) | 3 (38%) | 10 (50%) |
| Unknown/Declined | 0 (0%) | 0 (0%) | 0 (0%) | 2 (7%) | 1 (12%) | 1 (5%) |
| More than one race | 3 (14%) | 1 (12%) | 2 (15%) | 5 (18%) | 0 (0%) | 5 (25%) |
| Ethnicity, % Hispanic | 11/21 (52%) | 5 | 6 | 19/28 (68%) | 5 | 14 |
| Avg. yearly income | | | | | | |
| \$0–25,000 | 16 (76%) | 6 | 10 | 25 (89%) | 7 | 18 |
| \$25,001–50,000 | 4 (19%) | 2 | 2 | 3 (11%) | 1 | 2 |
| \$50,001–75,000 | 0 (0%) | 0 | 0 | 0 (0%) | 0 | 0 |
| ≥\$75,000 | 1 (5%) | 0 | 1 | 0 (0%) | 0 | 0 |
| Self-described exerciser, yes | 12 (57%) | 4 (50%) | 8 (62%) | 14 (50%) | 4 (50%) | 10 (50%) |
| Self-reported cardiometabolic-related medical history | 2 (10%) | 0 (0%) | 2 (15%) | 5 (18%) | 1 (13%) | 4 (20%) |
| Baseline daily steps | 5,992 ± 2,042 | 4,881 ± 2,093 | 6,675 ± 1,750 | 5,200 ± 2,298 | 5,496 ± 2,530 | 5,081 ± 2,257 |
| Baseline sedentary time (min/day) | 1,072 [814–1,194] | 1,156 [1,000–1,232] | 1,026 [785–1,084] | 1,068 [770–1,144] | 674 [638–963] | 1,111 [938–1,139] |
| Baseline wheelchair user’s shoulder pain index (WUSPI) score (pain ≥12) | 0 [0, 0] | 0 [0, 0] | 0 [0, 0] | 0 [0, 0] | 0 [0, 0] | 0 [0, 0] |

Data are presented as overall values (Total) for each intervention group (WODAA, PACE) as well as broken down into High Paraplegia (T2–T6; High) and Low Paraplegia (T7–L3; Low) subgroups. Values are presented as counts (percent %), mean ± 1SD or median [25%–75% Interquartile Range].

individual reported having shoulder pain on their initial WUSPI assessment (Table 1).

3.2 Program retention & sustainability

Both PA regimens were generally well-tolerated by participants in both groups during the 4-Month intervention. Of the 65 individuals cleared for participation in the intervention following the initial assessments, 54 (24 WODAA, 30 PACE) completed the 4-month intervention and Final Assessment. The WODAA group had 6 participants that did not complete the intervention (1 due to illness, 3 due to loss of contact, 2 incompletions due to Covid-19 Pandemic protocols) while the PACE group had 4 participants that did not complete the intervention (2 due to exacerbation of previously unreported elbow and neck pain, 1 due to moving out of state, 1 due to loss of contact). Contact with one additional individual was lost prior to randomization.

Overall, 26 adverse events were reported, with 22 unlikely to be related to study participation. Of the remaining 4 adverse events

that may be related to study participation, one event was minor, although directly attributable to the study (skin irritation from the activity monitor band, participant resumed after band replacement), and one was probably related (pain in elbow/biceps when lifting legs before transferring). The two possibly related events included a reaggravation of elbow pain from a participant with an initially undisclosed prior history and another with shoulder pain from increased arm cycling at high intensity in the absence of performing the recommended shoulder protection program.

3.3 Daily physical activity

3.3.1 Steps

Significant ($p < 0.05$) increases in average daily Steps for each intervention month (1–4) were only observed in the WODAA group (Figure 2A, Table 3). In addition, the improvement in daily Steps between Baseline and Month 4 was significantly higher in the WODAA group compared to the PACE group

TABLE 2 Group average daily minutes spent in the various activity levels and heart rate zones.

| | Baseline (7 days) | | | | Final intervention month (month 4) | | | | Change | | | |
|---|---------------------------|--------------------------|---------------------|----------------------------------|------------------------------------|----------------------|------------------------------|----------------------------------|----------------------------|-------------------------|------------------------|----------------------------------|
| | WODAA (<i>n</i> = 21) | PACE (<i>n</i> = 28) | t(df) or Z | <i>p</i> -value (effect size) | WODAA | PACE | t(df) or Z | <i>p</i> -value (effect size) | WODAA | PACE | t(df) or Z | <i>p</i> -value (effect size) |
| Total daily activity (steps) | 5,992 ± 2,042 | 5,200 ± 2,298 | <i>t</i> (47) = 1.3 | 0.217 (0.07) | 8,643 ± 3,265 | 5,564 ± 2,243 | <i>t</i> (33.6) = 3.7 | .003 (0.11) | 1,912 [1,117–4,582] | 451 [–309–1,106] | <i>Z</i> = –3.7 | 0.000 (0.27) |
| Activity zone minutes (daily average) | | | | | | | | | | | | |
| Sedentary (1MET, > 10 min) | 1,072 [749–1,206] | 1,066 [717–1,142] | <i>Z</i> = –0.1 | 2.8 (0.0) | 977 [649–1,059] | 1,050 [665–1,175] | <i>Z</i> = –1.3 | 0.62 (0.04) | –118 ± 229 | –47 ± 161 | <i>t</i> (47) = –1.3 | 0.207 (0.19) |
| Light (2–3 METs) | 248 ± 69 | 228 ± 82 | <i>t</i> (47) = 0.9 | 1.07 (0.02) | 252 ± 62 | 224 ± 76 | <i>t</i> (47) = 1.4 | 0.519 (0.03) | 4 ± 57 | –3 ± 44.0 | <i>t</i> (47) = 0.5 | 0.617 (0.01) |
| Fairly active (4–6 METs) | 14 [8–28] | 22 [4–41] | <i>Z</i> = –0.5 | 1.95 (0.01) | 29 [17–50] | 22 [10–31] | <i>Z</i> = –1.6 | 0.36 (0.05) | 12 [3–31] | 2 [–12–13] | <i>Z</i> = –2.0 | 0.048 (0.08) |
| Very active (>6 METs) | 8 [3–17] | 7 [0–24] | <i>Z</i> = –0.40 | 2.1 (0.00) | 23 [13–48] | 9 [4–21] | <i>Z</i> = –3.3 | 0.02 (0.22) | 13 [6–34] | 2 [–3–8] | <i>Z</i> = –3.8 | 0.000 (0.30) |
| Heart Rate zone minutes (daily average) | | | | | | | | | | | | |
| Fat burn (50–69% max HR) | 159 [67–390] | 340 [145–494] | <i>Z</i> = –2.1 | 0.078 (.09) | 236 [98–460] | 317 [177–507] | <i>Z</i> = –0.8 | 1.24 (0.01) | 62 ± 82 | 2 ± 115 | <i>t</i> (45) = 1.2 | 0.054 (0.04) |
| Cardio (70–84% max HR) | 0 [1–10] | 4 [1–8] | <i>Z</i> = –1.2 | 0.42 (0.03) | 11 [4–25] | 7 [3–11] | <i>Z</i> = –1.8 | .132 (0.07) | 5 [2–22] | 0 [–3–6] | <i>Z</i> = –2.5 | .011 (0.14) |
| Peak (85–100% max HR) | 0 [0–0] | 0 [0–0] | <i>Z</i> = –0.2 | 1.7 (0.00) | 0 [0–2] | 0 [0–0] | <i>Z</i> = –1.6 | 0.22 (0.06) | 0 [0–2] | 0 [0–0] | <i>Z</i> = –1.5 | .145 (0.03) |

Data are presented for each intervention group with significant differences between groups indicated in bold ($p < 0.05$). Values are presented as Median [25%–75% IQR] or as Average ± 1SD. Depending on the test, effect sizes are calculated using Cohen's d or η^2 .

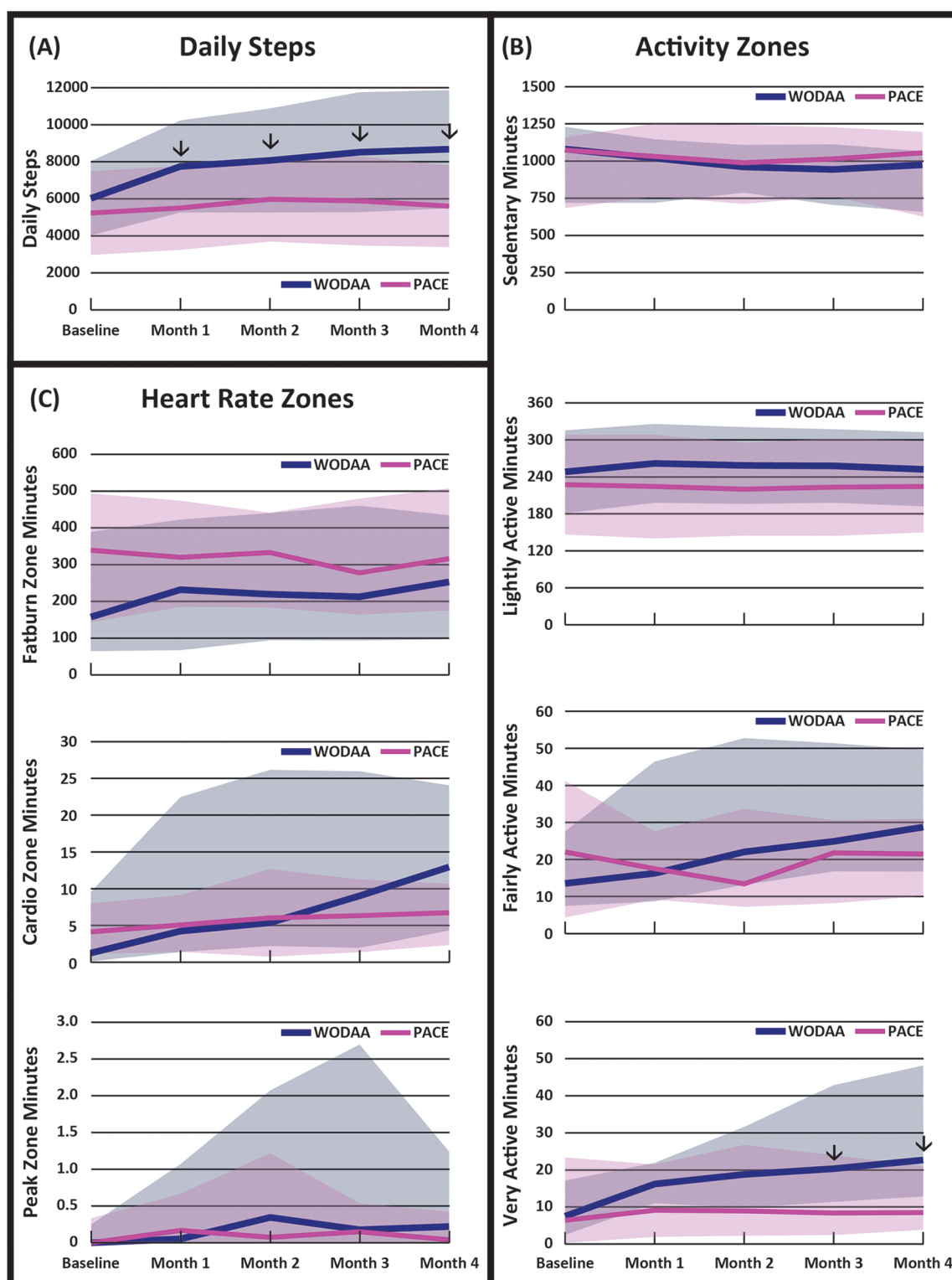


FIGURE 2

Daily averages of: (A) overall activity (steps), (B) minutes spent in different activity zones, and (C) minutes spent in different heart rate zones, obtained at five intervention assessment timepoints. Arrows (↓) denote time periods with significant differences ($p < 0.05$) between the WODAA and PACE groups. Please note the change in scales between variables. Daily step data are presented as means (lines) \pm 1 standard deviation (shaded area). All other data are presented as median (lines) and 25–75 interquartile range (shaded area). Activity Zones were defined to be Sedentary (1MET, >10 min), Light (2–3 METs), Fairly Active (4–6 METs), and Very Active (>6 METs). Heart Rate Zones were defined as Fat Burn (50%–69% Max HR), Cardio (70%–84% Max HR), and Peak (85%–100% Max HR).

TABLE 3 Comparison of average total daily activity (steps \pm 1SD) between the WODAA and PACE intervention groups.

| Time | Average daily steps | | | |
|---------|-------------------------------------|-------------------------------------|---------------------|-----------------------|
| | WODAA | PACE | t (df) | p-value (effect size) |
| BL | 5,992 \pm 2,042 | 5,200 \pm 2,298 | t (47) = 1.3 | 0.217 (0.03) |
| Month 1 | 7,706 \pm 2,540 | 5,473 \pm 2,305 | t (47) = 3.2 | 0.006 (0.07) |
| Month 2 | 8,035 \pm 2,870 | 5,942 \pm 2,323 | t (47) = 2.8 | 0.021 (0.06) |
| Month 3 | 8,483 \pm 3,316 | 5,852 \pm 2,450 | t (47) = 3.2 | 0.006 (0.07) |
| Month 4 | 8,643 \pm 3,265 | 5,564 \pm 2,243 | t (34) = 3.7 | 0.002 (0.11) |

BL, Baseline Period. Significant differences ($p < 0.05$) are presented in bold.

{1,912 [1,117–4,582 Interquartile Range (IQR)], vs. 451 [–309–1,106 IQR], $p = 0.000$ } (Table 2).

3.3.2 Activity zone minutes

The WODAA group spent significantly more daily minutes compared to PACE in the Very Active Zone (approximately >6 METS) during both Month 3 [20 (12–43 IQR) vs. 9 (3–24 IQR); $Z = -2.63$, $p = .027$, effect size $\eta^2 = 0.14$] and Month 4 [23 (13–48 IQR) vs. 9 (4–21 IQR); $Z = -3.25$, $p = .022$, $\eta^2 = 0.22$] (Figure 2B, Table 2). Relative to the PACE group, the WODAA group had significantly greater improvements (compared to Baseline) in daily minutes spent in both the Fairly Active [12 (3–31 IQR) vs. 2 (–12–14 IQR); $p = 0.048$] and Very Active Zones [13 (6–34 IQR) vs. 2 (–3–8 IQR); $p = 0.000$; Table 2].

3.3.3 Heart rate zones

The WODAA group had significantly greater improvement in daily minutes spent in the Cardio HR Zone from Baseline to Month 4 [5 (2–22 IQR) vs. 0 (–3–6 IQR) minutes; $p = 0.011$; Figure 2C, Table 2]. No other significant differences were observed within or between groups.

3.4 Cardiometabolic indicators

3.4.1 6-Minute Push Test (6-MPT)

The WODAA group demonstrated a significant decrease in Post 6-MPT Diastolic blood pressure following intervention (Baseline vs. Final Assessments) while PACE participants did not (–6 \pm 11 vs. 2 \pm 12; $t = 1.8$, $p = 0.019$; Figure 3). The resulting effect size, measured using Cohen's D, was 0.74, indicating a medium effect. No significant difference between intervention groups was observed in total distance pushed during the post-intervention 6-MPT assessment, with values for both groups similar to Baseline measurements (WODAA 727 \pm 141 m post vs. 697 \pm 126 m Baseline; PACE 718 \pm 152 m post vs. 682 \pm 176 m baseline; $p \geq 0.05$).

3.4.2 Fasting metabolic labs

No significant differences were noted between any metabolic laboratory values including HOMA index scores following either intervention ($p > 0.05$). Interestingly, relative to WODAA, there

was a trend towards significantly lower Triglycerides at the Final Assessment in the PACE group [80 mg/dl (57–136 IQR) vs. 123 mg/dl (94–189 IQR), $Z = -2.22$, $p = 0.052$, $\eta^2 = 0.11$] as well as a trend towards larger reductions in Triglyceride levels compared to baseline [–5 mg/dl (–29–9 IQR) vs. 7 mg/dl (7–46 IQR), $Z = -1.85$, $p = 0.092$, $\eta^2 = 0.06$].

3.5 Wheelchair User's Shoulder Pain Index (WUSPI)

Shoulder Pain Baseline median WUSPI index scores were 0 [0–0 IQR] in both intervention groups and did not change significantly with either PA intervention (Table 1).

4 Discussion

This is one of the first studies directly comparing a WODAA program to a traditional PACE program for PA promotion in a group of MWC users with SCI. Aligning with our hypothesis, our findings suggest that a WODAA approach to increasing physical exercise is viable, accessible, and of greater or similar benefit than a PACE program for persons with SCI using MWCs. While both groups improved their overall activity compared to baseline measurements, our WODAA intervention helped participants significantly increase daily activity (Steps) and total time spent in higher intensity activities (Fairly, Very Active, and Cardio Zones) when compared to the PACE program. The WODAA program may also improve cardiovascular fitness as suggested by a small, but significant decrease in diastolic blood pressure measured immediately following 6-MPT at program end compared to baseline. Neither of the PA programs (WODAA and PACE), when combined with the STOMPS shoulder exercise program instruction, resulted in an onset of shoulder pain (i.e., no significant change in WUSPI scores). However, contrary to our hypothesis, there were no significant changes in fasting metabolic lab measures (lipids, insulin resistance, glucose), nor other fitness measures from the 6-MPT (meters pushed, Pre/Post-test systolic, Pre-test diastolic BP, Pre-test systolic BP), although there was a tendency towards lower triglycerides at program end in the PACE group. Despite the absence of significant improvements in most cardiovascular health measures, when considering WODAA's positive impact on increasing both overall activity (Steps) and higher intensity activity, there is sufficient evidence to suggest that a WODAA approach is a viable clinical alternative to traditional exercise programs.

Further, the WODAA approach to exercise may be especially relevant for those with limited access to resources required in traditional programs such as PACE. By using commercially available wrist-worn activity monitors to provide feedback on activity accumulated throughout the day, a WODAA program has the potential to address accessibility and affordability challenges to PA encountered by many individuals with SCI. Our findings, which document the WODAA intervention's

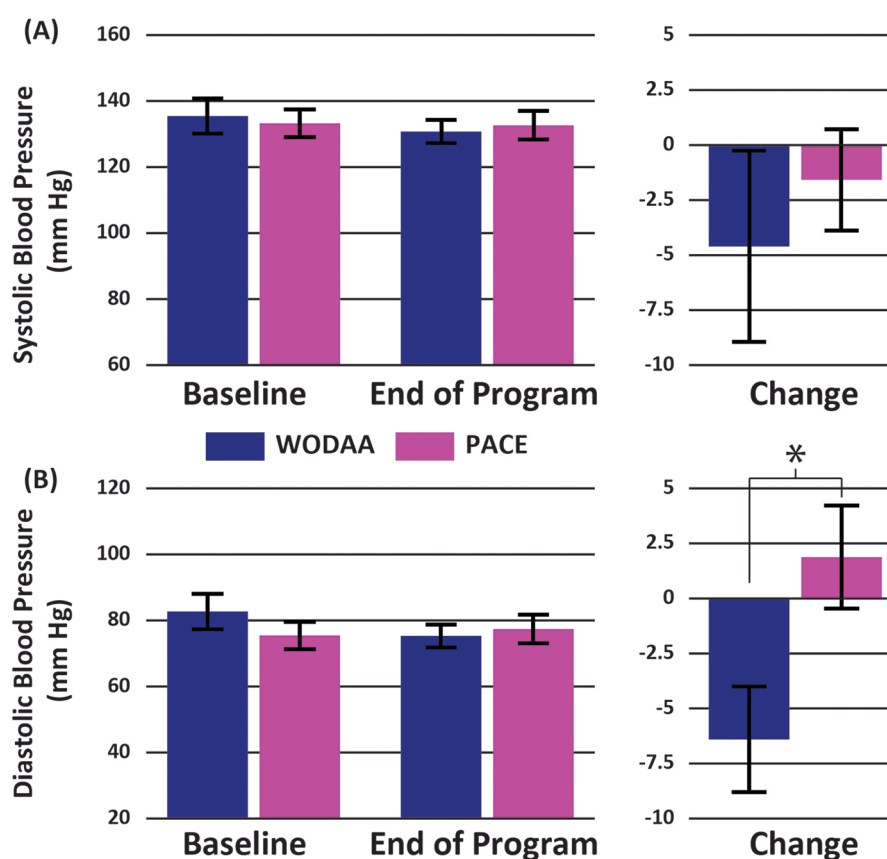


FIGURE 3

Group average Post 6-MPT (A) systolic and (B) diastolic blood pressure measurements for the WODAA and PACE groups at baseline and end of program (final assessment) timepoints (left column). Corresponding changes in values between the two timepoints are also presented (right column). All measurements were taken immediately following the completion of the 6-Minute Push Test. Error bars indicate Standard Errors. *Significant difference ($p < 0.05$) between the two intervention groups (WODAA, PACE).

effectiveness in a traditionally underrepresented community with limited-resources (>50% Hispanic, >75% low income; Table 1) represent a critical step towards identifying a potentially more accessible and equitable clinical prescription for increasing PA. In parallel, the advent of virtual and on-demand exercise programs – now widely available to the general population – can help overcome challenges in resource limited environments. However, few virtual/on-demand exercise programs tailored to MWC users and/or persons living with SCI currently exist and future work understanding how wearable sensors can be utilized to create and support these programs is needed.

A key component of both programs was the utilization of commercially based activity monitors to collect data and personalize PA programs for participants. While other research grade monitors may demonstrate higher accuracies, our approach that used a readily available and relatively low-cost activity monitor (Fitbit Blaze/Versa) was intentional: a primary consideration of the study was to evaluate the utility of commercially available activity monitors to promote PA in those with SCI, despite existing questions about data accuracy. While our overall outcomes were positive, suggesting that these devices can be used to promote PA, our findings should be interpreted

within this context. The most obvious challenge associated with utilizing these activity monitors is that these devices do not account for the fundamental differences in physiological response (e.g., heart rate, metabolic energy expenditure) to exercise that exist between those living with an SCI and the general population (5, 40–42). In addition, these compromised responses will vary based on level and completeness of injury, with higher level and more complete injuries associated with greater differences in cardiovascular response and muscular capacity than those with lower and less complete injuries (5, 41, 42). Here we focused on assessing these devices with persons living with paraplegia ($\leq T2$) to exclude the dramatically altered cardiovascular responses to exercise demonstrated by individuals with tetraplegia (5, 31). Of those studied, sixteen (16) individuals in this study had high paraplegia (T2–T6) and the remaining participants had low paraplegia ($\leq T7$), with similar distributions between the two groups (Table 1).

Because individuals with paraplegia may also have varying levels of compromised cardiovascular response, we performed a *post hoc* analysis of our HR and blood pressure data obtained during the Baseline 6-Minute Push Test (6-MPT) to assess the validity of our maximum HR estimate, a key component to using

commercial activity monitors. The analysis revealed no significant differences between individuals with high (T2–6) and low paraplegia (T7 and below) in maximum or average HR, total meters pushed, or peak and average HR when represented as a percentage of each participant's maximum HR obtained using an age-adjusted predictive equation (36). The only significant difference observed between groups was systolic blood pressure (BP) at assessment end. In this case, post-test systolic BP was reduced, on average, by 13.3 mmHg (9.6%) in those with T2–T6 paraplegia compared to subjects with lower-level injuries (high paraplegia; 124.6 ± 23.2 mmHg, low paraplegia; 137.9 ± 18.3 mmHg, $t = 2.099$, $p = 0.041$). Our *post hoc* findings largely fall in line with recent work studying relationships between injury level, maximal heart rate and age in eighty (80) individuals with thoracic SCI that demonstrated the traditional age-related decline in maximal HR is largely preserved, regardless of injury level (40).

With respect to the predictive equation for maximal HR used within our study, our estimates based on Tanaka, Monahan, and Seals (36) generated values that were 5–15 percent higher (depending on age) than those obtained using a predictive equation specific to individuals with low paraplegia that was published after our data collection (40). Despite this, we still believe that our findings related to differences in the amount of time spent in each HR Zone between groups are valid and contextually relevant. Because the maximum HR was likely overestimated for all individuals in our study, the Heart Rate Zones used in our analysis were also likely shifted upwards, resulting in a conservative approach that probably underestimated the amount of higher intensity PA performed by our participants, regardless of intervention group. This conservative approach strengthens our findings and overall conclusion that the WODAA program can be used to improve overall activity.

Similar to the HR Zones, Activity Zone data were determined using algorithms embedded within the commercially available activity monitor used in this study. In this case, each Activity Zone represents a predefined range of METS, calculated as the ratio of the current HR to resting HR. In this study, both the resting HR and activity-based HR were measured directly using the activity monitor. Because the underlying algorithms are designed for able-bodied individuals, the presentation of METS (and Activity Zones) obtained from these devices when studying those living with SCI should be done with caution. Fortunately, the validity and use of METS in this population has been studied previously, providing context for interpreting our findings (43). Using direct measurements of the metabolic cost of different activities in 170 individuals living with SCI (43), others have determined that the 1 MET equivalent for persons with SCI is lower than that of the general population (2.7 vs. 3.5 ml kg⁻¹ min⁻¹), with no significant difference in resting MET rates between different injury groups. Particularly relevant to the findings of this study, the authors proposed that arm crank exercises at medium to high intensities performed by those living with SCI correspond to a higher MET value relative to the general population (7.6 vs. 5.9 METS, respectively). Thus, like our HR Zone data, our presented Activity Zone data are likely to be conservative in nature and, as a result, significant increases in Activity Zones are likely underestimated.

For this study, we utilized a commercially available wrist-worn activity monitor (Fitbit Blaze/Versa) to record PA (Steps) and HR. At the time of data collection, the reliability and validity of these devices when measuring activity in wheelchair users (with or without SCI) had not been published. In preparation for this study, our pilot work demonstrated that the Fitbit Blaze/Versa was sufficiently accurate in recording the primary activities investigated in this study. More recently, the validity of such devices to document HR and energy expenditure have been widely investigated in able-bodied adults and, to a lesser extent, in MWC users (19, 26, 44–46). Importantly, the results of our pilot study are consistent with recent studies investigating the use of current commercially available activity monitors to measure HR and movement during MWC-based activities, with all findings supporting the notion that these devices can be used to support PA programs tailored for MWC users. For those with thoracic and lumbar SCI (T1–T5 and T6 and below), the Fitbit Charge 2 was found to have measurement errors in line with those we found in our pilot work (average errors of 6.2% and 4.1%, respectively for the two groups vs. 1.9%–4.9% in our pilot) when measuring HR during 11 different WC activities (26). These activities included arm-crank ergometry, where errors in HR measurements were found to be slightly higher, but still acceptable for the two groups (10% and 9.2%, respectively). A second study found that the Fitbit Versa reported lower HR during treadmill WC propulsion at 9 different intensities in WC users with physical disability (65% with SCI), although with a higher mean absolute percentage error (MAPE) of 17.4% (SD 12.4%) across conditions (45). In contrast, energy expenditure was greatly overestimated by the activity monitors in this study, averaging 71.2% across conditions (range 155.5 to 28.1%). However, MAPE consistently decreased with increasing intensity of propulsion, suggesting that the devices are better equipped to record high intensity activities such as PACE.

Though small (−6 mmHg), the significant decrease in diastolic BP after a bout of exercise at the end of the WODAA program supports the notion that our novel approach may improve cardiovascular health. For the general population, increased aerobic exercise has been associated with improved vasodilation and reduced vascular resistance, attenuating cardiovascular responses to stress post exercise and providing a cardioprotective benefit (47). However, this interpretation should be taken with caution as the number of studies that have systematically investigated how cardiovascular variables may change after a prescribed exercise program in those living with SCI are limited and have produced mixed results [e.g., (37, 48–50)]. While not studied here, this increased activity may hold further implications if this change persists over a long period of time, particularly if combined with positive nutritional changes. In contrast, there was no observed change in diastolic BP at program end for the PACE group (+2 mmHg). In addition, although not statistically significant, sedentary time in the WODAA group also had notable decreasing trends. When considered with the significant improvement of the post-6-MPT diastolic blood pressure, these two observations may indicate that the WODAA program can

assist in establishing life-long habits of PA that, when sustained and coupled with the STOMPS shoulder exercise program, will provide long-term PA benefits to those in the program. However, while positive and significant PA changes were accomplished over 4 months, a longer intervention period may be needed to induce more measurable cardiovascular and metabolic health improvements in this population.

There are several established guidelines to help individuals obtain the physical benefits associated with activity and exercise. The CDC established weekly exercise guidelines for the general population of “150 min of moderate-intensity activity [3–5.9 METs] or 75 min of vigorous-intensity activity [>6 METs]” (35). Guidelines specific to those living with SCI have also been proposed, with recommendations typically covering cardiovascular health, muscle strengthening, and stretching (51–55). Suggested amounts for each type of exercise can vary greatly, with the largest range being in aerobic recommendations [from 20 min twice a week (52) to 30 min five times a week (54)]. Intriguingly, at Baseline, individuals in both groups consistently met the weekly exercise guidelines established by the CDC for the general population as well as most of the aerobic guidelines suggested for those living with SCI, despite our efforts to include only those that were not regularly exercising. The observed substantial levels of Baseline exercise may be partially due to participants knowing that they are being tracked and, therefore, increasing their sense of accountability to PA despite our efforts to minimize this effect by instructing them to avoid making any lifestyle changes during the baseline PA recording period. Even with this relatively high starting point in both intervention groups, however, the WODAA program still steadily and significantly increased PA (Steps) and time spent in higher Activity Zones (approximately ≥ 4 –6 METs; Figure 2B), with observed increases in Fairly and Very Active Zone minutes, by the final month of intervention reaching 25 daily minutes (175 min/week). In contrast, PACE participants maintained similar activity levels throughout the intervention, suggesting a potential offsetting reduction of activity outside of PACE sessions. In addition, the larger decrease in daily sedentary time of 118 min in WODAA as compared to 47 min in PACE, while not statistically significant, may still hold import in addressing morbidity and mortality disparities amongst those with SCI who are also low-active (<2 h of activity per day), particularly if sustained over a longer duration. In fact, others have found that replacing 30 min of daily sedentary time with an equal amount of at least light activity time, as WODAA participants accomplished, was associated with a 20% reduction in mortality risk after 5 years, while a 39% mortality risk reduction was noted when replacing an hour daily of sedentary time [or non-activity] with an hour of exercise light activity among low-active individuals (56–58).

4.1 Limitations and future recommendations

The results of the current investigation must be considered alongside the limitations of the study. While our pilot work and current literature suggests that commercially available activity

monitors may be adequate for measuring activities performed by MWC users, the devices used in this study were not specifically designed for this purpose. However, a recent meta-analysis of Fitbit devices determined that the specific Fitbit model is not a significant factor when evaluating validity evidence of these devices (44), suggesting that the specific devices used in our study would have performed similarly to those evaluated in more recent validity tests. Regardless, documenting arm movements (as Steps), HR, and energy expenditure with these devices will introduce varying amounts of error dependent on the nature and intensity of the task. These errors would have presented across all participants within both interventions, minimizing their overall influence on study outcomes. In addition, the large differences in recorded activity levels between WODAA and PACE (e.g., average of 2,287 daily Steps at Month 4) suggests that any variance in recording accuracy would account for only a small portion of the observed change between groups. A second consideration is that the age-adjusted estimation of maximum HR used in this study was based on healthy adults without SCI. The equation used in this study (36) resulted in overestimation of max HR for our participants with paraplegia. Future work should utilize more accurate equations that were unavailable at the time of our data collection such as those proposed by Hamner and colleagues (40). Last, the WODAA group received constant feedback from their activity monitor while the PACE group received only HR feedback during PACE sessions. As a result, our study design did not allow us to determine how the two different levels of biofeedback (constant vs. minimal) may have influenced participant performance, including its influence on the observed decrease in PA outside of arm cycling sessions in the PACE group. Despite these limitations, our work represents what we believe would be a typical implementation of activity monitors to support both interventions and accurately represents the associated outcomes.

5 Conclusion

This study evaluated the viability of a whole of day activity accumulation (WODAA) approach PA intervention that uses a commercially available wrist-worn activity monitor for biofeedback. Depending on the measure used, the current study documents this approach to be more effective or provide similar PA improvements when compared to a traditional planned arm crank ergometry (PACE) program. Equally important, our results demonstrate our underlying assumption that using commercial activity monitors can be effective for promoting PA in MWC users with paraplegia is valid. When using a commercial activity monitor, we found that WODAA group participants demonstrated steady improvements throughout the program, including significant increases in daily arm (pushing) activity, time spent in moderate to vigorous intensity activities (≥ 4 –6 METs), and time spent in the Cardio HR Zone (70%–84% of participants' predicted maximum HR) by program end (Month 4). As a result, participants in this group met or exceeded established exercise guidelines during the final intervention month. In contrast, those engaged in the traditional

PACE program did not significantly increase overall PA, with ergometry sessions inducing a likely offsetting reduction in non-exercise activity. However, because these monitors are not tailored to account for the potential of a compromised cardiovascular response in those living with SCI, overall activity may be underestimated in both groups. Neither group experienced increases in shoulder pain, suggesting that, when appropriately implemented with shoulder pain prevention exercises (e.g., STOMPS), both PA programs can be implemented without increasing the likelihood of participants experiencing deleterious effects on shoulder health and function.

Future investigations to determine the impact of adding real-time PA feedback to a PACE intervention, pairing nutritional interventions to evaluate the effect that longer PA interventions may have on cardiometabolic health, and to evaluate alternative approaches for measuring activity levels in those with more compromised cardiovascular responses to exercise are critical moving forward. Results from this study may help healthcare providers and persons with SCI using MWCs for locomotion make informed decisions in choosing effective interventions to increase PA, particularly for those with limited resources, potentially impeding access to a traditional PACE program.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Institutional Review Board (IRB) at Rancho Research Institute, Downey, CA, USA. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JM: Data curation, Formal Analysis, Writing – original draft, Writing – review & editing. LH: Conceptualization, Data curation, Formal Analysis, Investigation, Project administration, Methodology, Supervision, Writing – original draft, Writing – review & editing. VE: Conceptualization, Data curation, Investigation, Project administration, Writing – review & editing. WW: Data curation, Investigation, Writing – review & editing.

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JR: Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY

David Arthur Hart,
University of Calgary, Canada

REVIEWED BY

Tsuyoshi Tatemoto,
Juntendo University, Japan
Dario Cerasola,
University of Palermo, Italy

*CORRESPONDENCE

Lauren E. Opielinski
✉ lauren.opielinski@marquette.edu

†PRESENT ADDRESS

Sandra K. Hunter,
Movement Science Program,
School of Kinesiology,
University of Michigan,
Ann Arbor, MI, United States

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COVID-19 and the impact of physical activity on persistent symptoms

Lauren E. Opielinski^{1*}, Toni D. Uhrich^{1,2,3}, Michael H. Haischer^{1,2},
Rachel N. Beilfuss³, Lindsey M. Mirkes Clark^{1,4}, Kamryn M. Kroner¹,
Rachel E. Bollaert¹, Michael J. Danduran¹, Linda B. Piacentine^{2,4},
Marie Hoeger Bement³, Paula E. Papanek¹ and Sandra K. Hunter^{1,2†}

¹Exercise Science Program, Marquette University, Milwaukee, WI, United States, ²Athletic and Human Performance Research Center, Marquette University, Milwaukee, WI, United States, ³Department of Physical Therapy, Marquette University, Milwaukee, WI, United States, ⁴College of Nursing, Marquette University, Milwaukee, WI, United States

Introduction: Physical activity is protective against chronic disease but whether activity is associated with persistent symptoms in non-hospitalized coronavirus disease 2019 (COVID-19) survivors is unknown. The purpose of the study was to determine the impact of the COVID-19 pandemic on physical activity levels and the influence of physical activity on acute COVID-19 and long COVID symptoms in non-hospitalized COVID-19 survivors.

Methods: In total, 64 non-hospitalized COVID-19 survivors (45 female participants, 40 ± 18 years) were assessed for activity levels, body composition, and symptoms of COVID-19 8.5 \pm 4.7 months post-infection and categorized into two groups: (1) persistent symptoms and (2) no symptoms at the time of testing. Furthermore, 43 of the 64 participants (28 female participants, 46 ± 18 years) completed a follow-up questionnaire online 51.0 \pm 39.7 months (4.25 years) post-infection. A subset of 22 COVID-19 survivors (16 female participants, 35 ± 16 years) were matched for age, sex, and body mass index with healthy controls. Physical activity was quantified using (1) self-reported questionnaire (International Physical Activity Questionnaire; IPAQ-SF) at three time periods; prior to COVID-19 infection, at the time of laboratory testing (8.5 \pm 4.7 months after infection), and during an online follow-up (51.0 \pm 39.7 months, i.e., 4.25 years after infection); and (2) 7 days of wearing an ActiGraph accelerometer following laboratory testing.

Results: Physical activity (IPAQ-SF) declined in COVID-19 survivors from pre-COVID-19 infection to 8.5 \pm 4.7 months after infection [3,656 vs. 2,656 metabolic equivalent of task (MET) min/week, 27% decrease, $p < 0.001$, $n = 64$] and rebounded to levels similar to pre-COVID-19 infection at 4.25 years after infection ($p = 0.068$, $n = 43$). Activity levels quantified with accelerometry did not differ between COVID-19 survivors and controls. However, COVID-19 survivors who reported persistent symptoms 8.5 months after infection ($n = 29$) engaged in less moderate-vigorous physical activity and steps/day than those without persistent symptoms ($n = 27$) (37 vs. 49 MET min/day, $p = 0.014$ and 7,915 vs. 9,540 steps/day, $p = 0.014$).

Discussion: Both COVID-19 survivors and matched controls reported reductions in physical activity indicating that lower levels of activity were likely due to the pandemic rather than COVID-19 infection alone. However, those who were most affected by COVID-19 infection with persistent symptoms had the greatest reductions in physical activity, even at ~8 months and ~4 years post-infection.

KEYWORDS

COVID-19, physical activity, persistent symptoms, accelerometer, long COVID, healthy control, fatigue

1 Introduction

Coronavirus disease 2019 (COVID-19) is caused by the virus SARS-CoV-2 and its rapid spread caused a global pandemic declared in March 2020, resulting in 7 million deaths globally and ~1 million in the United States by 2024 (1, 2). Acute infections range from mild symptoms to severe illness requiring hospitalization, including fever or chills, cough, shortness of breath, fatigue, muscle or body aches, headache, new loss of taste or smell, and sore throat (3, 4). Most COVID-19 cases (80%–90%) are less severe and do not typically require hospitalization (5).

Some symptoms from the COVID-19 infection, even in non-hospitalized patients, are persistent and develop into the chronic condition long COVID (also known as long haul COVID, post-COVID conditions, post-acute sequelae of COVID-19, post-acute COVID-19 syndrome, etc.) (6). Long COVID is defined as symptoms for at least 3 months post-infection, with some symptoms that emerge, persist, resolve, and then reemerge (7, 8). Common long COVID symptoms include fatigue, post-exertional malaise in response to physical or mental effort, shortness of breath, heart palpitations, difficulty thinking or concentrating (brain fog), and an overall decrease in quality of life (9–11). The percentage of American adults reporting long COVID symptoms was 6.9% in 2022 and grew to 17.9% in 2024 (12, 13). The risk of long COVID is greatest in people with severe acute illness, those who were infected multiple times, and those who are unvaccinated and become infected. In addition, the risk is heightened in women, Hispanic or Latino individuals, older adults (>65 years), and people with underlying health conditions (9, 14–16).

Physical activity (PA) is effective in improving health and longevity and protects against chronic disease (e.g., cardiovascular disease, diabetes, cancer, hypertension, obesity, depression, and osteoporosis) (17, 18). Additional benefits of PA include moderation of the immune system and protection against acute diseases, including reduced incidence of viral infections, intensity of symptoms, and mortality (19–23). Regular participation in PA may influence the risk of acute infection of COVID-19 and the development of persistent symptoms with long COVID, although there is minimal information on the association between activity levels and COVID-19 infection and

long COVID symptoms. A confounder to understanding the impact of activity levels on acute COVID-19 and long COVID symptoms is the isolation effects due to the pandemic on population activity levels, which declined markedly during the initial lockdowns (24–28).

A person's level of physical activity and sedentary behavior prior to the pandemic, however, appears to be predictive of the most severe effects of acute COVID-19 infection. From large datasets of medical records of people who had been hospitalized with COVID-19, it was shown that individuals who reported being consistently inactive had higher rates of ICU admission and death due to COVID-19 (20, 29). In addition, even people who participated in some PA but did not meet the recommended guidelines of 150 min of moderate-intensity physical activity per week had more positive outcomes than no activity, indicating that some PA is beneficial (29, 30). Inactivity was the strongest risk factor for hospitalization due to COVID-19, suggesting that PA is one of the most important protective therapies against acute COVID-19 infection and symptoms (21, 31, 32). Little is known about the influence of PA in those who experienced less severe infections and who did not require hospitalization.

Furthermore, the impact of PA on symptom recovery in people who have suffered long COVID is not understood. Recent studies report that PA in people with long COVID can improve persistent effects or in some worsen persistent symptoms (33–35). These mixed findings may contribute to reduced engagement and adherence to PA guidelines in individuals experiencing long COVID who may be limited by symptoms and even symptom exacerbations, including fatigue and post-exertional malaise (5, 36–38). Research focusing on longitudinal data from the acute phase throughout the potential development of long COVID is limited.

The primary aim of this study was to determine the impact of the COVID-19 pandemic on physical activity levels and the influence of physical activity on acute and long COVID symptoms in female and male COVID-19 survivors (COV) who had not been hospitalized. We hypothesized that (1) PA levels would decrease following acute COVID-19 infection in non-hospitalized COVID-19 survivors and be restored when reported years following the COVID-19 pandemic, (2) PA levels would be lower in non-hospitalized COVID-19 survivors than healthy matched controls, and (3) COVID-19 survivors with higher PA levels prior to COVID-19 infection would report the lowest number of persistent symptoms with long COVID.

Abbreviations

COVID-19, coronavirus disease 2019; PA, physical activity; COV, COVID-19 survivors; CON, non-COVID healthy matched controls; IPAQ-SF, International Physical Activity Questionnaire—Short Form; METs, metabolic equivalent of task min/week.

2 Materials and methods

2.1 Study overview

In total, 86 participants visited the laboratory for a single session followed by 7 days of physical activity monitoring as part of a larger, single-site cross-sectional study at the Athletic and Human Performance Research Center, Marquette University, Milwaukee, WI, USA, between November 2020 and November 2022. Laboratory assessments included resting heart rate and blood pressure, anthropometrics [height, weight, and body composition from a dual-energy x-ray absorptiometry scan (DXA)], a COVID-19 history questionnaire, a physical activity questionnaire, and instruction on the 7-day accelerometry. To understand the influence of COVID-19 on PA at this session, both a self-report questionnaire on PA levels and data collection of measured PA from an activity monitor were completed. The self-report questionnaire in COVID-19 survivors was captured for two time points at this session with (1) recall prior to COVID-19 infection and (2) 8.5 ± 4.7 months after infection. In addition, PA measured via accelerometry was compared between COVID-19 survivors and control-matched participants following laboratory testing. In total, 43 COVID-19 survivors went on to complete an online follow-up survey administered via Qualtrics (Qualtrics, UT, USA) between May and June 2024 that included questionnaires on COVID-19 symptoms and PA. Self-report PA was captured for an additional third time point, i.e., 51.0 ± 39.7 months or 4.25 years after infection, during this follow-up. These three time points of self-report PA allowed for a longitudinal study design in COVID-19 survivors to understand the influence of COVID-19 on PA over a long period of time.

2.2 Participants

Non-hospitalized COVID-19 survivors ($n = 64$, 19–77 years, 45 female and 19 male participants) and healthy controls ($n = 22$, 21–66 years, 16 female and 6 male participants) volunteered to participate in the study. Each participant provided written informed consent prior to participation, and the protocol was approved by the Marquette University Institutional Review Board (HR-3661) in accordance with the Declaration of Helsinki for human subject research. Participants were convenience sampled from Milwaukee, WI, USA, and surrounding areas. Recruitment strategies included printed flyers, emails, and online advertisements via social media on Marquette University's campus and alumni networks and a local news channel. All interested participants were screened online prior to being invited to participate in the study using the Physical Activity Readiness Questionnaire (PAR-Q+) that assesses contraindications to exercise (39–42). Exclusion criteria included asymptomatic acute COVID-19 infection, pregnancy, and any condition or disease that would preclude the individual from the ability to perform the various tests and measures involved in the

study (e.g., myocardial infarction in the last 12 months, pulmonary embolism, musculoskeletal issues, fibromyalgia, or active cancer). Participant groups included both COVID-19 survivors and healthy controls based on the following inclusion criteria:

- 1) *COVID-19 survivors (COV)*: self-reported positive test or diagnosis of COVID-19 at least 2 months prior to the laboratory session date and not hospitalized for their COVID-19 infection.
- 2) *Non-COVID healthy controls (CON)*: self-reported never experiencing a previous positive test, diagnosis, or symptoms of COVID-19.

The CON participants were recruited around the same time during the pandemic (within months) and were matched for age, sex, and body mass index (BMI). All participants included in the study were screened for COVID-19 symptoms and confirmed to be COVID-19 negative via a nasopharyngeal swab or saliva test on the day of the laboratory session.

2.3 Baseline measures

At the start of the laboratory session, resting blood pressure and heart rate were collected using an automatic blood pressure cuff (Omron Healthcare HEM-907XL, Kyoto, Japan). Height was recorded via a stadiometer (Seca, Hamburg, Germany), weight was recorded using the basic scale function of a multifrequency quadripolar bioelectrical impedance analysis scale (Tanita MC780-U, IL, USA), and body fat percentage was quantified from a DXA machine (Hologic Horizon A, MA, USA). BMI (kg/m^2) was calculated, and BMI categories were utilized (underweight $< 18.5 \text{ kg}/\text{m}^2$, normal weight $18.5\text{--}24.9 \text{ kg}/\text{m}^2$, overweight $25\text{--}29.9 \text{ kg}/\text{m}^2$, and obese $\geq 30 \text{ kg}/\text{m}^2$).

2.4 COVID-19 history questionnaire

All participants completed a questionnaire asking about sex, age, race, ethnicity, and COVID-19-specific vaccination history, and for the COV participants only, information about COVID-19 symptoms. At the laboratory session, the COV participants were asked to recall symptoms experienced during their first acute infection of COVID-19 via a 22-item symptom list (Supplementary Table 1) that included the most common symptoms identified by the Centers for Disease Control and Prevention. In addition, the COV participants were asked a yes/no question if they felt as though they had returned to their pre-COVID-19 state of health, and if not, they were surveyed about any new or persistent symptoms from the symptom list. The same questionnaire was included in the follow-up online survey for the COV participants (May–June 2024), including information on any new vaccinations and any new or persistent symptoms if applicable.

2.5 Physical activity questionnaire

PA levels were quantified using the International Physical Activity Questionnaire—Short Form (IPAQ-SF) (43). The IPAQ-SF is a self-reported seven-item questionnaire that asked about the previous 7 days and provided data on the different intensities of PA (i.e., vigorous, moderate, and walking) with appropriate examples of each and sitting time that people do as part of their daily lives. Self-reported minutes per week spent in each intensity (sitting is reported in minutes per day) were reported and contributed to the estimation of total PA in metabolic equivalent of task (MET) min week (total METs) using the IPAQ-SF. Participants filled out the IPAQ-SF for three time points: (1) retrospective recall of their PA prior to COVID-19 infection during an average week (COV only) administered at the laboratory session (25, 44), (2) previous 7 days of activity from the date (COV and CON) of the laboratory session, and (3) online follow-up survey in reference to their previous 7 days of activity from that date (COV only). Duration values from the IPAQ-SF were limited to a maximum of 180 min/day to reduce outliers according to guidelines (45, 46). For total METs and sitting time, the medians with interquartile ranges were reported according to guidelines (46).

2.6 Accelerometry to measure physical activity

PA was also quantified with a wearable device (ActiGraph GT3X+, FL, USA) that was distributed to all the participants (COV and CON) at the conclusion of the laboratory session. The participants were instructed to wear the device on the provided belt over the non-dominant hip for 7 days minus sleeping times (including naps) and water exposure (e.g., bathing, swimming). Upon completion of the 7-day wear, the device was returned to the laboratory for analysis. Participants were also provided with an activity log to aid in the validation and analysis of the data. Accelerometer wear time data were checked against the participant-recorded wear times from the log sheet, and only valid days (>10 h of wear time per day) were included in the analysis. Analysis was completed in ActiLife software (version 6.13.4) for average minutes per day completed for sedentary (≤ 99 activity counts/min), light (100–1,951 activity counts/min), and moderate-vigorous physical activity (MVPA) ($\geq 1,952$ activity counts/min) (47) and average step count per day.

2.7 Statistical analysis

Prior to analysis, variables were screened for normality using the Shapiro–Wilk test to assess data for normal distribution in addition to visual inspection of Q–Q plots and evaluation of skewness and kurtosis. In addition, variables were screened for linearity using Levene's test to assess the data to ensure homogeneity of variances. To verify the accurate matching of

pairs between COV and CON participants, paired samples *t*-tests or Wilcoxon signed-rank tests were performed as appropriate on the matching criteria of age and BMI in addition to other variables from the participant demographics. Further analysis into the differences between these pairs for PA variables from the measured accelerometer and IPAQ-SF was completed accordingly. Comparisons between groups based on sex for participant descriptors were completed with independent samples *t*-tests or Mann–Whitney *U*-tests as appropriate. To determine the PA levels in the COV participants and any changes over time, two separate mixed-model repeated-measures analysis of variance (ANOVA) procedures examined the individual between-subject (BS) effects of sex or the persistence of symptoms on the within-subject (WS) difference in self-reported PA intensity variables at the time points and the interaction of these two accordingly to determine if the effect of time differed between subjects. Follow-up analyses were planned to determine the difference between subjects using unadjusted Mann–Whitney *U*-tests to assess differences between the sexes or the persistence of symptoms between time points for the PA intensity and total METs variables obtained from the IPAQ-SF. Spearman correlation analyses were conducted to examine relationships between variables of PA and persistent symptoms, and correlation coefficients were calculated to assess the strength and direction of these relationships. Data are reported as means \pm standard deviation (SD) and median and interquartile range. Statistical significance was set at $p < 0.05$. Data were analyzed using Statistical Package for the Social Sciences software (SPSS version 29.0.0.0, IBM, New York, NY, USA) and GraphPad Prism (version 10.0.0 for Windows, GraphPad Software, Boston, MA, USA).

3 Results

3.1 Participants and baseline measurements

In total, 64 COV participants (40 ± 18 years, 45 female and 19 male participants) completed the laboratory session between February 2021 and October 2022 (8.5 ± 4.7 months after infection). The characteristics of the COV participants are reported in Table 1. Furthermore, 51 participants (80% of the COV cohort) were tested in 2021 and 13 participants (20%) in 2022. Participants identified as Caucasian (95%) or Asian (5%) and non-Hispanic (94%) or Hispanic (6%). Compared with the female participants, COV male participants were taller with greater body mass and similar BMI, lower body fat percentage, higher systolic blood pressure, and lower resting heart rates (Table 1).

A subset of 43 of the 64 COV participants (67%) (46 ± 18 years, 28 female and 15 male participants) completed the online follow-up survey between May 2024 and June 2024 (51.0 ± 39.7 months, i.e., 4.25 years after infection).

Moreover, 22 of the 64 COV participants (35 ± 16 years, 16 female and 6 male participants) were matched for age, sex, and BMI with CON participants. The characteristics of the matched pairs are reported in Table 2. The matched pairs completed the

TABLE 1 COV participant characteristics—comparisons between female and male participants.

| Variable | Total | Female | Male | Sig. (p) |
|---------------------------|-------------|-------------|-------------|---------------------|
| <i>n</i> , count (%) | 64 | 45 (70%) | 19 (30%) | — |
| Age (years) | 40 ± 18 | 37 ± 17 | 45 ± 20 | 0.236 |
| Age group, count (%) | | | | — |
| Young adult (18–39 years) | 36 (56%) | 28 (62%) | 8 (42%) | |
| Middle age (40–59 years) | 16 (25%) | 11 (25%) | 5 (26%) | |
| Older adult (60+ years) | 12 (19%) | 6 (13%) | 6 (32%) | |
| Height (cm) | 170.3 ± 8.6 | 167.0 ± 6.1 | 178.3 ± 8.3 | <0.001 ^a |
| Weight (kg) | 73.6 ± 15.7 | 70.0 ± 14.0 | 82.1 ± 17.0 | 0.004 ^a |
| BMI | 25.3 ± 4.7 | 25.1 ± 5.1 | 25.6 ± 3.9 | 0.485 |
| BMI category, count | | | | — |
| Underweight (<18.5) | 2 | 2 | 0 | |
| Normal weight (18.5–24.9) | 29 | 22 | 7 | |
| Overweight (25–29.9) | 24 | 15 | 9 | |
| Obese (≥30) | 9 | 6 | 3 | |
| Body fat (%) | 29.3 ± 8.4 | 32.5 ± 7.5 | 21.8 ± 4.7 | <0.001 ^a |
| Systolic BP (mmHg) | 122 ± 17 | 118 ± 15 | 130 ± 20 | 0.010 ^a |
| Diastolic BP (mmHg) | 75 ± 11 | 74 ± 10 | 76 ± 13 | 0.600 |
| Resting HR (bpm) | 67 ± 12 | 69 ± 12 | 61 ± 10 | 0.021 ^a |

Data are represented as mean ± standard deviation unless otherwise mentioned.

^aStatistically significant differences between male and female participants (sex effect, $p < 0.05$).

TABLE 2 Matched participant characteristics of COV and CON ($n = 22$ pairs).

| Variable | COV | CON | Sig. (p) |
|---------------------------------|---------------------------|---------------------------|--------------------|
| <i>n</i> | 22 | 22 | — |
| Sex, count (%) | F, 16 (73%) M, 6 (27%) | F, 16 (73%) M, 6 (27%) | — |
| Age (years) | 35 ± 16 | 36 ± 16 | 0.072 |
| Age group, count (%) | | | — |
| Young adult (18–39 years) | 14 (64%) | 14 (64%) | |
| Middle age (40–59 years) | 6 (27%) | 6 (27%) | |
| Older adult (60+ years) | 2 (9%) | 2 (9%) | |
| Height (cm) | 168.2 ± 6.6 | 168.1 ± 7.7 | 0.920 |
| Weight (kg) | 66.1 ± 9.1 | 64.0 ± 9.6 | 0.042 ^a |
| BMI | 23.4 ± 3.0 | 22.6 ± 2.6 | 0.114 |
| BMI category, count | | | — |
| Underweight (<18.5) | 0 | 1 | |
| Normal weight (18.5–24.9) | 14 | 15 | |
| Overweight (25–29.9) | 8 | 6 | |
| Obese (≥30) | 0 | 0 | |
| Body fat (%) | 24.7 ± 8.8 | 23.8 ± 7.6 | 0.439 |
| Systolic blood pressure (mmHg) | 121 ± 16 | 121 ± 16 | 0.848 |
| Diastolic blood pressure (mmHg) | 72 ± 12 | 73 ± 9 | 0.540 |
| Resting heart rate (bpm) | 66 ± 11 | 66 ± 14 | 0.951 |

Data are represented as mean ± standard deviation unless otherwise mentioned.

^aStatistically significant differences between pairs ($p < 0.05$).

laboratory session 2.0 ± 1.6 months apart between February 2021 and April 2022 and as expected, did not differ in age, sex, or BMI. In addition, there was no difference between pairs for height, body fat percentage, resting blood pressure, or resting heart rate. However, the COV participants were 2.1 kg heavier than the CON participants (Table 2). At the laboratory session, all the matched CON participants ($n = 22$) and 16 of the 22 COV participants reported being vaccinated against COVID-19.

Upon completion of the follow-up survey, three of these COV individuals reported being vaccinated sometime after completing the laboratory session.

3.2 COVID-19 history

The COV participants reported a wide range of symptoms affiliated with COVID-19 at three different time points including (1) during acute COVID-19 infection, (2) at the laboratory session (8.5 months on average after infection), and (3) during the follow-up survey (4.25 years on average after infection). All the COV participants reported at least one symptom during the acute infection.

Of the 64 COV participants, 34 (53%) reported persistent symptoms at the laboratory session (8.5 months after infection), which was the same for female and male participants (Table 3). The most common symptom reported was fatigue as 57 of 64 COV participants (89%) reported fatigue acutely and 16 of 34 COV participants (47%) reported fatigue 8.5 months after infection when tested at the laboratory session (Figure 1).

Of the 43 COV participants who completed the follow-up survey (4.25 years after infection), 15 (35%) reported persistent symptoms (32% of the female and 40% of the male participants) (Table 3). Furthermore, 29 of the 34 COV participants who reported persistent symptoms at the laboratory session completed the follow-up survey and 14 COV participants continued to report persistent symptoms at 4.25 years (Table 3). The most common symptom reported at the follow-up was fatigue with 5 of 15 COV participants (33%) (Figure 1).

3.3 Physical activity questionnaire (IPAQ-SF) over time

To understand the changes in PA in the COV participants, the IPAQ-SF asked questions about the intensity of PA before COVID-

TABLE 3 Number of COVID-19 survivors with persistent symptoms at 8.5 months and 4.25 years after infection.

| Variable | <i>n</i> (%) |
|---|--------------|
| Laboratory session (8.5 ± 4.7 months) ($n = 64$) | |
| No symptoms | 30 (47%) |
| Female | 21 (47%) |
| Male | 9 (47%) |
| Persistent symptoms | 34 (53%) |
| Female | 24 (53%) |
| Male | 10 (53%) |
| Follow-up (51.0 ± 39.7 months, i.e., 4.25 years) ($n = 43$) | |
| No symptoms | 28 (65%) |
| Female | 19 (68%) |
| Male | 9 (60%) |
| Persistent symptoms | 15 (35%) |
| Female | 9 (32%) |
| Male | 6 (40%) |

The percentages reported are of the total sample and for the number of female or male participants at that time interval of testing.

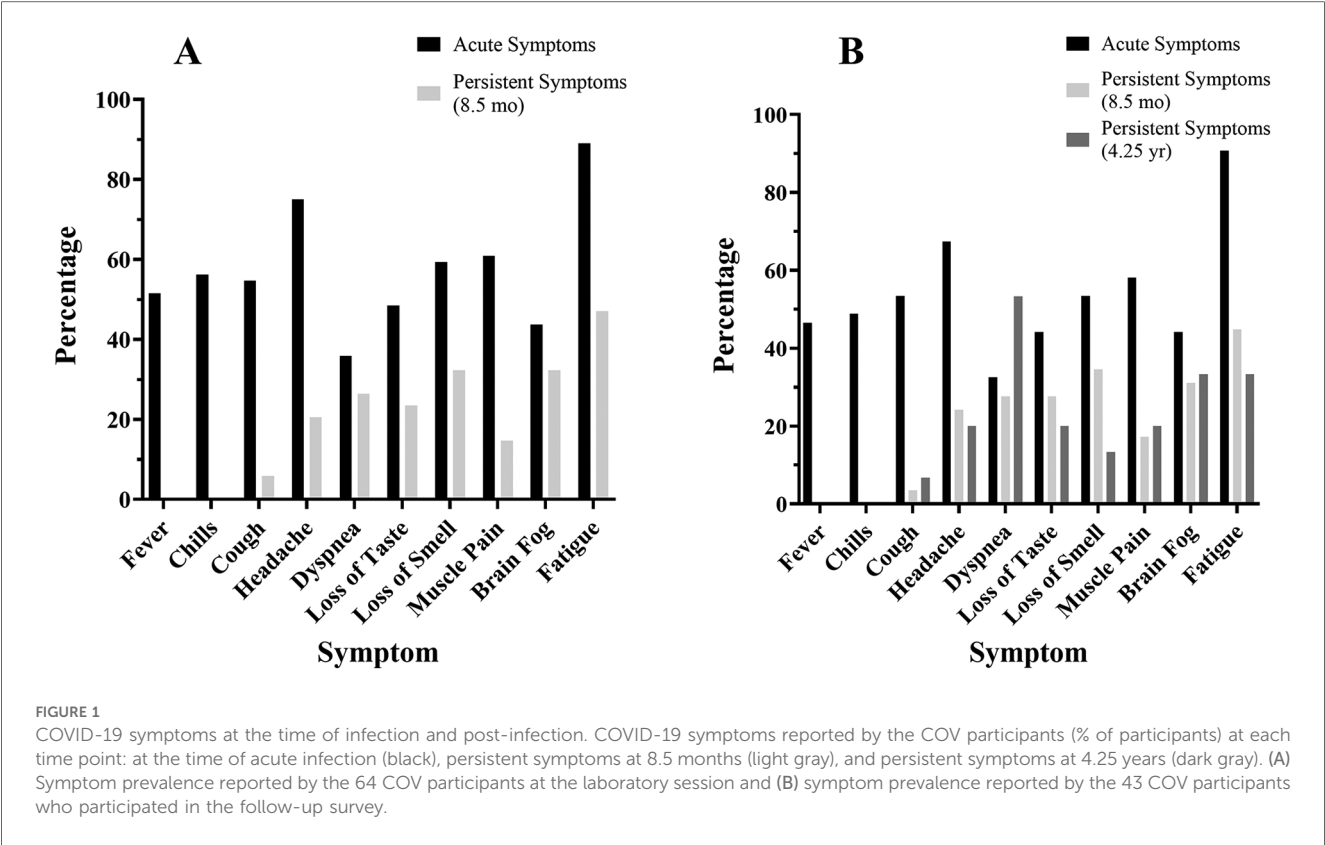


TABLE 4 Self-reported PA questionnaire for COV participants before and after COVID-19 infection.

| PA (min/week) | Pre-COVID-19 infection | | 8.5 months after COVID-19 infection | | 4.25 years after COVID-19 infection | |
|-------------------|------------------------|--------|-------------------------------------|--------|-------------------------------------|--------|
| | <i>n</i> = 64 | | <i>n</i> = 64 | | <i>n</i> = 43 | |
| | Mean ± SD | Median | Mean ± SD | Median | Mean ± SD | Median |
| Vigorous | 228 ± 202 | 180 | 153 ± 152 | 120 | 166 ± 138 | 135 |
| Moderate | 206 ± 174 | 180 | 144 ± 125 | 120 | 151 ± 172 | 120 |
| Walking | 305 ± 236 | 218 | 259 ± 177 | 210 | 285 ± 301 | 150 |
| Total METs | 3,656 ± 1,994 | 3,093 | 2,656 ± 1,483 | 2,314 | 2,875 ± 1,960 | 2,394 |
| Sitting (min/day) | <i>n</i> = 63 | | <i>n</i> = 63 | | <i>n</i> = 43 | |
| | 276 ± 127 | 300 | 297 ± 120 | 300 | 293 ± 139 | 300 |

Data are represented as mean ± standard deviation and median.

19 infection, after COVID-19 infection at 8.5 months, and at a follow-up survey 4.25 years later. PA decreased for the 64 COV participants between pre-COVID-19 infection to 8.5 months after infection. Analysis using unadjusted Wilcoxon signed-rank tests investigating the within-subject effect of time showed that all PA levels were significantly reduced with time in the COV cohort. On average, vigorous PA decreased by 75 min/week (34%, $p < 0.001$), moderate PA by 62 min/week (31%, $p < 0.001$), walking by 46 min/week (15%, $p = 0.027$), and total METs by 1,000/week (27%, $p < 0.001$). Sitting time, however, before and after COVID did not reach statistical significance although it trended in the direction of an increase of 21 min/day (8%, $p = 0.107$) (Table 4).

For the 43 COV participants who completed the follow-up survey 4.25 years after infection, PA levels remained lower than pre-COVID-19 infection reports. On average, moderate PA was

63 min/week (29%, $p = 0.048$) lower at 4.25 years than pre-COVID-19 infection reports (Table 4, Figure 2). However, analysis using unadjusted Wilcoxon signed-rank tests comparing pre-COVID-19 infection reports with PA levels reported at the follow-up showed that the PA levels and sitting time were not significantly reduced.

3.4 Sex differences in physical activity (IPAQ-SF) over time

Changes in PA from before COVID-19 infection to the time of testing in the laboratory session (8.5 ± 4.7 months after infection) for female ($n = 45$) and male ($n = 19$) participants were determined with a mixed-model repeated-measures ANOVA

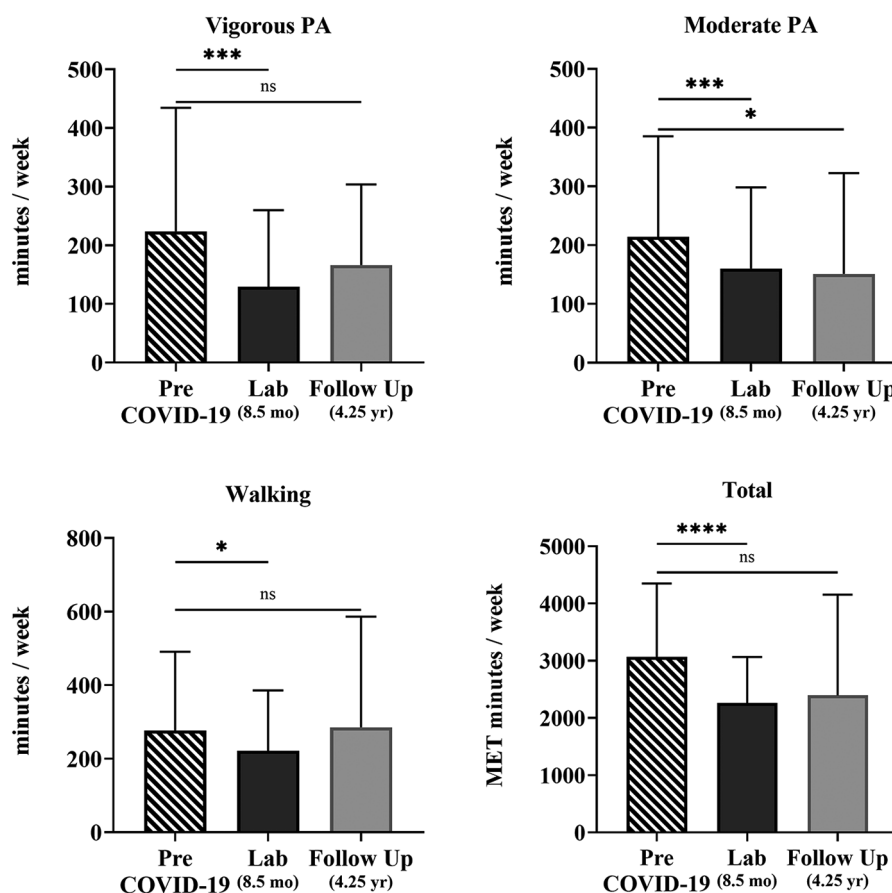


FIGURE 2

Self-reported physical activity over time of the COV participants. Shown are vigorous and moderate PA, walking, and total METs min/week quantified from the self-reported IPAQ-SF questionnaire for 43 COV participants. Shown are the mean \pm SD for all graphs except for total METs, which is presented as a median and interquartile range for each time point: pre-COVID-19 infection (striped), 8.5 months later at the laboratory session (black), and 4.25 years later at the online follow-up survey (gray). The solid lines show the unadjusted effect between individual time points with statistical significance; ns = $p > 0.05$; * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; **** $p \leq 0.0001$.

(Supplementary Table 2). There was a significant interaction of time \times sex for vigorous PA [$F(1,62) = 14.726$, $p < 0.001$, $\eta^2 = 0.192$] and total METs [$F(1,62) = 7.097$, $p = 0.010$, $\eta^2 = 0.103$], indicating that the change between pre-COVID-19 infection and 8.5 months post-COVID-19 infection in both vigorous PA and total METs per week differed by sex. Mann-Whitney U -tests revealed that COV male participants had higher levels of vigorous PA by 192 min/week (72%, $p = 0.002$) and total METs by 1,399/week (36%, $p = 0.017$) than female participants (Figure 3). At 8.5 months post-infection, there were no differences in PA levels between female and male participants. However, sitting time was greater in male than female participants by 66 min/day (21%, $p = 0.039$).

3.5 Physical activity (IPAQ-SF) over time with and without persistent symptoms

Changes in PA from before COVID-19 infection to the time of testing in the laboratory session (8.5 ± 4.7 months after infection)

for the COV participants who reported persistent symptoms ($n = 34$) at 8.5 months and the COV participants who reported no symptoms ($n = 30$) at 8.5 months were determined with a mixed-model repeated-measures ANOVA (Supplementary Table 3). There was a significant interaction of time \times persistence of symptoms for vigorous PA [$F(1,62) = 7.286$, $p = 0.009$, $\eta^2 = 0.105$], moderate PA [$F(1,62) = 5.045$, $p = 0.028$, $\eta^2 = 0.075$], and total METs [$F(1,62) = 8.513$, $p = 0.005$, $\eta^2 = 0.121$], indicating that the change between pre-COVID-19 infection and the laboratory session in these self-reported IPAQ-SF variables differed by the persistence of symptoms (persistent symptoms vs. no symptoms). Mann-Whitney U -tests revealed that the COV participants who reported persistent symptoms at 8.5 months after infection ($n = 34$), in contrast to expectations, reported higher moderate PA levels pre-COVID-19 infection than those who reported no symptoms ($n = 30$) at 8.5 months after infection (Figure 4). Prior to COVID-19 infection, those who reported persistent symptoms at 8.5 months had higher levels of moderate PA (by 98 min/week) than those who did not report symptoms (48%, $p = 0.047$). At 8.5 months post-infection, there were no

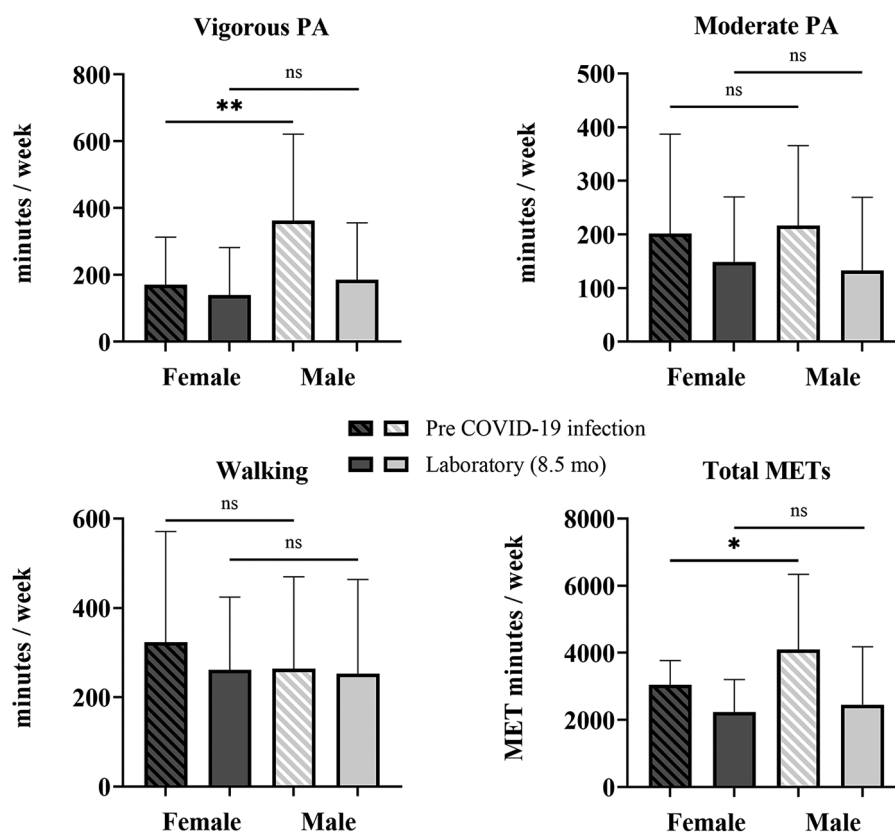


FIGURE 3

Sex differences in self-reported physical activity. Shown are vigorous and moderate PA, walking, and total METs quantified from the self-reported IPAQ-SF questionnaire for COV participants: 45 female and 19 male participants. Shown are the mean \pm SD for all graphs except for total METs, which is presented as a median and interquartile range, where female participants are represented by the darker bars and male participants are represented by the lighter bars at pre-COVID-19 infection (striped) and 8.5 months later at the laboratory session (solid). The solid lines above show the preliminary unadjusted between-subject effect of sex with statistical significance; ns = $p > 0.05$; * $p \leq 0.05$; ** $p \leq 0.01$.

differences in PA levels between those with persistent symptoms at 8.5 months and those without any symptoms at 8.5 months (Figure 4).

persistent symptoms 37 ± 21 min, no symptoms 49 ± 18 min, 28%, $p = 0.014$; steps/day: persistent symptoms $7,915 \pm 3,148$ steps, no symptoms $9,540 \pm 2,286$ steps, 19%, $p = 0.014$.

3.6 Accelerometry to measure physical activity

Of the 64 COV participants, 56 (87.5%) had valid accelerometer data when collected following the laboratory session (8.5 months after infection). Wear times of 5–7 days were included (6.4 ± 0.77 days) and a minimum of 600 min/day was included in the analysis (821 ± 72 min average wear time per day). The COV cohort was divided based on the presence of persistent symptoms ($n = 29$) and those who did not report symptoms ($n = 27$) at the laboratory session (8.5 months after infection). There were no differences in sedentary time per day (persistent symptoms 510 ± 66 min, no symptoms 504 ± 55 min, $p = 0.717$) or light activity (persistent symptoms 254 ± 76 min, no symptoms 290 ± 63 min, $p = 0.063$) between the groups. However, there were higher levels of activity and greater step counts in the COV participants who reported no persistent symptoms (MVPA:

3.7 Accelerometry comparisons between COV and matched CON participants

To address the hypothesis that PA would be lower in the COV participants ($n = 22$) compared with matched CON participants ($n = 22$), PA from accelerometry was compared at 8.5 months after infection (time of testing of the laboratory session). Participant wear times for days worn (COV 6.3 ± 1.0 days, CON 6.6 ± 0.58 days) and minutes/day worn (COV 805 ± 62 min, CON 835 ± 79 min average wear time per day) are provided. There were no differences in activity levels between the COV and CON cohorts for light activity (COV 257 ± 69 min, CON 262 ± 57 min, $p = 0.829$), MVPA (COV 40 ± 23 min, CON 45 ± 25 min, $p = 0.455$), or steps per day (COV $8,768 \pm 3,493$ steps, CON $9,514 \pm 3,774$ steps, $p = 0.367$). In addition, there were no differences between COV and CON participants in sedentary time per day (COV 507 ± 64 min, CON 528 ± 60 min, $p = 0.185$).

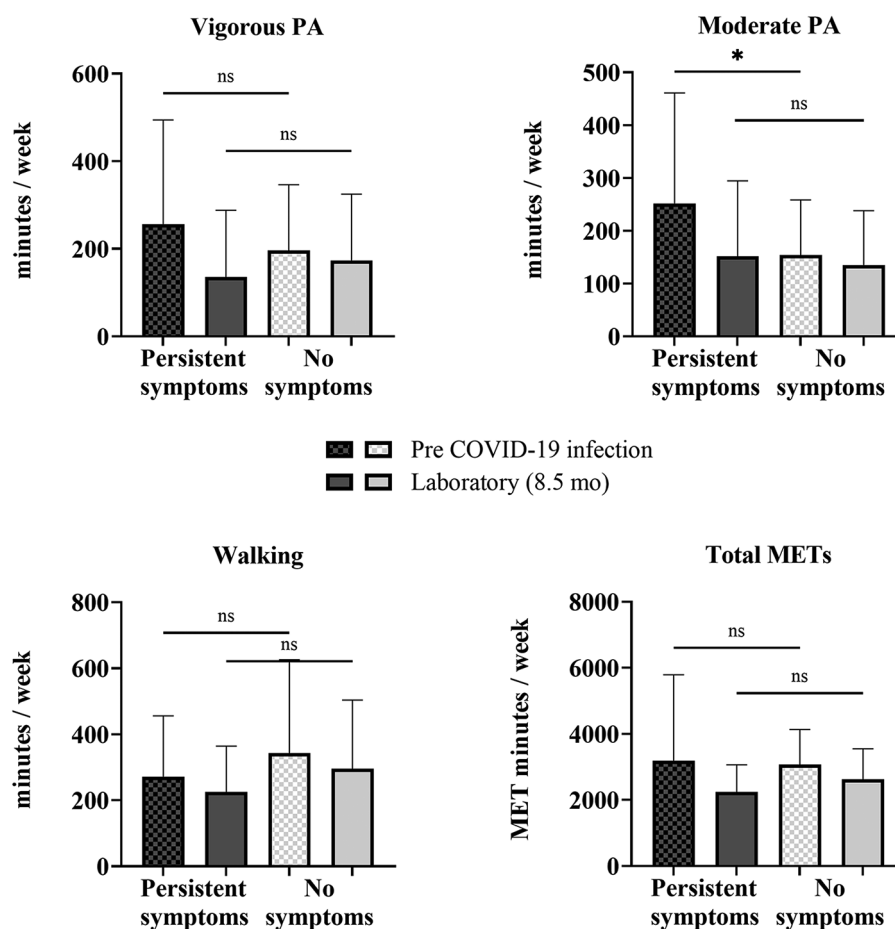


FIGURE 4

Self-reported physical activity between COV participants with and without persistent symptoms. Shown are vigorous and moderate PA, walking, and total METs quantified from the self-reported IPAQ-SF questionnaire for COV participants: 34 with persistent symptoms at 8.5 months and 30 with no symptoms at 8.5 months. Shown are the mean \pm SD for all graphs except for total METs, which is presented as a median and interquartile range, where the COV participants with persistent symptoms are represented by the darker bars and COV participants without symptoms are represented by the lighter bars at pre-COVID-19 infection (checkered) and 8.5 months later at the laboratory session (solid). The solid lines above show the preliminary unadjusted between-subject effect of sex with statistical significance; ns = $p > 0.05$; * $p \leq 0.05$.

The COV cohort was divided based on the presence of persistent symptoms ($n=14$) and those who did not report symptoms ($n=8$) at the laboratory session (8.5 months after infection), and matched with CON participants ($n=22$) (Figure 5). One-way ANOVA analysis showed there were no differences between the groups for light activity: $[F(2,43) = 0.134, p = 0.875]$, MVPA $[F(2,43) = 2.645, p = 0.083]$, sedentary time/day $[F(2,43) = 1.167, p = 0.322]$, or steps/day $[F(2,43) = 0.864, p = 0.429]$. However, when separate analyses were completed in the COV cohort to compare those with persistent symptoms ($n=14$) and those who reported no symptoms ($n=8$) at the laboratory session, MVPA was lower in those with persistent symptoms by 22 min/week (51%, $p = 0.006$). Interestingly, when the average MVPA/day completed was estimated per week by multiplying by 7 days, all eight (100%) of the COV participants who reported no symptoms met the PA guidelines of at least 150 min/week at 8.5 months. In contrast, nine of the COV participants (64%) with persistent symptoms met the guidelines.

3.8 Comparisons between measures of physical activity

Self-reported PA from the IPAQ-SF was also compared between COV ($n=22$) and CON ($n=22$) participants when captured at 8.5 months post-COVID-19 infection. There were no differences in self-reported activity levels or sitting time between the COV and CON cohorts. Comparisons were made between accelerometry and self-reported PA levels in COV and CON participants. The IPAQ-SF calculates the average minutes per week of MVPA and the accelerometer analysis calculates the average MVPA per day. To compare these variables, the IPAQ-SF average minutes per week of MVPA was divided by 7 days as an estimate to make a comparison with the average MVPA per day. Self-reported daily MVPA was comparable to daily MVPA measured via accelerometry (COV: self-reported 41 ± 28 min, accelerometer 40 ± 23 min, $p = 0.894$; CON: self-reported 55 ± 39 min, accelerometer 45 ± 25 min, $p = 0.196$).

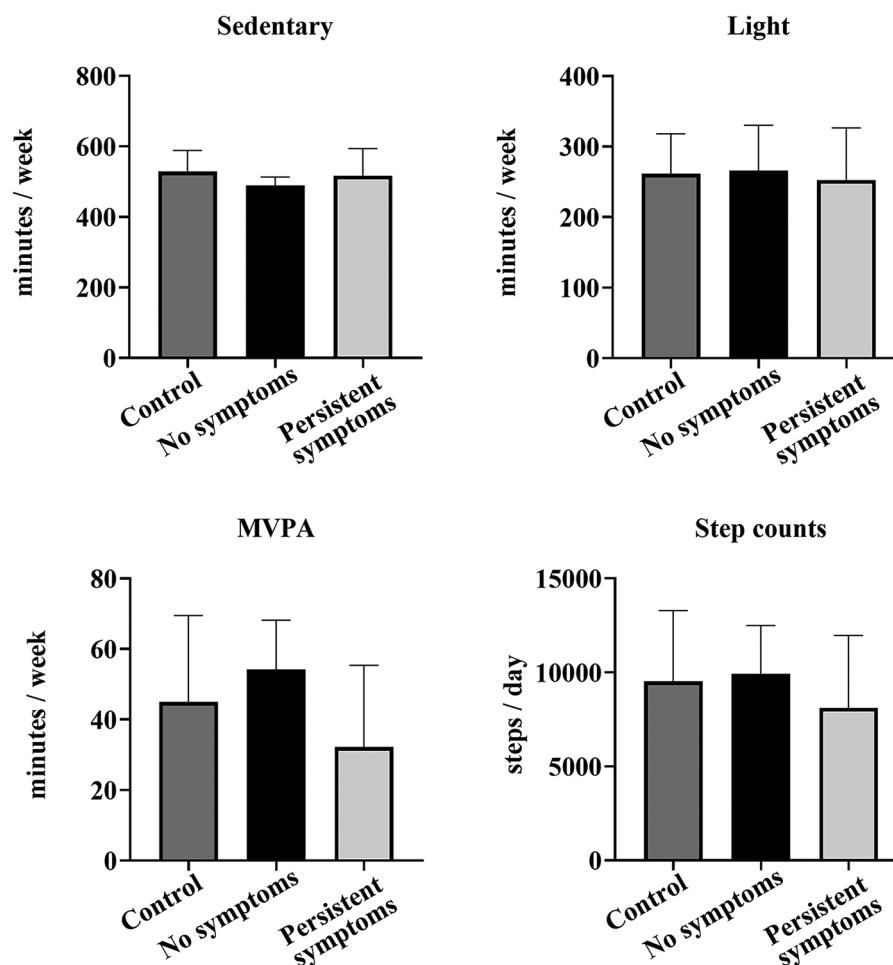


FIGURE 5

Comparison of accelerometry between the COV and CON participants. Shown are sedentary, light PA, MVPA, and step counts per day measured by accelerometry for 22 CON participants (dark gray), 8 COV participants without any symptoms at the laboratory session (black) (8.5 months after infection) and 14 COV participants with persistent symptoms at the laboratory session (light gray) (8.5 months after infection). Shown are the mean \pm SD for all graphs.

3.9 Associations between measures of physical activity and persistent symptoms

Correlation analyses were conducted to assess the relationship between the number of symptoms reported by the COV participants ($n=64$) during the acute infection and at the laboratory session (8.5 months after infection) and self-reported PA measures (IPAQ-SF). There were no significant correlations between pre-COVID-19 infection PA levels and the number of acute symptoms or with the number of persistent symptoms at 8.5 months, suggesting that pre-COVID-19 infection PA levels were not protective for acute COVID-19 or long COVID symptoms. However, associations were found at 8.5 months post-infection between vigorous PA ($r_s = -0.250$, $p = 0.046$) and total METs ($r_s = -0.264$, $p = 0.035$) with the number of persistent symptoms, suggesting that lower PA levels are associated with more persistent reported symptoms when assessed at 8.5 months. Additional analyses found no association between the number of

symptoms reported by the COV participants ($n=43$) at 4.25 years after infection (online follow-up) and any of the IPAQ-SF variables.

Furthermore, in the COV participants ($n=56$), there were negative associations between the number of symptoms and MVPA ($r_s = -0.283$, $p = 0.034$) and steps per day ($r_s = -0.340$, $p = 0.010$) measured with accelerometry, providing further evidence to suggest that lower PA levels are associated with more persistent symptoms at 8.5 months post-infection.

4 Discussion

The aims of this study were to determine the impact of the COVID-19 pandemic on PA levels and the influence of PA on acute and persistent symptoms of non-hospitalized COVID-19 survivors. We hypothesized that (1) PA levels would decrease following acute COVID-19 infection but recover over time, (2)

PA levels would be lower in COV participants than matched CON participants, and (3) those who reported higher PA levels prior to infection would have the greatest protection against long COVID. We found that our sample of non-hospitalized COVID-19 survivors experienced a decline in reported PA levels with acute infection and at 8.5 months on average after infection. However, when reassessed 4.25 years on average after infection, PA levels were largely restored to pre-pandemic levels. The decline in PA at 8.5 months after infection for the COV participants was also experienced in the matched controls who were tested at the same time during the pandemic. This suggests that the stay-in-place orders and the pandemic itself resulted in a reduction in activity levels for many people whether or not they had been infected with COVID-19. Interestingly, 53% of our COV cohort experienced at least one long COVID symptom (the most common was fatigue) at 8.5 months post-infection, and 35% of the sample did at the 4.25-year follow-up. Contrary to our hypothesis, those who were most active prior to COVID-19 infection were not protected against long COVID. We found that COVID-19 infection and persistent symptoms impacted people who participated in high-intensity PA prior to infection (self-reported and accelerometry). Finally, male participants and those with persistent symptoms at the laboratory session (8.5 months post-infection) had greater reductions in PA levels following COVID-19 infection than female participants and those reporting no persistent symptoms.

4.1 Persistent symptoms of COVID-19 were prevalent in non-hospitalized COV participants

Self-reported symptoms for the acute infection phase showed that, as expected, the COV participants experienced fatigue, headache, muscle pain, loss of smell, chills, cough, and fever. However, 8.5 months on average after acute infection, 53% of the COV non-hospitalized participants reported persistent symptoms. The most common symptoms reported at this time were fatigue, brain fog, loss of smell, and dyspnea. In addition, in a follow-up survey 4.25 years after acute infection, 35% of the participants reported persistent symptoms that included dyspnea, fatigue, and brain fog. These findings are consistent with the Centers for Disease Control and Prevention for common symptoms acutely and persistently (3, 7). In an international online survey of 3,762 participants with COVID-19, 65% of respondents experienced persistent symptoms for at least 6 months and the most common persistent symptoms were fatigue, cognitive dysfunction, headaches, and memory issues (48). While few studies have followed patients more than 1 year after infection and none have done so in non-hospitalized COVID-19 survivors, one study of previously hospitalized patients with long COVID reported that in 199 patients, the most common symptoms at 26 months after infection were fatigue, shortness of breath, and loss of smell and taste (49). Our findings indicate that even in non-hospitalized COVID-19 survivors, over 1/3 of the cohort (35%) reported

experiencing persistent symptoms up to and over 4 years post-infection.

4.2 Physical activity levels declined during the pandemic

Overall, self-reported PA declined from pre-COVID-19 infection levels to 8.5 months following infection with COVID-19 with the greatest declines in higher PA intensities (34% decrease in vigorous intensity PA and 31% decrease in moderate-intensity PA). When PA was assessed again 4.25 years following infection in the same individuals, PA levels remained lower than pre-COVID-19 infection reports where vigorous PA was 26% lower and moderate PA was 29% lower. These findings were similar to Dunton et al. who reported a 35% decrease and 46% decrease in vigorous and moderate PA, respectively, measured with the IPAQ-SF from pre-COVID-19 pandemic (February 2020) to 2 months later (April 2020) (44). Other studies reported that the most active individuals had the highest decrease in vigorous PA when compared with less active individuals (50, 51). Our findings align with these studies, despite our participants being non-hospitalized and generally more active overall.

While the self-reported questionnaire data indicated activity levels declined in the COV participants at 8.5 months, we also showed no differences in activity levels between the matched controls and COVID-19 survivors in the self-report questionnaire and accelerometry data. This important finding suggests that the decline in activity levels was global and due to the pandemic and not exclusive to prior COVID-19 infection. We further examined this with the accelerometry data, comparing the COV participants with persistent symptoms to those without symptoms and to CON participants: the lack of differences in activity between the groups confirms that the pandemic had a large effect by lowering activity levels population-wide.

4.3 Effect of persistent symptoms on activity levels

The COV participants who reported persistent symptoms had reduced levels of PA. A comparison of accelerometry data between COV participants with persistent symptoms and those without showed that those with persistent symptoms engaged in less MVPA. The Physical Activity Guidelines for Americans recommend that healthy adults (18–65 years) should participate in at least 150 min of moderate-intensity physical activity each week (30). Despite the health benefits, ~47% American adults do not meet these exercise guidelines (30). From the measured accelerometer data in 22 COV participants and 22 matched CON participants, we found that 77% of our sample met PA guidelines, indicating overall that our sample was highly active. We also showed that for activity assessed with accelerometry, 100% of the COV participants who reported no symptoms met the PA guidelines whereas only 64% of those with persistent symptoms met them. This finding further shows that even in a

highly active group, persistent symptoms had an impact, resulting in lower PA levels at even 8.5 months after infection.

In addition, in contrast to expectations, people with persistent symptoms at 8.5 months after infection self-reported higher moderate PA levels pre-COVID-19 infection than those who reported no symptoms at 8.5 months after infection. This was surprising because we expected that people who were the most active prior to COVID-19 infection would be protected against long COVID. Previous studies in the literature on acute COVID-19 infection and the risk of hospitalization due to COVID-19 have shown that inactivity was the strongest risk factor of hospitalization, ultimately suggesting that PA may be protective against acute infection (21, 31, 32). Activity levels prior to infection, therefore, are not protective against long COVID symptoms, suggesting activity-related mechanisms that protect against other chronic diseases are not relevant to long COVID.

4.4 Limitations

There are several limitations in this study. First, both groups of participants in our study were highly active and may not be representative of the general American population. Our participants were primarily Caucasian and non-Hispanic, yet Black and Hispanic populations experienced disproportionately higher rates of COVID-19 infection and related mortality (52). In addition, the COVID-19 pandemic impacted the most disadvantaged populations concerning the social determinants of health, which were not explored in this study (53). Further, there is no measurable clinical tool currently available to diagnose long COVID and therefore self-reported symptoms were reported. There is a need to establish a quantifiable tool that considers the prevalence and duration of long COVID (54). In addition, there may have been a self-selection bias because COVID-19 survivors with persistent symptoms were likely more inclined to participate in the laboratory session and the subsequent follow-up survey. Finally, self-reported measures of activity levels (IPAQ-SF) may be higher compared with data from accelerometry. In addition, the use of retrospective self-reported measures to assess activity levels prior to COVID-19 infection may have introduced reporting biases with the IPAQ-SF.

5 Conclusion

This study is the first to our knowledge to study and understand physical activity engagement and persistent symptoms in non-hospitalized COVID-19 survivors roughly 4 years after infection. We showed that activity levels were reduced likely as a result of the pandemic even 8.5 months after infection in the COV participants and healthy matched controls who had no known prior COVID-19 infection. However, even those who reported high levels of activity prior to COVID-19 infection experienced persistent symptoms and hence activity was not protective against long COVID. Fatigue was notably the most

common symptom across all time points and even at just over 4 years post-infection. Health professionals and researchers should not overlook COVID-19 survivors who were not hospitalized for their infection of COVID-19 as these individuals continue to experience persistent symptoms that impact engagement in activity. Finally, male participants and people with persistent symptoms of long COVID had the greatest reduction in activity levels. Conducting longitudinal studies on non-hospitalized COVID-19 survivors who represent the majority of those affected by COVID-19 infection will be important to understand the lasting impact of activity levels in more diverse populations.

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 humans were approved by Marquette University Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

LEO: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing, Data curation. TDU: Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. MHH: Investigation, Methodology, Project administration, Writing – review & editing. RNB: Data curation, Investigation, Writing – review & editing. LMMC: Investigation, Writing – review & editing. KMK: Formal analysis, Writing – review & editing. REB: Methodology, Writing – review & editing. MJD: Methodology, Writing – review & editing. LBP: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. MHB: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. PEP: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. SKH: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fspor.2025.1560023/full#supplementary-material>

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EDITED BY

David Broom,
Coventry University, United Kingdom

REVIEWED BY

David Arthur Hart,
University of Calgary, Canada

*CORRESPONDENCE

Kathleen E. McKee
✉ kathleen.mckee@imail.org

[†]These authors have contributed equally to this work

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Parkinson's Elevated: improving healthspan

Kathleen E. McKee^{1*}, Miriam R. Rafferty^{2,3†}, Theadora W. Sakata^{1,4,5†}, David M. Hedges⁶, Garrett J. Griffith⁷, Maddison M. K. Bingham¹, Stephanie A. Obradovich⁸, M. Nicholas Francis⁹ and Daniel M. Corcos⁷

¹Department of Neurology, Intermountain Medical Center Neurosciences Institute, Intermountain Health, Salt Lake City, UT, United States, ²Shirley Ryan AbilityLab, Chicago, IL, United States, ³Department Physical Medicine & Rehabilitation, Northwestern University, Chicago, IL, United States, ⁴Department of Family Medicine, Intermountain Health, Salt Lake City, UT, United States, ⁵Healthcare Delivery Institute, Intermountain Health, Salt Lake City, UT, United States, ⁶Department of Analytics, Select Health, Salt Lake City, UT, United States, ⁷Department of Physical Therapy and Human Movement Sciences, Northwestern University, Chicago, IL, United States, ⁸Neurologic Physical Therapy, Intermountain Park City Hospital, Park City, UT, United States, ⁹Lifestyle Medicine and Wellness Center, Intermountain Park City Hospital, Park City, UT, United States

As Parkinson's disease (PD) progresses, relatively mild symptoms advance to a major disorder that affects every organ system in the body. Current care for people with PD (PwP) reacts to rising disability. There is a missed opportunity to keep PwP as healthy as possible. In this perspective, we spell out our vision for a proactive, value-based health care model built around a patient-centered integrated practice unit (IPU) for PD. The IPU will provide integrated interdisciplinary care overseen by a specialized Parkinson's primary care physician working closely with a movement disorders neurologist. The IPU will implement an evidence-based exercise program for people early in the disease. The focus of this intervention is a heart rate driven high-intensity aerobic exercise program, which is the only treatment with evidence that it can slow disease progression. It will also include resistance exercises, flexibility exercise and balance exercise. For people whose disease is moderate or severe, the IPU will provide care curated through a network of rehabilitation providers with expertise in PD all of whom understand the exercise prescription. By integrating care, slowing disease progression, and incorporating specialized rehabilitation we anticipate improving healthspan. In creating the IPU as a fully capitated (shared-risk) model in which the IPU and the insurance company assume joint accountability for quality and cost of care we anticipate demonstrating financial sustainability of implementing the exercise prescription and providing integrated care.

KEYWORDS

Parkinson's disease, healthspan, integrated practice unit, proactive care, high-intensity aerobic exercise

1 Introduction

The dominant narrative of Parkinson's disease (PD) in the United States is one of rising disability managed reactively through a fragmented healthcare system (1). The first goal of this perspective is to propose a new narrative: one that keeps people with PD (PwP) healthy. This is accomplished through an integrated proactive model that extends healthspan. Healthspan is defined as the period of life spent with relatively good physical and mental function (2). The second goal of this perspective is to make clear that financial incentives must be realigned to support what is best for the patient,

not what is best for the health system, physician, or insurance company. Without such realignment the new model of care we propose will never be financially viable.

We suggest an Integrated Practice Unit (IPU) (3, 4) as a vehicle through which financial incentives can be harmoniously aligned with best clinical practice. In an IPU the health providers and the insurance company share joint accountability for quality and cost of care. Integrated care is already a suggested best practice in PD (1, 5, 6) and there are centers across the United States providing at least partially integrated services. These include The Struthers Parkinson's Center in Minnesota and the Neuromedicine Service and Science Hub Model at the University of Florida (7). Parkinson's Foundation Centers of Excellence also provide more comprehensive care than most clinics. Yet, none of these centers exist as Integrated Practice Units in the true definition of the term because none have assumed joint accountability for quality *and* cost of health care (8). Through examples from our ongoing efforts to implement the *Parkinson's Elevated* IPU at Intermountain Health in Salt Lake City, UT we highlight real-world barriers and solutions to completely reshaping the narrative of PD from one of disability to health.

2 Current problems in the Parkinson's journey

Clinical care for PD unfolds under a chronic illness model in which the patient-physician dyad reacts to symptoms as they arise (9). We worked with our Parkinson's Patient Family Advisory Committee (PFAC) and reviewed the literature to better understand the current state of PD care in the United States. Our patients and their carers shared that many PD journeys start with a diagnostic odyssey in which the patient sees various specialists (e.g., orthopedist for 'frozen shoulder,' gastroenterologist for severe constipation, primary care for tremor) before enough motor symptoms manifest to raise the possibility of parkinsonism as a root cause for all symptoms. The subsequent delivery of the diagnosis is notoriously poor; one member of our PFAC shared that after her abrupt diagnosis, she was left so unsupported by her care team that she lost two years in unfounded despair because she thought her life was over. Her experience has been echoed in published reports (10, 11).

In those initial years after diagnosis, patients are prescribed dopamine replacement therapy and managed at ~3–6-month intervals by neurologists. Review of the literature reveals that these patients are lucky to even see a neurologist. Wait times for neurologic care are high and according to Medicare claims data one-third of people with PD do not receive any regular neurologic care (12). PwP are generally sent to physical therapy (PT) only if they have impaired balance or gait, with utilization increasing only as the disease progresses (13). They might be told verbally that exercise is important for PD, but little is done to reinforce or support this. Referrals to sub-specialists such as sleep medicine, gastroenterology, and urology may be placed to address non-motor symptoms of the disease, but patients are left on their own to navigate between these providers (11). Patients

are also expected to coordinate their care between their neurologist and their primary care physician (PCP).

It is only when disability increases and patients start falling and aspirating that services escalate: more referrals to PT/occupational therapy/speech-language pathology, more frequent primary care and neurology visits (13). Inevitably, an event such as pneumonia or hip fracture necessitates inpatient admission; the literature confirms PwP are more likely to have unplanned hospital admissions than their age-matched peers (14). From there, PwP are less likely to return to their pre-morbid place of residence and have higher in-hospital mortality than their age matched peers (15). Finally, when PwP transition to hospice they usually have no further contact with their movement physician and PCP as per hospice regulations.

3 The ideal Parkinson's journey

After exploring problems with the current state of care, our PFAC helped us map the ideal journey (Figure 1), which we then separated into four main stages. Starting at the very earliest point, when someone is at risk for PD but has no pathology, they need **Prevention** or delay of disease. Once someone has clinically relevant symptoms such as rapid eye movement sleep behavior disorder (16), they need a rapid **Early Diagnosis** and referral to a Parkinson's IPU. There have been several very promising advances in how to detect Parkinson's earlier and with greater certainty. They include: (1) CSF biomarkers (17) (2) alpha synuclein skin biopsies (18) and (3) advanced brain imaging techniques and artificial intelligence (19). The earlier a person is diagnosed, and the earlier a person receives comprehensive healthcare, the better the prognosis. Diagnosing PD early is important because it allows initiation of disease modifying treatment as early as possible and reduces unnecessary suffering, healthcare utilization and cost.

The remaining phases of a person's journey take place within the IPU: first **Healthspan Promotion and Maintenance** (the longest phase of the journey spanning several decades and including different forms of rehabilitation) and finally, the **Dignified Endgame** in which hospice care is provided as part of the IPU. We take the term 'Endgame' from Samuel Beckett's drama of the same name (20). Our PFAC members expressed appreciation for the use of this term because it clearly describes a phase they know is coming and should be approached with care and compassion. Such candid acknowledgment facilitates preparation for and control of their own end-of-life plans.

For the rest of this paper, the focus is exclusively on the care that unfolds within the IPU (**Healthspan Promotion and Maintenance** and **Dignified Endgame**)– the vehicle through which we propose to provide financially sustainable proactive integrated health care.

4 The integrated practice unit

First described in 2013 by Porter and Lee, an IPU provides care organized around a medical condition or set of closely related

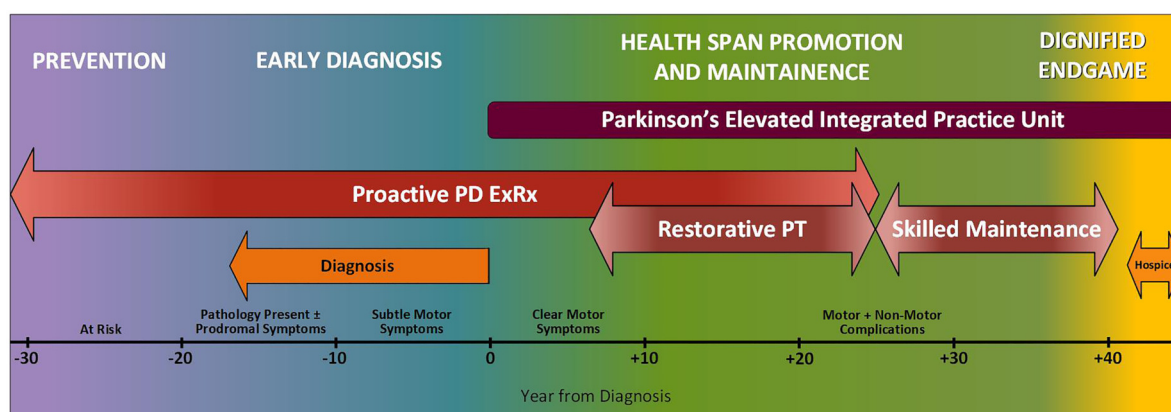


FIGURE 1

Ideal journey of a person with Parkinson's disease. The ideal journey will accelerate diagnosis, extend the healthspan, and make the endgame shorter and more meaningful.

conditions that is delivered by a dedicated and connected multidisciplinary team who assume joint accountability for quality and cost of care (3, 4). In the *Parkinson's Elevated IPU*, we will provide integrated proactive and reactive care. Strategic, insight-driven proactive care will reduce the likelihood of needing complex, expensive reactive care. Outcomes that matter to the patient will serve as our barometer of clinical success. Existing outcome measure sets are compared elsewhere (21) but, in brief, the *Parkinson's Elevated IPU* will deploy fidelity measures (eg: percent of patients adhering to the PD Exercise Prescription) along with measures of quality of life such as those proposed by the International Consortium for Health Outcomes Measurement (22).

New models of care must focus on cost because the current healthcare system cost structure is not aligned to incentivize best patient care, nor is it fiscally sustainable in the long-term. The current fee-for-service (FFS) healthcare payment model supports only reactive care by paying for each service or procedure rendered individually to a patient with disease or disability. In the FFS model there are no financial incentives to provide proactive or integrated care, or care that achieves outcomes that matter to the patient. We describe in the final section of this perspective how an IPU properly aligns financial incentives through joint accountability between insurance companies and healthcare providers to ensure high quality care at a sustainable cost. Because Parkinson's Disease affects every organ system in the body, it is an ideal condition around which to pilot an IPU (1). The approach we present will reduce both disease and financial burden over the lifespan of the person with PD while simultaneously improving their quality of care and patient experience.

5 The five elements of the *Parkinson's Elevated integrated practice unit*

The general tenets of an IPU are described in a "Playbook for Health Care Leaders" (4). Guided by this, we have defined 5 core clinical elements of the *Parkinson's Elevated IPU*.

5.1 Integrated, interdisciplinary care, including primary care

The backbone of the IPU will be integrated care that is "coordinated across professions, facilities, and support systems, continuous over time and between visits, and tailored to patient and family needs, values, and preferences" (23). To achieve this as well as to maintain control over total cost of care, a person's primary care physician (PCP) and movement neurologist must work closely, as originally proposed by Bloem, Okun, and Klein (24). But what does this look like in practice? We are currently running a healthcare delivery experiment by integrating a primary care physician (TWS) into the Intermountain movement disorders clinic to see only PwP and their carers. To date this has been met with immense satisfaction from patients and physicians. Care coordinators (Nurse, Exercise Health Coach) provide support for this integrated approach (6).

5.2 Proactive implementation of the Parkinson's exercise prescription (PD ExRx)

One major goal of the *Parkinson's Elevated IPU* is to promote early and high adherence of PwP to the Parkinson's Exercise Prescription (PD ExRx) which we have detailed elsewhere (25). In short, when we refer to PD ExRx, we are referring to an exercise prescription that includes four components. The first component, PD ExRx *aerobic exercise*, has the most evidence to suggest positive disease modification (26–34). The other three components of the exercise prescription—PD ExRx *resistance training*, PD ExRx *flexibility training*, and PD ExRx *neuromotor training*—have not been shown to be directly disease modifying; however they can improve physical function (35) and are associated with better long-term motor outcomes (36). Long-term participation in these modalities can also prevent frailty and debility which if left unaddressed significantly increase morbidity and mortality (37, 38).

The neuromotor component of the prescription is particularly important for improving locomotion, improving balance, and reducing falls (39).

Although the IPU will ultimately focus on implementation of all four components of the PD ExRx, we have focused our initial efforts heavily on PD ExRx *aerobic exercise* because a cure for PD remains elusive (40), and decades of drug trials have failed to produce a disease-modifying treatment (41, 42). Medication and surgery provide a way to mitigate disability and return some quality of life, but they do not slow disease progression. A growing body of evidence suggests that aerobic exercise may be disease-modifying when performed at high intensity (30 min three times a week at 80%–85% heart rate maximum) (26–29). Although the exact mechanism for probable disease modification is unknown, one reason why aerobic exercise is so beneficial for people with PD is that it causes positive health related benefits on the endocrine system, the inflammatory system, and also the neurotrophic system (Luthra et al. manuscript accepted pending revision). If the PD ExRx *aerobic* can be deployed at the earliest phases of the disease, longer-term complications will likely be delayed: the very definition of proactive care. Although there are many areas of care that can be provided to PwP proactively as detailed in the perspective by Bloem et al. (1), here, we highlight aerobic exercise specifically, because failure to routinely deploy a treatment that most likely slows disease progression is a huge missed opportunity in current PD care.

Figures 2A–C detail the hypothetical trajectory of healthspan for people with and without Parkinson's and demonstrate that healthspan is modifiable based on interventions such as the PD ExRx started in mid-life.

Despite mounting evidence that the PD ExRx will meaningfully improve healthspan (29), many PwP are not routinely engaging in exercise for a variety of well-studied reasons (43–45). Certainly, the American healthcare system does not facilitate exercise adherence because financial incentives are not aligned with delivery of such a proactive intervention. In construction of our *Parkinson's Elevated* IPU, we are using an implementation science-informed approach to expedite the availability of this intervention to patients. So far, we have identified five key barriers to implementing the high-intensity aerobic exercise component of the Parkinson's exercise prescription (PD ExRx_{aerobic}) at Intermountain Health (Table 1). We are piloting solutions in a single-site 48-person feasibility/efficacy/cost effectiveness study.

5.3 Specialist network for restorative and skilled maintenance therapy

Although we will always try to enroll PwP early in their disease course into all four-components of the PD ExRx, some people may not be ready for the high-intensity aerobic exercise component initially, and others may never be able to undertake such rigorous exercise because they enter the IPU late in their disease course or have non-modifiable comorbidities preventing participation. Additionally, although

implementing the PD ExRx early should reduce disability, none of the treatments we deploy are curative; many people will still experience functional decline over time and will require adaptations to the ExRx. At the first sign that a person with PD could benefit from person-specific adaptations to therapy, they must be referred early and often to specialized physical therapy—which along with continued exercise and physical activity will definitively improve PD motor and non-motor symptoms and physical function (25, 29, 35, 36, 38, 51–59). When needed, PwP should also be referred to specialized occupational and speech therapy (58). This therapy should be conceptualized in two phases: restorative therapy and skilled maintenance therapy (See Figure 1).

It is important to stress that not all people with PD will respond to therapy in the same way. This is why people with PD should be treated by neuroPTs who have the skillset to prescribe appropriate person-specific therapy based on how an individual responds. It is also the case that many people with PD have a variety of comorbidities such as mobility/osteoarthritis or cardiovascular issues and cannot perform aerobic exercises at moderate to high intensity. These individuals will receive individualized exercise prescriptions.

Restorative therapy is focused on fixing or mitigating a deficit to restore function. For example: PT to improve balance, swallow therapy by a speech and language pathologist to reduce aspiration, and occupational therapy to improve hand dexterity for dressing or handwriting. Most existing physical, occupational, and speech/swallow therapy is set up as restorative therapy in which the therapist works with the patient to improve function or fix a specific deficit. However, many PwP can also benefit from *skilled maintenance therapy* toward the end of their life to maintain basic physical function—e.g., safe mobility in the home, communication, and basic activities of daily living (60). Healthspan at this late stage has clearly fallen from the person's prior baseline level and may not be able to be restored. However, with skilled maintenance therapy, further decline may be forestalled and some measure of health preserved to allow a higher quality last phase of life.

There are three problems with existing therapy infrastructure that limit high-quality restorative and skilled maintenance therapy. The first is that a fragmented care system does not even direct PwP to PT in appropriate numbers. In 2016–2018, only 18%–25% of participants in the Parkinson's Foundation Quality Initiative were referred to PT (13). To solve this problem PwP treated in our IPU will be referred to PT through an integrated pathway. The second problem is that, even when PwP make it to PT, they often do not receive specialized Parkinson's PT (61, 62). Although it is recommended that PwP be treated by rehabilitation therapists specialized in PD (63–65), patients frequently cannot access these specialized clinicians due to transportation barriers or lack of appropriate referrals. To solve this problem, a network modeled after Parkinson Net (66) is needed. In this Dutch network, PwP are preferentially directed to therapists who have received extra training and maintain a certain minimum volume of PwP as patients. Parkinson Net has demonstrated improved quality and reduced costs for PwP (67). This approach is becoming more

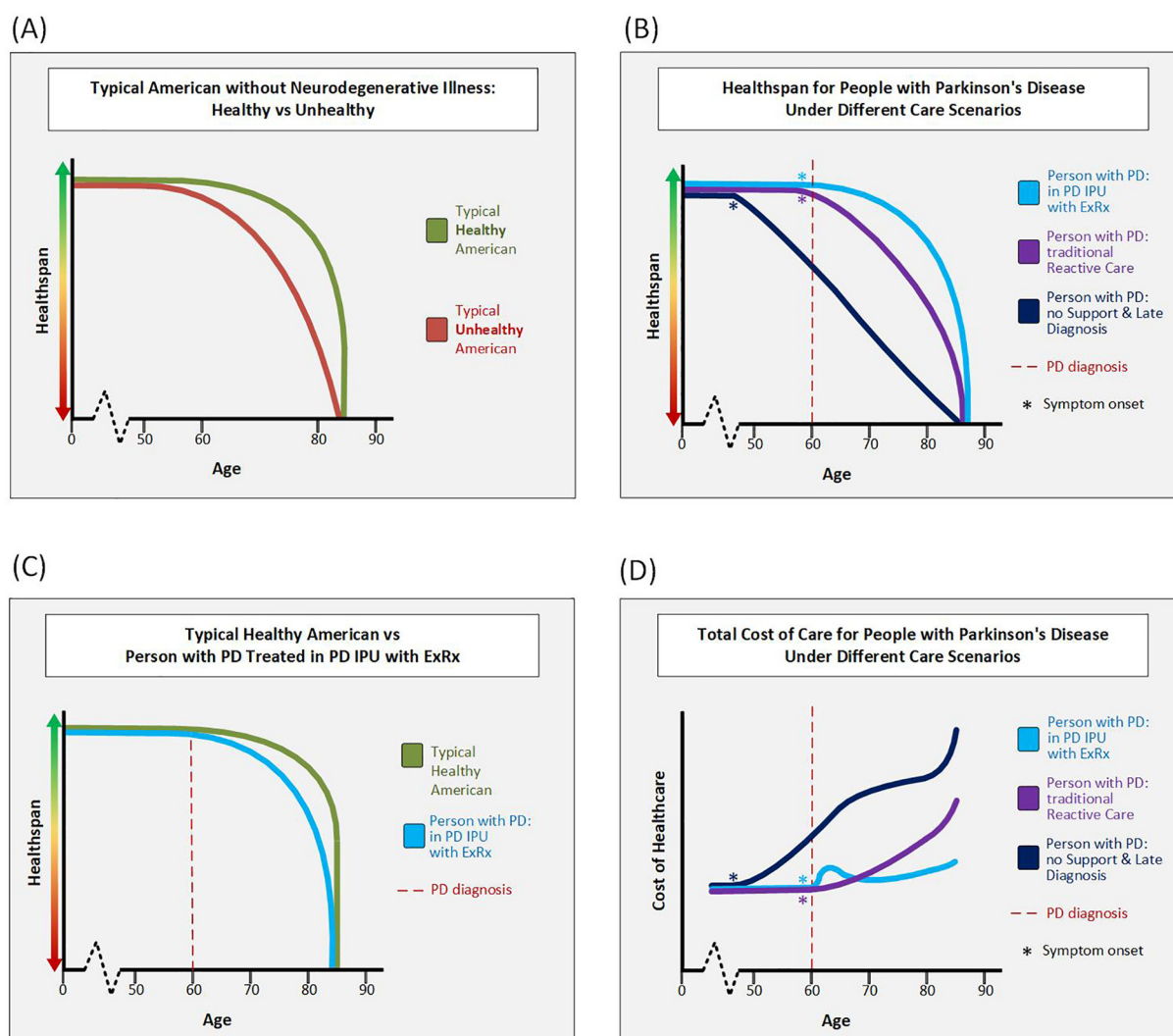


FIGURE 2

Hypothetical clinical and cost trajectories. (A) This figure depicts the hypothetical healthspan of typical Americans without PD or other neurodegenerative illness. A typical unhealthy American does little to promote health and may develop metabolic syndrome which increases risk of type II diabetes, heart disease, and/or stroke. These unhealthy Americans likely experience a “marginal decade” (75) or more at the end of their life in which they are alive, but have poor health and poor quality of life. In contrast, by early middle age at the latest, a typical healthy American engages in multi-modal exercise, healthy eating, quality-sleep, and care for their mental health. As long as these healthy Americans do not develop a disease out of their control such as cancer or a neurodegenerative illness, they maintain a high healthspan until their time of death. (B) This figure depicts the hypothetical healthspan of 3 PwP all diagnosed at age 60, but treated under different care scenarios. The person with PD treated in the *Parkinson's Elevated* IPU with the PD ExRx maintains the highest healthspan. The person with PD who receives good neurologic and family support, but is treated in the traditional reactive care model has more disability in their later decades than the person in the IPU. The third person with PD is someone without support who is diagnosed over a decade into their decline and thus starts at a much lower level of health at time of diagnosis. This person continues a precipitous decline due to continued lack of support. (C) This figure overlays the hypothetical typical healthy American and the hypothetical person with PD treated in the *Parkinson's Elevated* IPU model. While the healthspan of the person with PD is lower than that of the healthy person without PD, it is not that much lower. (D) This figure compares the hypothetical total cost of healthcare for PwP in different care scenarios. The lifetime cost is denoted by the area under each curve. Note that for a person with PD with late diagnosis and little support the cost of care is hypothesized to rise even before diagnosis. For a person with PD in the *Parkinson's Elevated* IPU, cost is hypothesized to rise at diagnosis when resources are invested in proactive care, but over time the cost curve falls below that of a person with PD treated in the traditional reactive-only care model. We anticipate that the *Parkinson's Elevated* IPU will reduce long-term costs through steering patients toward a more benign trajectory for both their PD and non-PD comorbidities (because exercise and care coordination help far more than just PD). In a more benign trajectory, less reactive care is needed. When reactive care is needed however, there will be reduced spend by bringing most of the care into the unit. Finally, transition to hospice at the right time will save high-but-futile spending in the last few months of life. Note that the IPU curve is the only one without steep rise in cost at end of life due to the team being able to proactively transition PwP to hospice. Abbreviations: PD, Parkinson's disease; PwP, people with Parkinson's disease; IPU, integrated practice unit.

TABLE 1 Barriers and solutions to implementation of the Parkinson’s disease exercise prescription (PD ExRx).

| Barrier | Solution |
|---|--|
| Misaligned financial incentives | We are working with our integrated payer Select Health (DMH) to build a system in which the care team is jointly accountable for quality and costs of care. This will allow freedom to direct resources toward exercise. |
| Lack of physical therapist training to support PwP in achieving the PD ExRx | The high heart rate intensity intervention is led by a seasoned neurologic physical therapist (SAO) to develop a PT-based pathway to deliver the PD ExRx at Intermountain. A neurologic physical therapist with implementation research expertise and extensive experience in delivering and scaling evidence-based PT for PD (MRR) is overseeing pathway development. |
| Lack of clinical access to maximum CPET which is needed to determine maximum heart rate* | The protocol for CPET testing from prior PD-specific clinical trials (26, 46) is being used and overseen by experienced PD exercise physiology researchers (DMC, GJG). Full details are provided in (47). |
| No existing system to coordinate care between neurologist, physical therapist, CPET | A project coordinator (MMKB) completes all patient scheduling for the PD ExRx components. We will track the cost and resource utilization of this role to allow future scaling. |
| No existing mechanism for frequent-contact coaching—which is what has been used in successful clinical trials of exercise for PwP (26, 46). | The same project coordinator (MMKB) serves as an exercise coach. She has a certification as a health coach and has received training from experienced exercise interventionists (DMC, GJG). Analysis of the time and training for this role will allow future scaling. |

We are piloting these solutions in a single-site 48-person feasibility study. In this study, a neurologic physical therapist (SAO) screens participants. If the participant is not suitable for the PD ExRx intervention, they receive restorative physical therapy (further described below) and may be eligible for the intervention in the future. If the participant is currently suitable for the ExRx intervention, they undergo a cardiopulmonary exercise test (CPET) performed by an exercise physiologist trained in PD (MNF). The neurologic physical therapist then gives the participant their aerobic exercise prescription based on maximum heart rate obtained during CPET. The prescription is to achieve 3 sessions per week of 30 min of aerobic exercise at 80%–85% heart rate max (plus warm up/cool down). The neurologic physical therapist supervises participant exercise using in-person sessions until the person with PD demonstrates ability to use the Polar heart rate monitor (provided to them as part of the study) to measure heart rate and consistently hit their individually tailored target heart rate. The project coordinator (MMKB) extracts and monitors participant heart rate data and serves as their coach via weekly contact to ensure they continue to meet their target. At the discretion of the physical therapist the other three components of the full PD ExRx (resistance training, flexibility, neuromotor) are prescribed for the participant.

*To write an accurate ExRx, accurate maximum heart rate is needed. The most rigorous method to determine maximum heart rate is a maximum CPET (48). This is how the exercise prescriptions have been set in clinical trials (26–28, 46). Common formulas to estimate maximum heart rate do not work for many PwP because they have autonomic dysfunction or are on chronotropic medications (49, 50). It is unknown if an accurate maximum heart rate can be determined in some PwP without CPET. Abbreviations: CPET, cardiopulmonary exercise test; PD, Parkinson’s disease; PT, physical therapy; PD ExRx, Parkinson’s disease exercise prescription.

recognized and available in the United States, with examples in North Carolina (68) and in California (69).

The third problem with the existing therapy infrastructure is lack of insurance funding for rehabilitation focused on “maintenance.” Many FFS insurance providers, including Medicare, base authorization and payment on the short-term achievement of functional gains rather than goals to ‘maintain’ function over the long-term. This forces therapists to discharge patients once no further ‘rehabilitation’ is possible, when in fact patients would still benefit tremendously from skilled therapists helping to maintain their function. In skilled maintenance, therapy progress should be measured by absence of decline over longer-term episodes of care.

5.4 Physician specialist care provided in the unit and through a tight network of subspecialists

All people—but especially PwP in whom every organ system is affected —need clinicians who understand the whole person and orient care around them (24). Wherever possible the *Parkinson’s Elevated* IPU will bring the first several steps of organ-specific care into the unit. When people’s needs exceed what can be provided directly by the IPU, referrals will go to specific physicians within a tight referral network. This will promote higher quality and more coordinated care because the specialists will develop PD-specific expertise and the IPU team need only coordinate with 1–2 specialists per organ-system.

5.5 A dignified endgame: hospice provided in the IPU

A **Dignified Endgame** involves a smooth and supported transition to hospice in which the care team that has followed the person with PD through their **Health Promotion and Maintenance** phase continues to be involved in their care. This continued involvement preserves a multi-year relationship in addition to facilitating the ongoing technical management of a disease that renders many palliative pharmacologic agents contraindicated. It also promotes a *proactive* transition to hospice because the patient knows they will continue with the care team they trust. Such an arrangement is not possible in a FFS system: in that system, once a patient enrolls in hospice, insurance will no longer pay for them to see any clinicians outside the hospice team. Many of our patients have cited this as the main reason they do not wish to enroll in hospice at all. We are piloting a program with Intermountain hospice in which the movement neurologist serves as attending physician when a patient transitions to hospice. To-date this partnership has been met with high patient and family satisfaction as well as ongoing support from Intermountain Hospice leadership.

6 How will we pay for this: joint accountability for quality and cost of care

Programs that provide proactive integrated care likely produce the best health outcomes; yet existing financial incentives are not

aligned to support these programs (70). Rather, in our current FFS system, care is provided in medical departments only after the problem has occurred. Because such reactive care is the only thing insurance will pay for, it has become the only type of care clinicians are set up to provide. Care providers financially benefit when the number of billable services are maximized (71). Insurance companies financially benefit by denying services or delaying care. When care of a person is reduced to discrete reactive care snapshots like this, patients suffer while care providers and insurance companies fight over the “necessary” and “clinically justifiable” dollars and cents of reactive care.

The *Parkinson’s Elevated* IPU will solve these problems through a value-based care model (72) in which financial incentives are aligned with clinical best practices including proactive care. Specifically, we are planning a capitated (risk-sharing) model in which the insurance company and healthcare provider in close conjunction with the clinical care team jointly assume responsibility for quality and cost of care for all patients in the IPU. In such a model, the IPU will be paid a set amount of reimbursement per patient per year. The IPU will then be responsible for using that money to effectively manage all the care (not just Parkinson’s specific care) for all the patients attributed to the IPU. If the average cost of care falls below the annual set amount, cost savings will be shared by both healthcare provider and insurance company. (Note—to prevent unplanned catastrophically high costs from crippling the program, “stop-loss” insurance will be in place.) In such an arrangement, because we will be able to re-direct funds towards services not traditionally covered in a FFS system, we will be able to implement evidence-based mechanisms of care such as the proactive PD ExRx. Success will be measured not by volume of billable services rendered but rather by outcomes that matter to the patient weighed against total cost of care. **Figure 2D** demonstrates the theoretical life-time cost of care for PwP in different care scenarios.

7 Conclusion

The ideal journey of a PwP is one of early, compassionate and optimistic diagnosis followed by referral to a Parkinson’s Disease Integrated Practice Unit. Our proposal for the *Parkinson’s Elevated* IPU at Intermountain Health uses integrated care to deliver a heavy dose of sustainable proactive care while still providing any reactive care needed. The five core elements of the *Parkinson’s Elevated* IPU are: 1- Integrated, Interdisciplinary Care, including Primary Care, 2-Proactive Implementation of the Parkinson’s Disease Exercise Prescription (PD ExRx), 3-Specialist Network for Restorative and Skilled Maintenance Therapy, 4-Physician Specialist Care Provided in the Unit and through a Tight Network of Subspecialists, and 5- A Dignified Endgame: Hospice Provided in the IPU. To ensure financial sustainability, the healthcare providers in the IPU will be jointly accountable with insurance companies for the quality and total cost of care delivered to PwP in the IPU.

As the national debt continues to increase (currently \$35.91 Tr in late 2024) (73), the age of the population continues to increase, and healthcare expenditures continue to increase (\$4.8 Tr in 2023)

(74), there has never been a more urgent time to improve the quality and decrease the cost of healthcare in the US. The *Parkinson’s Elevated* IPU has the potential to greatly improve the healthspan of PwP while reducing the overall cost of care over the course of the disease. Creation of objective healthspan indices as well as the ability to measure cost over a lifetime in people with and without PD as they age with and without proactive measures are needed to prove the value of this conceptualization of treating PwP. However, there is enough circumstantial evidence supporting the hypothetical healthspan and cost curve trajectories we have proposed (**Figure 2**), that we are planning to implement the *Parkinson’s Elevated* IPU now, rather than wait for more data.

Data availability statement

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

Author contributions

KM: Conceptualization, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing. MR: Conceptualization, Writing – review & editing. TS: Conceptualization, Writing – review & editing. DH: Conceptualization, Writing – review & editing. GG: Writing – review & editing. MB: Project administration, Visualization, Writing – review & editing. SO: Writing – review & editing. MF: Writing – review & editing. DC: Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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