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Locomotor Adaptation Training to Prevent Mobility Disability

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Abstract: Mobility disability is prevalent in aging populations. While existing walking interventions improve aspects related to mobility, meaningful and sustained changes leading to preventing and reversing mobility disability have remained elusive. Split-belt treadmills can be used to train gait adaptability and may be a potential long-term rehabilitation tool for those at risk for mobility decline. As adaptability is necessary for community walking, we investigated the feasibility of a small, randomized controlled 16-week gait adaptability training program in a cohort of 38 sedentary older adults at risk for mobility disability. Individuals were randomly assigned to one of three groups: traditional treadmill training, split-belt treadmill training, or no-contact control. Both treadmill interventions included progressive training 3 days a week, focusing on increasing duration and speed of walking. Cognitive, functional, cardiovascular, and gait assessments were completed before and after the intervention. While individuals were able to complete split-belt treadmill training, only Timed Up and Go performance was significantly improved compared to traditional treadmill training. As the stimulus provided by the split-belt training was difficult to control, we did not observe a clear benefit for split-belt treadmill training over traditional treadmill training. Our findings indicate a cautionary tale about the implementation of complex training interventions.

Keywords: gait training; split-belt treadmill; mobility disability

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1. Introduction

Preserving mobility is vital to maintaining independence and high quality of life. Thus, increased mobility disability (i.e., the negative impact associated with the decreased ability to complete activities of daily living) is pivotal to monitor in older adults. Walking speed is considered the sixth clinical vital sign [1] as it is reflective of integrated physiological systems and general health status [2,3]. Walking speed reduces with age, and is associated with difficulty during activities of daily living [4,5], reduced quality of life [6,7], poorer cognitive performance [8–10], and even increased mortality risk [3]. Therefore, it is unsurprising that the single measure of preferred walking speed is often used to monitor and predict mobility disability [2,11].

Walking interventions improve functional capacity, cardiovascular fitness, and ultimately walking speed in older adults [12–14]. While such interventions have been popular for decades, the ultimate goal of preventing and reversing progressive mobility disability with age remains elusive. Practicing walking, such as walking during repetitive treadmill use or general gait training, may be insufficient stimulus to generate meaningful change in persons at risk of mobility disability [13].

Nine domains of walking adaptability have been suggested as necessary for walking outside of the home environment [15]. Dysregulation or impairment in any of these nine domains, which include temporal, cognitive and motor dual tasking, postural transitions, and maneuvering in traffic, could lead to mobility disability. A complex training environment, such as split-belt treadmill walking, can theoretically enhance the skills required to successfully improve locomotor adaptability. Split-belt treadmill walking allows individual control of the right and left belt speeds, which subsequently requires greater executive resources, and simultaneously challenges both physical and cognitive systems [16,17]. As the belts can be controlled independently, individuals can practice recovering from or adapting to a wide variety of training perturbations in a safe environment [18,19]. Unilateral adaptability in step length and speed are necessary for walking in complex environments to effectively meet task demands [15,20,21]. For example, turning requires adaptability of step length and time which is a skill trained walking on a split-belt treadmill. As 24% of daily steps are within a turn, and falls are more likely to occur during turns than forward walking [22], training adaptation of step length may be especially important in maintaining independent mobility. Therefore, split-belt treadmills have the potential to improve mobility disability.

The Complexity Account of Treatment Efficacy theorizes that efficacy and generalization of skills is improved when training in complex environments [23], leading to more pronounced corticospinal reorganization [24–26]. Walking on a split-belt treadmill is a more complex behavior than traditional treadmill walking, demanding continuous adaptation [27,28] and accurate foot placement which requires stronger corticospinal activation [29–31]. Motor adaptation, rather than merely increased motor activity, is required to induce significant changes in patterns and strength of neural connectivity [32–35]. Split-belt treadmill walking can reduce movement variability due to cerebellar-dependent learning, leading to more optimal utilization of sensory inputs with different amounts of uncertainty [36]. Several levels of the nervous system may contribute to the control required to walk on a split-belt treadmill, including cortical processes, basal ganglia, cerebellum, and spinal mechanisms, all of which participate in the neural networks important for mobility function [37–40]. Prior studies have found associations between gait performance and volume of basal ganglia, cerebellum, and cortical structure [41]. Additionally, slower gait is associated with poorer performance on measures of executive function, working memory, processing speed, and visuospatial attention [11]. It has been hypothesized that walking speed and executive function, including processing speed, may rely on shared brain networks in older adults [42,43]. As aging is associated with degeneration of many of the regions in the central nervous system associated with locomotion and adaptation (see [21] for a review), it is imperative to employ interventions targeting these specific declines. Indeed, split-belt treadmill walking has been shown to demand greater executive resources than traditional treadmill walking, thus simultaneously engaging and challenging both physical and cognitive abilities during training [16,17].

Split-belt treadmill walking challenges gait mechanics, increasing adaptation demands [44,45]. Adaptability is required for fall prevention, and several studies have clearly demonstrated the feasibility of fall reduction through treadmill slip training [46–49], and a single session of perturbation training on a treadmill can generalize to real-life fall events [49,50]. By repetitively manipulating differences in individual treadmill belt speeds, split-belt treadmill walking can provide an infinite number of perturbations from which a locomotor adaptation skill set can be created. Conversely, several studies have suggested variable-speed traditional treadmill training does not acutely alter locomotor patterns, leading the authors to suggest this type of training does not require the updating of the internal walking model [38,51,52]. Thus, locomotor adaptability training on a split-belt treadmill may benefit multiple systems, including cognitive, locomotor, and cardiovascular, which is particularly valuable in individuals at risk of mobility disability.

Here, we present a controlled 16-week gait adaptability training program in a cohort of sedentary older adults at risk for mobility disability. We hypothesized that split-belt treadmill training would provide a powerful and complex neuromuscular stimulus capable of enhancing gait performance and functional capacity in an at-risk population. As a secondary aim, we compared the effect of split-belt treadmill training to traditional treadmill training and a control no-contact group on mobility outcomes and hypothesized that we would see the greatest improvements in mobility outcomes for the split-belt training group.

2. Materials and Methods

A priori sample size calculations were performed (NCSS-PASS), with a 3 (group) × 2 (time) repeated-measures design, powered on the interaction effect with responsiveness to gait speed in split-belt (0.2 m/s improvement) and treadmill (0.04 m/s). These calculations indicated 16 participants per group, for power = 0.99 with an effect size of Cohen's f = 1.97 at α= 0.05. Thus, 150 sedentary older adults were screened to enroll in our study. "Sedentary" was defined as individuals who engaged in less than two hours of moderate physical activity per week, as determined by the Community Health Activities Measurement Scale for Older Adults [53]. Participants were excluded if they had prior experience walking on a split-belt treadmill with belts moving at different speeds, cardiovascular, pulmonary, or neurologic disease, severe rheumatoid arthritis or osteoarthritis that affected their walking, or insulin-treated diabetes. Participants were also excluded if they were cognitively impaired as determined by their education-corrected Mini-Mental State Examination score [54]. Persons with 8 years of education or less were excluded if they scored a 20 or lower; persons with 9 to 12 years of education were excluded if they scored a 22 or lower; persons with 13 or more years of education were excluded if they scored a 24 or lower. To target pre-mobility-impaired older adults, the Short Physical Performance Battery was used to determine levels of physical function; participants scoring a 6 or lower or a perfect score of 12 were excluded from the study. As gait speeds between 0.6 m/s and 1.2 m/s are used to identify older adults at risk for mobility disability, participants who walked overground on a GaitRite (CIR Systems, Inc., Franklin, NJ, USA) faster than 1.15 m/s were excluded [3,55,56]. Gait speed can be considered the sixth clinically vital sign [1]; thus, it is our primary outcome measure on the effectiveness of the intervention.

All procedures were explained and written consent was obtained as approved by the Institutional Review Board. Participants completed cognitive testing, functional testing, cardiovascular performance testing, and gait testing on three separate days. All tests were administered by researchers trained in each specific assessment. Experimental sessions occurred within one calendar month, with 10 days between testing appointments, on average. All tests were performed, on average, one week before and after the intervention.

2.1. Functional Testing

Participants completed three functional tests of mobility: (1) Short Performance Physical Battery (SPPB), (2) Dynamic Gait Index (DGI), and (3) Timed Up and Go (TUG). The SPPB assesses lower-extremity physical function across standing balance, walking speed, and repeated chair stand tests [57,58]. Participants were scored based on time or ability to complete the assessments in the following order, with a maximum score of 12 indicating no mobility restriction: (1) balance within a semi-tandem/staggered stance for 10 s, then regress or progress to feet side-by-side or in a tandem stance, respectively, depending on results of staggered stance, (2) 3 m walk, (3) stand from a chair five times. The DGI assesses an individual's ability to alter gait in response to dynamic task demands such as turning one's head, pivot turning, crossing and avoiding obstacles, and climbing stairs [59], with a highest possible score of 24. The TUG is a common test of functional mobility where participants stand from a seated position, walk three meters to turn around a cone and return back to their chair [60]. TUG scores are based on the time to complete the task, averaged across three trials.

2.2. Cardiovascular Testing

Participants completed a physician-supervised maximal oxygen consumption test (VO2max) with electrocardiogram monitoring. This provided an opportunity to detect severe cardiac disease that could increase risk of an acute event during the intervention period. The Orthopedic Sports Medicine Institute administered the testing and analysis and provided outcomes of importance: VO2max and the maximum speed individuals reached in miles per hour. Gait efficiency was calculated as maximum oxygen consumption (mL/kg/min)/maximum velocity (m/min).

2.3. Cognitive Testing

Participants completed the Mini-Mental State Exam (MMSE) to assess global cognitive function [61]. A maximum score of 30 indicated no cognitive impairment [62]. The Trail Making Test (TMT) was administered and consists of two sections: performance on part A (TMT-A) is related to visual scanning and visuomotor processing speed and part B (TMT-B) assesses working memory and inhibition control, elements of executive function [63,64]. The change in TMT (TMT-B–TMT-A, dTMT) detects cognitive impairment [65]. Participants completed each part as quickly and accurately as possible without being instructed to correct errors [66].

2.4. Gait Testing

Participants completed gait testing barefoot, walking at their self-selected speed across an 8 m walkway. Retroreflective markers, placed according to the Vicon Plug-In Gait model, were collected at 120 Hz with a 12-camera, three-dimensional motion capture system (Vicon Motion Systems, Denver, CO, USA). Ground reaction forces were collected at 1200 Hz by three force platforms (AMTI, Watertown, MA, USA) embedded level and matched to the appearance of the laboratory flooring. Filtering cut-offs for trajectory and force data were determined via independent power spectral analysis using custom MATLAB software (MathWorks, Natick, MA, USA) [67]. Marker trajectories and force data were filtered using a fourth-order zero-lag low-pass Butterworth filter (cut-off frequency: 8 Hz and 15 Hz, respectively). The Vicon Dynamic Plug-In Gait model was used to obtain peak ankle plantarflexion moment, peak eccentric ankle plantarflexor power, and peak concentric hip flexor power from all gait cycles with clean force platform contact. As the ankle plantarflexors and hip flexors are known to be the primary drivers of forward walking speed [68], only these kinetic variables were calculated. Gait speed, cadence, stride length, stride time, step width, and stance time were calculated from the marker located on the calcaneus of each foot. Variability of these gait outcomes are reported as standard deviation.

2.5. Intervention

Participants were randomized into one of three intervention groups (1: control, 2: traditional treadmill training, 3: split-belt treadmill training) using a stratified-block method, stratified by age, gender, and SPPB score. Participation in additional physical activities that may influence study outcomes, such as balance or strength training, was not allowed and individuals who initiated additional training were excluded.

The control group had no training contact with researchers between pre- and post-testing visits and were instructed to continue their usual physical activity throughout the 16 weeks. Physical activity levels were estimated monthly via a telephone call using the Leisure Time Physical Activity Questionnaire [69]. Control participants were offered the option of partaking in the exercise program of their choice following completion of all testing sessions.

Both treadmill groups trained three times a week for 16 weeks, following the guidelines provided by the American College of Sports Medicine [70]. Exercise intensity began at targeted low levels (50% of maximal heart rate reserve) and increased approximately 5% every week to a maximum target of 75% of heart rate reserve as tolerated. Exercise time progressed from an initial 25 min per session to the maximum 45 min by increasing duration, approximately 5 min every week. Each session began with stretching and a 5 min warm-up and ended with a 5 min cool-down and stretching. Throughout each training session, heart rate (HR, T31 Coded Chest Sensor, Polar Electro, New York, NY, USA) and self-reported ratings of perceived exertion (RPE) [71] were monitored continuously and the treadmill speed and/or incline (variable incline only possible with the traditional treadmill group) was adjusted accordingly to maintain target HR. Specifically, each training session was monitored by a trained researcher. After walking at a self-determined comfortable walking speed during the warm-up, the training speed was determined with consensus between the researcher and the participant based on the HR recorded at the end of the warm-up. Every 3 min, HR and RPE were recorded and training speed was re-evaluated. For participants in the traditional treadmill group, if training speed could not be increased (e.g., participant uncomfortable walking faster), incline was increased starting at 1% and increased by 0.5% as needed. Participants were encouraged to walk without holding on to handrails if they felt comfortable to do so. If participants were holding on to handrails, they were encouraged to use a light touch. Further measures to increase HR, if speed or incline could not be changed, included initiating conversation or limiting handrail use. Rest breaks during training were discouraged, but allowed upon request by participants.

For participants in the intervention groups (i.e., either traditional or split-belt treadmill groups), overground walking tests were performed every 4 weeks to determine comfortable and fastest comfortable walking speeds. These speeds were used as guidelines during the following 4-week cycle to provide progressive training, but actual speeds were modified when necessary to achieve target HR as reported by participants throughout the training session. The traditional treadmill group walked at speeds (and adjusted incline levels) set to target their specific HR range. The split-belt group was programmed into four 4-week cycles, with each cycle including three different walking conditions (1: constant split-belt, 2: noisy split-belt, 3: acute perturbation; see Appendix A). These different conditions have been shown to influence the rate of adaption, learning, and generalization. The "constant" condition was chosen as a similar ratio paradigm to other split-belt interventions, e.g., [28,72–74], and abrupt changes in training environment induce greater learning, adaptation, and generalization effects [75]. The "noisy" condition introduces unpredictable variability within the intervention, enhancing generalization [76], and the "perturbation" condition was selected to simulate a fall response, which is a popular approach in the literature and generalizes to overground walking [77]. Across 4-week cycles, the order of conditions was randomized.

In the ″constant split-belt" condition, participants walked in 3 min intervals with the ratio between the belt speeds ranging from 1:1 to 2:1 depending on the interval (Figure 1). The faster belt was set to the participant's previously determined fastest comfortable speed, when possible, but was modified when necessary to accommodate the target HR. The ″noisy split-belt" condition was similar to the ″constant split-belt" condition, as in participants walked in 3 min intervals at belt ratios between 1:1 and 2:1. The session difficulty was altered during the ″noisy split-belt" conditions by varying the belt speed of the fast belt within ±0.4 m/s range every five seconds (Figure 2). Finally, participants completed an ″acute perturbation" condition which alternated between split-belt and tied-belt walking in 3 min intervals (Figure 3). During the split-belt intervals, participants walked at a 2:1 split ratio and alternated between dominant and non-dominant limbs on the fast belt. The dominant limb was determined as the leg the participant would use to kick a ball [78]. During the tied-belt intervals, both belts moved at the same speed and a perturbation was delivered by acutely accelerating both belts to 1.5 times the belt speed at an acceleration of 2.0 m/s^2. The perturbation was delivered during the single-support phase to isolate the perturbation to a single limb. Participants received multiple perturbations randomly for each limb in each trial block. An example 4-week training block is outlined in Appendix A.

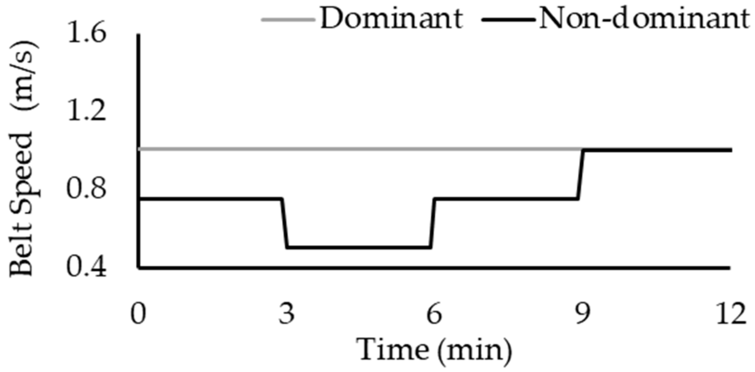

Figure 1. Sample training protocol for a "constant split-belt" condition.

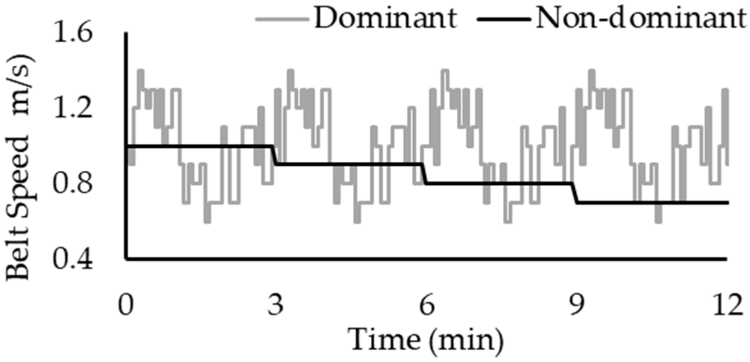

Figure 2. Sample training protocol for a "noisy split-belt" condition.

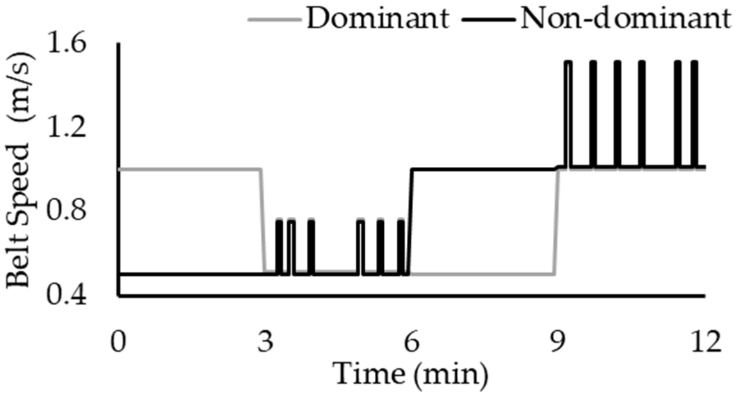

Figure 3. Sample training protocol for an "acute perturbation" condition.

2.6. Statistical Analysis

An exploratory statistical analysis determined the feasibility of a novel split-belt intervention. For each of the five dimensions of mobility disability, a mixed-effects ANOVA was used to test both primary and secondary aims with a within-subject factor of time (2 levels: pre-intervention, post-intervention) and between-subject factor of intervention group (3 levels: control, traditional treadmill, split-belt treadmill) for each outcome. The primary aim of this study was to examine changes resulting from the intervention; thus, for each group, we performed planned post hoc comparisons across time (pre- versus post-intervention). The planned comparisons allow us to test our hypothesis that the control group would not change and the traditional treadmill group would improve across time, while independently identifying the effects of the split-belt intervention. A one-way ANOVA compared demographics between groups at the pre-intervention time point. All analyses were performed in SPSS ($p < 0.05$, version 27, SPSS, Inc., Chicago, IL, USA).

For ease of interpretation, we provide effect sizes as partial eta squared (${\eta_p}^2$), following convention [79], where ${\eta_p}^2 = 0.01$ is considered a small effect, ${\eta_p}^2 = 0.06$ is a medium effect, and ${\eta_p}^2 \geq 0.14$ is a large effect.

3. Results

We investigated five dimensions of mobility disability: (1) clinical function, (2) cardiovascular fitness, (3) cognitive function, (4) spatiotemporal gait parameters (means and variability), and (5) gait kinetics. For all dimensions, the control group did not change significantly over our intervention period. All results are presented as mean ± standard error.

3.1. Participants

Of the initial 150 people screened to enroll in the intervention study, 58 were enrolled, and 38 participants completed the study (Table 1). Twenty participants dropped out during the study, of which 18 were from the split-belt treadmill group (further details in Appendix B). A one-way ANOVA comparing group differences at the pre-intervention time point supported that there were no significant between-group differences in age (F(1) = 1.11, $p = 0.342$, $\eta^2 = 0.060$), sex (F(1) = 0.59, $p = 0.560$, $\eta^2 = 0.033$), mass (F(1) = 2.25, $p = 0.120$, $\eta^2 = 0.114$), height (F(1) = 0.01, $p = 0.995$, $\eta^2 < 0.001$), or SPPB score (F(1) = 0.194, $p = 0.825$, $\eta^2 = 0.011$).

Table 1. Means ± standard error of participant characteristics by group assignment, pre-intervention.

Group	n	Age (y)	Mass (kg)	Height (m)	MMSE (Max Score: 30)	SPPB (Max Score: 12)	Walking Speed (m/s)	VO2max (mL/kg/min)
Control	2 M 11 F	73 ± 1	77.68 ± 4.91	1.66 ± 0.03	27.67 ± 0.50	8.92 ± 0.41	1.01 ± 0.04	15.15 ± 1.28
Traditional	4 M 8 F	73 ± 1	90.49 ± 4.01	1.65 ± 0.02	28.33 ± 0.52	8.44 ± 0.47	0.94 ± 0.04	17.42 ± 1.23
Split-belt	4 M 9 F	71 ± 1	94.60 ± 8.04	1.65 ± 0.03	27.85 ± 0.48	9.08 ± 0.41	0.94 ± 0.04	17.03 ± 1.23

M = Male, F = Female.

Average training speed, HR, and RPE are presented in Table 2 for the two training groups, for the final week of each 4-week training cycle. Training speeds were calculated by averaging the middle 15 min across the final week of training days for each 5-week cycle; for the split-belt treadmill group, only constant split-belt days were included. RPE and average HR were also calculated by averaging the middle 17 min of each day during the final week of each 4-week cycle. Percent from target HR was defined as the percentage achieved compared to the target, with positive numbers indicating a higher HR than the target.

Table 2. Means ± standard error [range] of training outcome measures for normal and split-belt treadmill groups. D: dominant limb; ND: non-dominant limb.

Week	Group	Treadmill Speed (m/s)	Individual Treadmill Belt Speed (m/s)	Target HR (bpm)	Average HR (bpm)	Percentage from Target (%)	RPE
Week 4	Traditional	0.7 ± 0.0 [0.5, 0.9]		96 ± 1 [91, 101]	98 ± 2 [88, 113]	2 ± 1 [−3, 12]	2 ± 0 [1, 3]
	Split-belt	0.7 ± 0.1 [0.4, 1.2]	D: 0.7 ± 0.1 [0.4, 1.3] ND: 0.7 ± 0.1 [0.4, 1.1]	97 ± 1 [92, 101]	93 ± 2 [81, 111]	−4 ± 2 [−18, 12]	2 ± 0 [1, 5]
Week 8	Traditional	1.0 ± 0.1 [0.6, 1.3]		110 ± 1 [105, 116]	109 ± 1 [103, 114]	−1 ± 1 [−4, 7]	3 ± 0 [2, 5]
	Split-belt	0.9 ± 0.1 [0.4, 1.1]	D: 0.8 ± 0.1 [0.4, 1.1] ND: 0.9 ± 0.1 [0.4, 1.2]	111 ± 1 [102, 116]	99 ± 2 [82, 111]	−11 ± 2 [−28, −3]	3 ± 0 [1, 6]

Table 2. *Cont.*

Week	Group	Treadmill Speed (m/s)	Individual Treadmill Belt Speed (m/s)	Target HR (bpm)	Average HR (bpm)	Percentage from Target (%)	RPE
Week 12	Traditional	1.1 ± 0.1 [0.7, 1.3]		110 ± 1 [105, 116]	109 ± 1 [102, 116]	−2 ± 1 [−5, 2]	3 ± 0 [2, 5]
	Split-belt	0.8 ± 0.1 [0.4, 1.1]	D: 0.8 ± 0.1 [0.4, 1.1] ND: 0.9 ± 0.1 [0.4, 1.2]	111 ± 1 [102, 116]	98 ± 3 [82, 114]	−12 ± 2 [−28, 1]	3 ± 0 [1, 7]
Week 16	Traditional	1.1 ± 0.1 [0.6, 1.3]		110 ± 1 [105, 116]	109 ± 1 [104, 115]	−1 ± 1 [−7, 1]	3 ± 0 [2, 5]
	Split-belt	0.8 ± 0.1 [0.4, 1.1]	D: 0.8 ± 0.1 [0.4, 1.1] ND:0.9 ± 0.1 [0.4, 1.2]	112 ± 1 [106, 116]	97 ± 3 [83, 110]	−13 ± 2 [−28, −3]	3 ± 0 [1, 7]

3.2. Dimension 1: Clinical Function

Neither DGI nor SPPB scores changed across time points (SPPB: F(1,30)= 0.035, $p = 0.863$, $\eta_p{}^2 = 0.001$; DGI: F(1,30) = 3.44, $p = 0.074$, $\eta_p{}^2 = 0.103$), and no time × group interaction effects were detected (SPPB: F(2,30) = 2.62, $p = 0.118$, $\eta_p{}^2 = 0.133$; DGI: F(2,30) = 1.34, $p = 0.661$, $\eta_p{}^2 = 0.027$). There was an interaction between time and group for TUG score (F(2,30) = 4.89, $p = 0.017$, $\eta_p{}^2 = 0.237$). The split-belt treadmill group reduced TUG time by 1.27 ± 0.42 s ($p = 0.005$, 95% CI [0.41 2.12]) from pre- to post-intervention, while no other group saw changes in TUG performance (all $p \geq 0.171$). Clinical function outcomes are presented in Appendix C, while changes in TUG are presented in Figure 4.

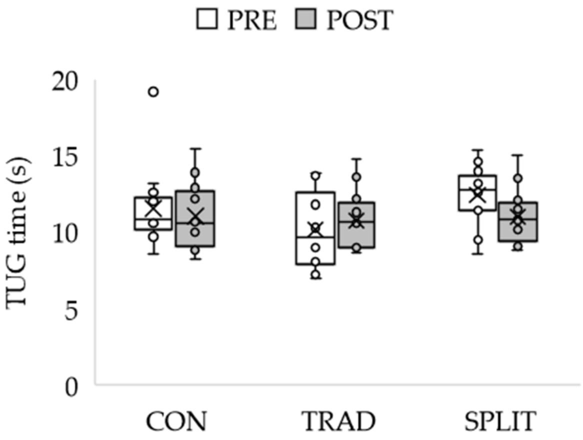

Figure 4. Timed Up and Go (TUG) performance for three groups (CON = control, TRAD = traditional treadmill training group, SPLIT = split-belt treadmill training group) at two time points (PRE = before 16-week intervention [white bar]; POST = following 16-week intervention [gray bar]).

3.3. Dimension 2: Cardiovascular Fitness

There was a strong main effect of time for VO2max, indicating improvements of 1.05 ± 0.43 mL/kg/min from pre- to post-intervention (F(1,32) = 6.02, $p = 0.020$, $\eta_p{}^2 = 0.158$, 95% CI [0.18 1.93]). Examining planned between-group comparisons reveals that this effect is driven by improvements in the traditional treadmill group (1.63 ± 0.73 mL/kg/min, $p = 0.034$, 95% CI [0.13 3.12]). There was no significant change in the control group ($p = 0.647$), nor in the split-belt group ($p = 0.116$). Analysis revealed a strong, significant time × group interaction for gait efficiency (F(2,32) = 4.07, $p = 0.027$, $\eta_p{}^2 = 0.203$). Post hoc comparisons indicated that the traditional treadmill group improved their gait efficiency by 0.04 ± 0.02 mL/kg/m ($p < 0.01$, 95% CI [0.01 0.07]). However, no efficiency improvements were observed for the split-belt treadmill group ($p = 0.54$). There were no main effects of time for HR (F(1,32) < 0.01, $p = 0.953$, $\eta_p{}^2 < 0.001$), nor RPE (F(1,32) = 0.34, $p = 0.564$, $\eta_p{}^2 = 0.011$), nor time × group for HR (F(2,32) = 0.97, $p = 0.391$, $\eta_p{}^2 = 0.057$), nor

RPE (F(2,32) = 0.04, p = 0.961, $\eta_p{}^2$ = 0.003). Cardiovascular fitness outcomes are presented in Appendix D and significant findings are presented in Figure 5.

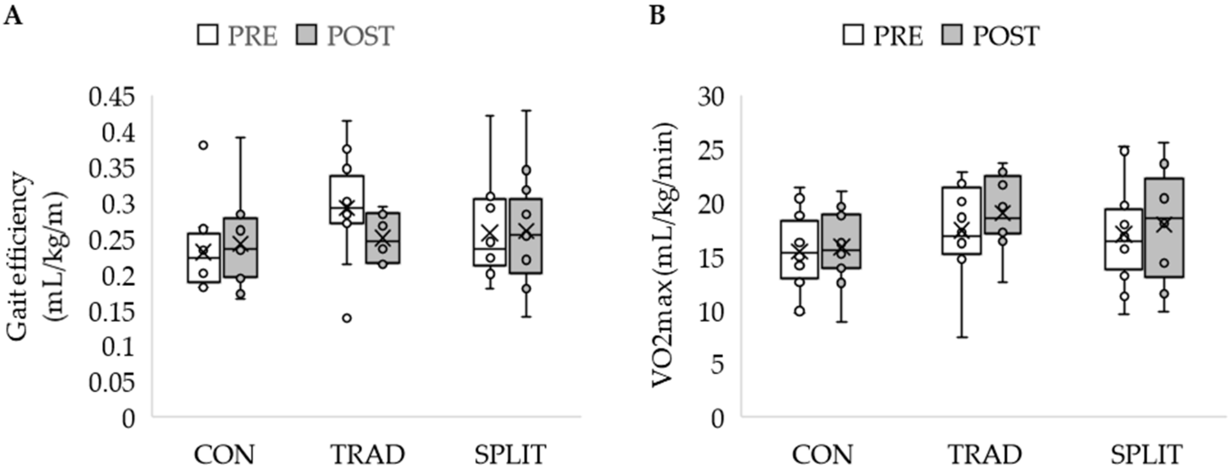

Figure 5. (**A**) Gait efficiency, and (**B**) maximal oxygen uptake (VO2max) for three groups (CON = control, TRAD = traditional treadmill training group, SPLIT = split-belt treadmill training group) at two time points (PRE = before 16-week intervention [white bar]; POST = following 16-week intervention [gray bar]).

3.4. Dimension 3: Cognitive Function

For MMSE score, there were no main effects of time (F(1,33) = 0.29, p = 0.592, $\eta_p{}^2$ = 0.009) nor a time × group interaction (F(2,33) = 0.07, p = 0.929, $\eta_p{}^2$ = 0.004). For TMT-A, there was no significant main effect of time (F(1,33) = 1.41, p = 0.244, $\eta_p{}^2$ = 0.041) nor a time × group interaction (F(2,33) = 0.63, p = 0.538, $\eta_p{}^2$ = 0.037). For TMT-B, there was no significant time × group interaction, despite a moderate effect size (F(2,33) = 2.61, p = 0.089, $\eta_p{}^2$ = 0.137), but there was a strong main effect of time (F(1) = 6.17, p = 0.018, $\eta_p{}^2$ = 0.158). Planned between-group comparisons indicated that TMT-B performance became significantly worse following the intervention for both traditional (p = 0.015, 95% CI [7.56 65.19]) and split-belt treadmill groups (p = 0.041, 95% CI [1.15 54.16]). However, dTMT did not change at either time point (F(1,33) = 3.23, p = 0.082, $\eta_p{}^2$ = 0.089) nor was a time × group interaction detected (F(2,33) = 1.48, p = 0.243, $\eta_p{}^2$ = 0.082). Cognitive performance results are presented in Appendix E with TMT-B performance presented in Figure 6.

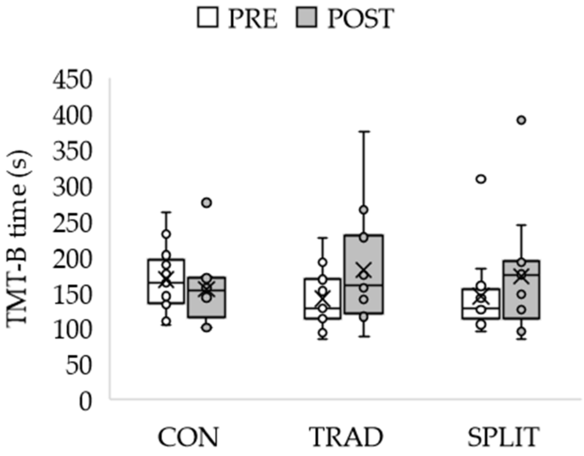

Figure 6. Trail Making Test part B time (TMT-B) for three groups (CON = control, TRAD = traditional treadmill training group, SPLIT = split-belt treadmill training group) at two time points (PRE = before 16-week intervention [white bar]; POST = following 16-week intervention [gray bar]).

3.5. Dimension 4: Gait Parameters

A significant time × group interaction was present for stride length (F(2,35) = 3.56, $p = 0.039$, $\eta_p^2 = 0.169$); specifically, stride length increased for the traditional treadmill group by 0.06 ± 0.02 m ($p = 0.009$, 95% CI [0.02 0.11]) after the intervention. The split-belt treadmill group did not exhibit the same improvement ($p = 0.331$). Furthermore, there was no significant time × group interaction for gait speed, despite a strong effect, (F(2,35) = 2.96, $p = 0.065$, $\eta_p^2 = 0.145$), cadence (F(2,35) = 0.78, $p = 0.468$, $\eta_p^2 = 0.042$), stride time (F(2,35) = 0.72, $p = 0.495$, $\eta_p^2 = 0.039$), step width, despite a moderate effect (F(2,35) = 2.79, $p = 0.075$, $\eta_p^2 = 0.138$), or stance time (F(2,35) = 0.40, $p = 0.676$, $\eta_p^2 = 0.022$).

There was no significant effect of time for gait speed (F(1,35) = 3.69, $p = 0.063$, $\eta_p^2 = 0.095$), cadence (F(1,35) = 1.45, $p = 0.235$, $\eta_p^2 = 0.040$), stride time (F(1,35) = 0.81, $p = 0.374$, $\eta_p^2 = 0.023$), step width (F(1,35) = 3.86, $p = 0.058$, $\eta_p^2 = 0.099$), or stance time (F(1,35) = 1.71, $p = 0.185$, $\eta_p^2 = 0.050$). Pre-planned post hoc comparisons indicated significant differences between time points for gait speed and step width for the intervention groups. Traditional treadmill walking improved gait speed following the intervention by 0.08 ± 0.03 m/s ($p = 0.009$, 95% CI [0.02 0.14]), yet this was not the case for the split-belt treadmill group ($p = 0.526$). The split-belt group exhibited wider steps post-intervention by 0.02 ± 0.01 m ($p = 0.005$, 95% CI [0.01 0.03]).

Examining spatiotemporal variability showed a strong significant time × group interaction effect for stride length variability (F(2,33) = 4.05, $p = 0.027$, $\eta_p^2 = 0.197$); however, post hoc comparisons revealed no group significantly changed following the intervention (all $p \geq 0.646$). There was a significant main effect of time for stance time variability (following intervention, there was a reduction 0.143 + −0.069 s, F(1,33) = 4.27, $p = 0.047$, $\eta_p^2 = 0.114$), although planned post hoc comparisons indicated no significant changes in each group (all $p \geq 0.600$). No other measures of gait variability exhibited a significant main effect of time (speed: F(1,33) = 0.18, $p = 0.672$, $\eta_p^2 = 0.005$; cadence: F(1,33) < 0.01, $p = 0.924$, $\eta_p^2 < 0.001$; stride time: F(1,33) = 0.35, $p = 0.560$, $\eta_p^2 = 0.010$; step width: F(1,33) = 0.28, $p = 0.603$, $\eta_p^2 = 0.008$), nor time × group interaction (speed: F(2,33) = 1.74, $p = 0.192$, $\eta_p^2 = 0.095$; cadence: F(2,33) = 1.57, $p = 0.223$, $\eta_p^2 = 0.087$; stride time: F(2,33) = 1.17, $p = 0.322$, $\eta_p^2 = 0.066$; step width: F(2,33) = 1.37, $p = 0.269$, $\eta_p^2 = 0.077$; stance time: F(2,33) = 0.52, $p = 0.596$, $\eta_p^2 = 0.031$). Detailed results for gait parameters are presented in Table 3 and changes in stride length, walking speed, and step width are presented in Figure 7.

Table 3. Spatiotemporal gait performance outcomes based on group and time (means ± standard error).

Measure	Group	Time	Mean ± SE	Variability Mean ± SE
Speed (m/s)	Control	Pre	1.01 ± 0.04	0.046 ± 0.004
		Post	1.04 ± 0.05	0.052 ± 0.003
	Traditional	Pre	0.94 ± 0.04 *	0.049 ± 0.004
		Post	1.02 ± 0.05 *	0.044 ± 0.004
	Split-Belt	Pre	0.94 ± 0.04	0.047 ± 0.004
		Post	0.92 ± 0.06	0.042 ± 0.003
Cadence (steps/min)	Control	Pre	112 ± 3	3.1 ± 0.2
		Post	114 ± 3	3.5 ± 0.2
	Traditional	Pre	108 ± 3	3.1 ± 0.3
		Post	110 ± 3	2.9 ± 0.3
	Split-Belt	Pre	105 ± 3	3.4 ± 0.3
		Post	105 ± 3	3.2 ± 0.3
Stride Length (m)	Control	Pre	1.08 ± 0.03	0.035 ± 0.003
		Post	1.09 ± 0.04	0.041 ± 0.004
	Traditional	Pre	1.05 ± 0.04 *	0.042 ± 0.003
		Post	1.11 ± 0.04 *	0.034 ± 0.004
	Split-Belt	Pre	1.08 ± 0.03	0.039 ± 0.003
		Post	1.06 ± 0.04	0.033 ± 0.004

Table 3. *Cont.*

Measure	Group	Time	Mean ± SE	Variability Mean ± SE
Stride Time (s)	Control	Pre	1.08 ± 0.03	0.031 ± 0.004
		Post	1.07 ± 0.03	0.034 ± 0.004
	Traditional	Pre	1.11 ± 0.03	0.032 ± 0.004
		Post	1.10 ± 0.03	0.029 ± 0.004
	Split-Belt	Pre	1.15 ± 0.03	0.038 ± 0.004
		Post	1.16 ± 0.03	0.034 ± 0.004
Step Width (m)	Control	Pre	0.098 ± 0.010	0.026 ± 0.002
		Post	0.097 ± 0.010	0.029 ± 0.002
	Traditional	Pre	0.095 ± 0.010	0.029 ± 0.002
		Post	0.099 ± 0.010	0.027 ± 0.002
	Split-Belt	Pre	0.104 ± 0.010 *	0.028 ± 0.002
		Post	0.121 ± 0.010 *	0.029 ± 0.002
Stance Time (% gait cycle)	Control	Pre	63.4 ± 0.5	1.46 ± 0.11
		Post	63.1 ± 0.6	1.36 ± 0.10
	Traditional	Pre	64.6 ± 0.5	1.66 ± 0.12
		Post	64.1 ± 0.7	1.42 ± 0.11
	Split-Belt	Pre	64.9 ± 0.5	1.49 ± 0.11
		Post	64.8 ± 0.6	1.39 ± 0.11

* denotes significant time * group interaction.

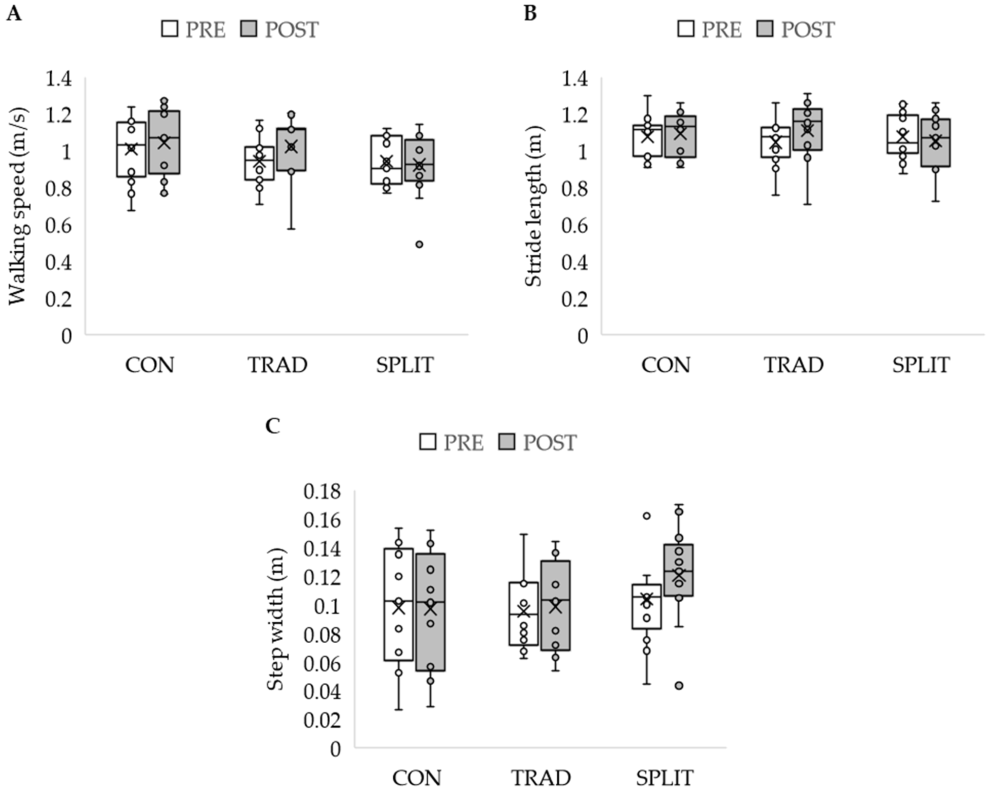

Figure 7. (**A**) Walking speed, (**B**) stride length, and (**C**) step width for three groups (CON = control, TRAD = traditional treadmill training group, SPLIT = split-belt treadmill training group) at two time points (PRE = before 16-week intervention [white bar]; POST = following 16-week intervention [gray bar]).

3.6. Dimension 5: Gait Kinetics

There was no main effect of time on ankle moment (F(1,25) = 0.39, $p = 0.540$, $\eta_p^2 = 0.015$), ankle power (F(1,25) < 0.01, $p = 0.957$, $\eta_p^2 < 0.001$), nor hip power (F(1,25) = 0.31, $p = 0.583$, $\eta_p^2 = 0.012$). Despite moderate effect sizes, there were no significant group*time interactions for ankle moment (F(2,25) = 0.81, p = 0.455, ${\eta_p}^2$ = 0.061), ankle power (F(2,25) = 1.90, p = 0.171, ${\eta_p}^2$ = 0.132), nor hip power (F(2,25) = 1.79, p = 0.189, ${\eta_p}^2$ = 0.125). Kinetic gait outcomes are presented in Appendix F.

4. Discussion

A 16-week gait adaptability training intervention did not considerably influence mobility outcome measures in a cohort of sedentary older adults at risk of mobility disability, contrary to our hypothesis. Indeed, across the domains of mobility disability that we investigated (cognitive function, clinical functional mobility assessments, cardiovascular fitness, spatiotemporal gait parameters and their variability, and lower-limb gait kinetics), only 7/26 variables were affected by the walking interventions. The traditional treadmill training group displayed greater improvements for most outcomes when compared to the split-belt treadmill group. Due to the inherent variability and complexity of the split-belt treadmill protocol, the general stimulus provided to the split-belt group was more difficult to regulate and progress over time, limiting its ability to transfer to mobility-related tasks. While split-belt treadmill training is possible in individuals at risk for mobility disability, the current study demonstrates that long-term, complex split-belt treadmill training may not be more beneficial than traditional treadmill training for improving walking.

Importantly, our treadmill-based interventions did elicit cardiovascular fitness improvements in individuals at risk of mobility disability, providing some level of construct validity to both walking interventions. The traditional treadmill group increased their VO2max by an average of 1.63 ± 0.27 mL/kg/min, exceeding the minimal clinically important difference previously reported (1 mL/kg/min) [80]. Conversely, the split-belt group did not reach the minimal clinically important difference threshold (0.91 ± 0.06 mL/kg/min). Oxygen uptake, and cardiovascular fitness in general, is an important component of mobility disability [81]; thus, this progression indicates an improvement in the fitness aspect of mobility disability. Additionally, gait efficiency can provide more detailed insight into the relationship between cardiovascular function and walking ability, as gait efficiency can be compared across participants regardless of changes in gait speed [82]. The traditional treadmill group used significantly less oxygen per unit velocity following the intervention, but this measure was not different over time for the split-belt treadmill group. One potential reason for this observed training group difference is that only the traditional treadmill group was tested on the same apparatus on which they trained. The traditional treadmill group had the benefit of practicing walking on a single-belt treadmill for 16 weeks, with the potential to increase the incline, similar to the VO2max test our participants underwent. A potential area of interest would be to measure cardiovascular ability during split-belt treadmill walking in both groups to better understand the influence split-belt training has on fitness. Regardless, the initial intent of the study intervention was to match aerobic intensity between conditions. However, our cardiovascular results indicate that we struggled to control the stimulus in the split-belt treadmill group to elicit progressive improvements in gait efficiency, which may be reflected in the lack of transfer to mobility and gait measures.

Spatiotemporal gait parameters and gait kinetics were anticipated to improve in both groups who underwent the intervention, as treadmill training has been widely used in rehabilitation settings to target changes in spatiotemporal parameters (see [83] for a recent review). However, our findings indicate that this hypothesis can only be partially accepted. Traditional treadmill training improved walking speed following our intervention by 0.08 ± 0.03 m/s, approaching the clinically meaningful difference of 0.1 m/s previously established [84]. This level of improvement was not seen following split-belt treadmill training, which may be attributable to the differences in average walking speed throughout the intervention between traditional and split-belt treadmill groups (Table 2). Furthermore, we observed that the traditional treadmill group significantly increased the length of their strides following the intervention during self-selected overground walking. While the other gait parameters did not improve significantly, mean stride length is the only gait characteristic relevant to predicting overall gait speed decline [85]. This is the first study, to our knowledge, to investigate the effect of treadmill training interventions (traditional or otherwise) on walking for those at risk for mobility disability, with the majority of the literature focusing on older adults who are already frail [86], institutionalized [87], or fallers [88]. As individuals who are more impaired may display greater gains in physical interventions [89,90], it is unsurprising that this sample did not show larger improvement in 16 weeks. Yet, our findings indicate improvements in the important measures of stride length in a population at risk of mobility disability. Thus, mean stride length may represent the variable most sensitive to change in this population and should be monitored in those at risk for mobility decline. However, the split-belt treadmill group did not significantly improve any of the chosen walking variables, other than step width, indicating a lack of generalizability to overground walking of learning effects caused by the split-belt paradigm. Split-belt training focuses explicitly on the process of changing and adapting step length and step time to fit various belt speeds. Thus, individuals who participated in the split-belt training did not practice the same number of constantly-sized steps as those in the traditional treadmill group. Additionally, the assessments used to test general walking ability, including the primary outcome measure of walking speed, were more closely aligned with traditional treadmill walking. Perhaps more specific walking tasks related to adaptability, such as obstacle crossing, would have demonstrated improvements for individuals in the split-belt intervention group. It is important to acknowledge that we did not control for overground walking speed in our pre–post assessments, as this is known to alter spatiotemporal gait parameters [91,92], yet we do not consider this a confounding factor in the minimal changes we observed.

We anticipated an improvement across all assessments of clinical function, and yet saw only TUG performance improved following the intervention for the split-belt treadmill group. Individuals who completed the split-belt treadmill training improved TUG time by an average of 1.4 s (or 10%), which is above the clinically relevant change in mobility for frail older adults [93]. To our knowledge, there is no reported minimal detectable change score for community-dwelling older adults for the TUG. Therefore, we calculated a sample-specific standard measure of error and minimal detectable change as previously outlined [94]. Including all participants (n = 38), the calculated standard error was 0.4 s ([ICC2,1] = 0.97 [95]) resulting in a minimal detectable change of 0.9 s. Even with our relatively small sample, the improvements observed by the split-belt treadmill group are not likely due to measurement error, and thus reflect true improvement. Yet, the SPPB and DGI did not significantly change between pre- and post-testing. The differences in improvement between the TUG, SPPB, and DGI may be due to the inherent nature of the assessments. Compared to the TUG, both the DGI and SPPB tests have been identified to have a greater ceiling effect [96]. Additionally, the DGI and SPPB include several ordinally scored sub-items that add to an overall score, which has a definite maximum and limits variation between scores. Specific sub-items of the DGI and SPPB may be more or less responsive to interventions than others, which are not reflected in the overall score [97]. Therefore, the TUG may be a more appropriate test for this specific sample. As mentioned, simply walking overground without obstacles or complex tasks may not adequately test the skills regularly practiced during split-belt treadmill walking. The TUG contains a turning component that may reflect transferable skills from the split-belt training group that are not experienced by traditional treadmill walking. The TUG is arguably the assessment we used that employs the most similar mechanics and adaptation to the split-belt treadmill training; specifically, participants must create and adjust to disparities in step length difference as they navigate around the cone [98–100]. Turning, which is a complex walking task, requires distinct asymmetric gait patterns and increased prefrontal cortex activation than straight walking [101]. To successfully complete a turn, the inside leg must reduce its step length compared to the outside leg in order to stabilize the center of mass [99]. Split-belt treadmill interventions train individuals to successfully adapt to asymmetric walking patterns, allowing those in the split-belt group to capitalize on this practice during the TUG assessment. We did not analyze the TUG with instrumentation to retain clinical applicability, yet it would be of interest to segment the individual sections of the TUG into straight walking vs. turning to determine which portion was improved in the split-belt group. While the DGI contains a pivot turn, it is subjectively scored and may not be sufficiently sensitive to turning changes in a population at risk for mobility disability. The TUG is moderately responsive to a decline in activities of daily living but has only a small effect on predicting improvements in activities of daily living [102]. Thus, the TUG may capture a change in general fitness better than other, perhaps more costly measures, such as gait analysis of forward walking or VO2max.

The cardiovascular benefits we observed could impact cognitive function, as cerebral small vessel disease has been implicated in cognitive impairment [103,104], but we saw no improvements in measures of cognitive function for either training group. Instead, we observed a worsening in TMT-B time in both training groups, indicating a decline in executive function [63]. We previously showed that executive function did not correlate with short-term adaptation to split-belt walking [105], yet the impact of 16 weeks of split-belt treadmill training was unclear. Our results suggest no benefit of split-belt treadmill training over traditional treadmill training on cognitive performance. A systematic review of central nervous system control of adaptation to split-belt treadmill walking indicated that proprioceptive and visual feedback are utilized by motor planning, and that sensory integration areas of the cortex and cerebellum make anticipatory changes [106], while executive function is primarily associated with prefrontal cortex [107]. Our walking interventions did not enhance global cognitive function, as we observed no change in MMSE score. Given the fact that we observed no change in pre- to post-performance in cognitive measures, four months is enough time between testing to mitigate significant practice effects that could enhance performance on repeated cognitive tests. However, the lack of detectable cognitive decline over a 4-month period in our control group suggests that this may be an insufficient time period to show meaningful change in clinical outcome measures of cognition in pre-mobility disability adults. It is possible that our recruitment efforts did not target individuals at risk of cognitive decline, and we may have recruited older adults who were too high functioning cognitively. Although a more cognitively impaired group may have shown substantive cognitive declines during the intervention period, we recruited individuals at a point where a mobility intervention was still feasible, and highly impaired older adults may not have been able to complete the protocol.

There was high inter-subject variability in the response to 16 weeks of split-belt treadmill training. As overground walking speed was our primary outcome, we classified individuals as either responders or non-responders based on a 0.05 m/s change in walking speed [94]. With this threshold, 6/12 individuals in the traditional treadmill group and 1/12 individuals in the split-belt treadmill group were classified as responders. There were no differences in selected baseline measures between responders and non-responders including cognitive test performance, fitness performance, functional tests, nor gait parameters (Appendix G). However, given that 50% of the traditional treadmill group improved walking speed compared with 8% of the split-belt treadmill group, it is clear that there is no additional benefit to split-belt treadmill training.

While pre–post VO2max assessment changes were not significant, throughout the training intervention, we did anecdotally observe group differences in RPE, HR, and progression of treadmill speed. These training-related differences indicate that the split-belt and traditional treadmill groups received different training stimuli. The intervention was designed to progress individuals based on estimated maximum heart rate (HRmax) while increasing walking duration and training speed, but this was difficult to achieve in the split-belt treadmill group. Overall, the traditional treadmill group was trained successfully with incremental increases in HR, starting at an average of 66% of HRmax and finishing the last quarter of the intervention at 74% of HRmax. The split-belt treadmill group trained at a lower intensity, starting at 62% of HRmax and ending the last quarter of the intervention at 65% of HRmax. We initially planned to use exercise intensity defined by a percentage of maximal heart rate reserve observed during the VO2max testing. However, during the maximal testing session, many participants stopped before reaching a maximum or were on medications that prevented heart rate from increasing. Because we proposed to use 50% of maximal heart rate reserve in the first week, this was difficult given that some participants ”prescribed target heart rate” was lower or near their resting heart rate. As a result of these issues, we instead used an age-predicted maximum heart rate. Given our demographic of pre-clinically disabled older adults, our exercise physiologists recommended that we targeted the intervention based on perceived physiological exertion instead (RPE).

Split-belt treadmill walking might have been perceived as more physiologically demanding as RPE was, on average, 1 point higher than the traditional treadmill group at every time point during the intervention. However, these participants often had lower HR than prescribed at these higher RPE values, indicating the increased exertion was not due to a fitness challenge. Average RPE during training sessions for both the traditional treadmill and split-belt treadmill group was 2 to 3 (i.e., easy to moderate). Of note, a subset of participants in the split-belt treadmill group would rate physical exertion as high as 7 or 8 (i.e., really hard), and thus required more breaks or regression of speed during individual training days. We also had considerable drop-out in our split-belt treadmill intervention group. Despite initially high recruitment levels, 17 individuals ceased participation in the split-belt treadmill group due to unrelated medical issues, relocation, or “too much time” required to participate. Anecdotally, individuals within the split-belt treadmill group reported soreness at a greater rate than those in the traditional treadmill group. It is possible that asymmetric loading during split-belt treadmill gait is less familiar or uncomfortable over long periods of time for older adults, which could detrimentally impact adherence to a split-belt treadmill-based intervention.

During training, we also observed a lack of progression in the training treadmill speed for the split-belt group. For the traditional treadmill group, 12/13 participants increased their treadmill training speed over the 16 weeks, with an average 78% increase of day 1 speed. In the split-belt treadmill group, four participants could not increase their speed over the length of the intervention, and the average increase in speed for this group was 23% of day 1 speed. While care was taken to progress individuals throughout the study, safety and comfort were a priority to increase retention and prevent further drop-out. Future investigations should determine how the relationships between RPE, HR, and speed of individual limbs affect training during repeated split-belt treadmill walking.

Our protocol is similar to that described previously to evaluate generalization of adaptation [108] in which authors may test the short-term motor learning processes that split-belt treadmill walking can provide [37]. While asymmetric adaptation is necessary to navigate a variety of environmental demands, these adaptations often manifest as short-term perturbations [109–111] and symmetric walking returns quickly [74,112,113]. As all our participants were otherwise healthy, no asymmetry was expected in their walking patterns and our thrice-weekly training program for 16 weeks may not have been generalizable to their specific gait impairments or future decline. Researchers demonstrated that repeated split-belt treadmill training can elicit long-term mobility and walking improvements in post-stroke individuals [114], indicating the specific use of asymmetric split-belt treadmill walking to target the asymmetric walking observed in post-stroke individuals. However, it is possible that increased specificity comes at a cost of sensitivity. In our sample of those at risk of mobility disability, a greater overall stimulus may be necessary to train the various dimensions contributing to mobility disability such as strength and cardiovascular fitness. The protocol for the split-belt treadmill group may have been perceived as too challenging for this population, resulting in less progression over the course of the intervention. Imposing asymmetrical loads aimed at targeting adaptability was not advantageous compared to traditional treadmill training for individuals who presented with mobility limitations.

As mentioned, split-belt treadmills have been used successfully to cause long-term locomotor adaptation in neurologically impaired populations, such as those with Parkinson’s Disease [73,115,116] or post-stroke [114,117–119]. However, our results suggest that split-belt treadmills used with older adults at risk of mobility disability show no additional advantage over traditional treadmill walking. The split-belt treadmill does not challenge short-term volitional step control, which is necessary when navigating complex environments, but rather challenges inter-limb coordination. Gait adaptation training on a split-belt treadmill would be beneficial for individuals with sub-pyramidal deficits who need improvement with inhibition, excitation, reflexive stepping, and motor coordination [106,120]. Our findings suggest that different pathways are responsible for age-related mobility impairments compared with the neurologically impaired populations that benefit from split-belt treadmill training. Typical aging leads to disruption in prefrontal, parietal, putamen, and cerebellum neural circuitry which have been implicated in mobility impairments [121]. Neurological pathways implicated in mobility impairments include cortical processing for sensorimotor control [122], reduced neuromuscular activation [30], and executive function [123,124]. Our findings suggest that traditional treadmill walking may target some of these pathways, yet individuals at risk for mobility disability (who may rely on executive function for step placement in adaptive walking) do not develop that skill on the split-belt treadmill.

Future interventions focused on enhancing locomotor adaptability in older adults at risk of mobility disability should consider a design that targets each of the nine domains of locomotor adaptability [15]. We strived to control exposure to aerobic training between the split-belt and traditional treadmill groups throughout our intervention, yet this must be better controlled in future studies. Indeed, our experience in this study suggests that controlling the intensity of an intervention targeting long-term locomotor adaptability may be important for future success. To achieve this, it may be important to randomize participants into groups not only by age and gender, but also by fitness level based on initial assessments.

While split-belt treadmill gait adaptation training is feasible in a cohort of adults at risk for mobility disability, we found that controlling the stimulus was challenging and did not provide additional benefit over traditional treadmill training. Our findings indicate a cautionary tale about the implementation of complex and variable gait adaptation training interventions on mobility outcomes.

Author Contributions: Conceptualization, C.H.; methodology, J.R., T.R. and C.H.; software, M.T.; formal analysis, M.T., J.R., T.R., S.B. and C.H.; investigation, J.R., T.R., A.S., S.B. and C.H.; resources, C.H.; data curation, M.T., A.S., S.B. and F.W.; writing—original draft preparation, F.W., S.B. and J.R.; writing—review and editing, F.W., S.B., A.S., T.R. and C.H.; visualization, A.S.; supervision, C.H.; project administration, J.R., A.S., T.R., S.B. and F.W.; funding acquisition, C.H. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of University of Florida (IRB201400915, Date Approved: 17 July 2018).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are openly available at https://doi.org/10.5281/zenodo.6584789 (accessed on 31 July 2022).

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Appendix A

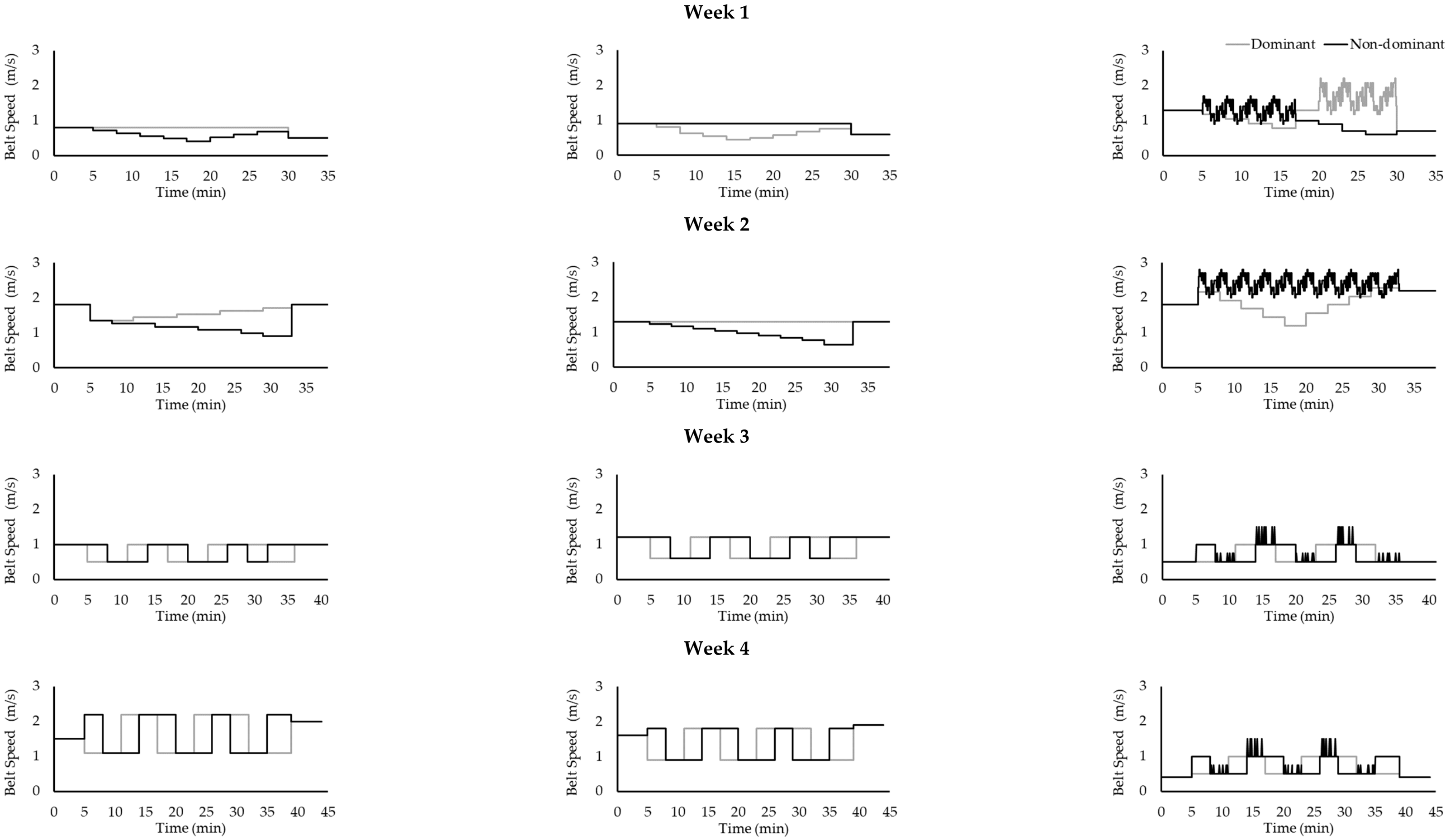

Figure A1. Exemplar 4-week training block. Figure documents split-belt speeds between dominant and non-dominant limb treadmill belts for each intervention for an exemplar 4-week training block. Day 1 and 2 for each week are shown in the first two columns, highlighting the ″constant″ condition, Day 3 (in the right-hand column) highlights the ″noisy″ condition in Week 1 and 2, and the ″Perturbation″ condition in Week 3 and 4.

Appendix B. Participant Drop-Out

Why did subjects drop out?

Across the groups, 20 participants dropped out of the study.

For the split-belt treadmill group, 18 participants dropped out:

- 5 participants reported an unrelated health issue;
- 1 participant had a cardiac event approximately halfway through the study;
- 10 participants reported that the time commitment was too much;
- 2 participants moved away from the area.

For the traditional treadmill group, 1 participant dropped out:

- 1 participant reported the time commitment was too much.

For the control group, 1 participant was withdrawn:

- 1 participant was withdrawn due to starting exercising regularly.

When did subjects drop out?

For the split-belt training group:

- 2 participants dropped out before training began;
- 5 participants dropped out in the first quarter (Weeks 1–4);
- 6 participants dropped out in the second quarter (Weeks 5–8);
- 4 participants drooped out in the third quarter (Weeks 9–12);
- 1 participant dropped out in the fourth quarter (Weeks 13–16).

For the traditional treadmill group:

- 1 participant dropped out at week 5.

For the control group:

- 1 participant was withdrawn at week 12.

Of note, 7 participants dropped out within 1 week of an acute perturbation session, which occurred on Weeks 3, 4, 7, 8, 11, 12, and 16.

Appendix C

Table A1. Clinical function measures based on group and time (means ± standard error).

Measure	Group	Time	Mean ± SE
Short Physical Performance Battery Score (SPPB; maximum possible score: 12)	Control	Pre	8.9 ± 0.4
		Post	8.5 ± 0.6
	Traditional	Pre	8.4 ± 0.5
		Post	9.3 ± 0.6
	Split-belt	Pre	9.1 ± 0.4
		Post	8.8 ± 0.6
Dynamic Gait Index (DGI; maximum possible score: 24)	Control	Pre	20.1 ± 0.6
		Post	21.3 ± 0.6
	Traditional	Pre	21.2 ± 0.7
		Post	21.4 ± 0.7
	Split-belt	Pre	20.5 ± 0.6
		Post	21.6 ± 0.6
Timed Up and Go (TUG; s)	Control	Pre	11.6 ± 0.7
		Post	11.1 ± 0.6
	Traditional	Pre	10.5 ± 0.8
		Post	11.2 ± 0.7
	Split-belt	Pre	12.2 ± 1.0 *
		Post	10.9 ± 0.6 *

* denotes significant time * group interaction.

Appendix D

Table A2. Cardiovascular fitness measures based on group and time (means ± standard error).

Measure	Group	Time	Mean ± SE
Maximal Oxygen Uptake (mL/kg/min) †	Control	Pre Post	15.2 ± 1.3 15.5 ± 1.2
	Traditional	Pre Post	17.4 ± 1.2 * 19.0 ± 1.2 *
	Split-belt	Pre Post	17.0 ± 1.2 18.2 ± 1.2
Heart Rate (bpm)	Control	Pre Post	128.9 ± 4.4 126.1 ± 4.7
	Traditional	Pre Post	141.5 ± 4.2 143.5 ± 4.5
	Split-belt	Pre Post	132.5 ± 4.2 133.6 ± 4.5
Rating of Perceived Exertion (maximum possible score: 20)	Control	Pre Post	15 ± 1 15 ± 1
	Traditional	Pre Post	14 ± 1 14 ± 1
	Split-belt	Pre Post	15 ± 1 15 ± 1
Gait Efficiency (mL/kg/m)	Control	Pre Post	0.23 ± 0.02 0.24 ± 0.02
	Traditional	Pre Post	0.29 ± 0.02 * 0.25 ± 0.02 *
	Split-belt	Pre Post	0.26 ± 0.02 0.27 ± 0.02

† denotes significant effect of time; * denotes significant time*group interaction.

Appendix E

Table A3. Cognitive function measures based on group and time (means ± standard error).

Measure	Group	Time	Mean ± SE
Mini-Mental State Exam (maximum possible score: 30)	Control	Pre Post	27.7 ± 0.5 27.3 ± 0.5
	Traditional	Pre Post	28.1 ± 0.5 28.0 ± 0.5
	Split-belt	Pre Post	27.8 ± 0.5 27.8 ± 0.5
Trail Making Test-A (s) †	Control	Pre Post	106.2 ± 7.5 106.2 ± 7.8
	Traditional	Pre Post	98.9 ± 7.8 106.9 ± 8.1
	Split-belt	Pre Post	101.9 ± 7.2 104.3 ± 7.5
Trail Making Test-B (s) †	Control	Pre Post	159.8 ± 13.2 154.3 ± 20.7
	Traditional	Pre Post	140.9 ± 13.8 177.3 ± 21.6
	Split-belt	Pre Post	144.6 ± 12.7 172.3 ± 19.9

Table A3. *Cont.*

Measure	Group	Time	Mean ± SE
Difference between Trail Making Test-B and Trail Making Test-A (dTMT, B-A) (s)	Control	Pre	53.6 ± 9.7
		Post	48.0 ± 17.8
	Traditional	Pre	42.1 ± 10.1
		Post	70.3 ± 18.6
	Split-belt	Pre	42.6 ± 9.3
		Post	67.9 ± 17.1

† denotes significant effect of time.

Appendix F

Table A4. Kinetic gait performance outcomes based on group and time (means ± standard error).

Measure	Group	Time	Mean ± SE
Peak Ankle Plantarflexion Moment (Nm)	Control	Pre	37.2 ± 13.5
		Post	41.1 ± 9.0
	Traditional	Pre	74.8 ± 13.5
		Post	61.4 ± 9.0
	Split-belt	Pre	44.4 ± 11.0
		Post	43.7 ± 7.3
Peak Eccentric Ankle Plantar Flexor Power (W/kg)	Control	Pre	0.22 ± 0.04
		Post	0.14 ± 0.04
	Traditional	Pre	0.15 ± 0.04
		Post	0.15 ± 0.04
	Split-belt	Pre	0.17 ± 0.03
		Post	0.23 ± 0.04
Peak Concentric Hip Flexor Power (W/kg)	Control	Pre	0.34 ± 0.07
		Post	0.19 ± 0.04
	Traditional	Pre	0.21 ± 0.07
		Post	0.26 ± 0.04
	Split-belt	Pre	0.33 ± 0.06
		Post	0.36 ± 0.03

Appendix G. Responders vs. Non-Responders to the Intervention

Participants were considered responders if they achieved a faster overground walking speed of $\geq$0.05 m/s [88]. Control participants were not considered. In summary, 6/12 individuals in the traditional treadmill group and 2/13 individuals in the split-belt treadmill group were classified as responders. This was an exploratory analysis focused on determining which characteristics at baseline, if any, differed between responders and non-responders. Due to the small sample size, independent-samples Mann–Whitney U tests were used to compare the responders vs. non-responders in three separate analyses:

1. Both traditional treadmill and split-belt together (total n = 25, responders n = 8, non-responders n = 17);
2. Traditional treadmill only (total n = 12, responders n = 6, non-responders n = 6);
3. Split-belt treadmill only (total n = 13, responders n = 11, non-responders n = 2).

Significance was set to $p < 0.05$. In total, 16 variables were included in each analysis.

In all three analyses, there were no statistical differences between responders and non-responders. Only the change in overground speed, the variable that sorted the individuals, was different between groups. Means, standard error (SE), test statistic (U), and exact significance (p) are provided in the table below. Variability measures were calculated with standard deviation. Non-responders (NR) are in gray and responders (R) are in white. Bolded values represent significant variables.

Measure		**Combined Groups**				**Traditional Treadmill**				**Split-belt Treadmill**			
		n	**Mean ± SE**	**U**	***p*-Value**	**n**	**Mean ± SE**	**U**	***p*-Value**	**n**	**Mean ± SE**	**U**	***p*-Value**
Change in Walking Speed (m/s)	NR	17	−0.03 ± 0.02	136	**<0.001**	6	−0.01 ± 0.03	36	**0.002**	11	−0.04 ± 0.03	22	**0.026**
	R	8	0.16 ± 0.03			6	0.17 ± 0.04			2	0.12 ± 0.03		
Age (years)	NR	17	71 ± 1	78.5	0.549	6	73 ± 2	16	0.818	11	70 ± 1	12.5	0.769
	R	8	72 ± 2			6	72 ± 2			2	72 ± 6		
Mass (kg)	NR	17	97 ± 6	47	0.238	6	94 ± 5	12	0.394	11	98 ± 9	5	0.308
	R	8	84 ± 5			6	87 ± 6			2	77 ± 9		
Height (m)	NR	17	1.66 ± 0.02	60	0.669	6	1.66 ± 0.01	18	1.000	11	1.66 ± 0.03	8	0.641
	R	8	1.64 ± 0.03			6	1.65 ± 0.04			2	1.62 ± 0.05		
Short Physical Performance Battery	NR	17	9 ± 0	52.5	0.374	6	9 ± 1	21.5	0.589	11	9 ± 0	4.5	0.231
	R	8	9 ± 0			6	9 ± 0			2	8 ± 1		
Dynamic Gait Index	NR	17	21 ± 0	85	0.344	6	21 ± 1	23	0.485	11	21 ± 0	5.5	0.308
	R	8	21 ± 1			6	22 ± 1			2	19 ± 3		
Timed Up and Go (s)	NR	17	11.6 ± 0.6	42	0.562	6	10.3 ± 1.1	11	0.914	11	12.4 ± 0.6	10	0.923
	R	6	10.9 ± 1.1			4	10.0 ± 1.4			2	17.7 ± 0.1		
Maximal Oxygen Uptake (mL/kg/min)	NR	17	17.18 ± 1.29	60.5	0.834	6	17.05 ± 2.32	17.5	0.937	10	17.26 ± 1.63	7	0.606
	R	8	17.31 ± 0.85			6	17.78 ± 1.07			2	15.9 ± 0.20		
Gait Efficiency (mL/kg/m)	NR	17	0.27 ± 0.02	67.5	0.834	6	0.29 ± 0.04	15.5	0.699	10	0.26 ± 0.02	8	0.758
	R	8	0.28 ± 0.02			6	0.29 ± 0.02			2	0.25 ± 0.05		
Mini-Mental State Exam	NR	17	28 ± 0	53	0.406	6	29 ± 1	8.5	0.132	11	28 ± 0	12.5	0.769
	R	8	28 ± 1			6	27 ± 1			2	28 ± 2		
Walking Speed (m/s)	NR	17	0.96 ± 0.03	52	0.374	6	0.96 ± 0.07	16	0.818	11	0.96 ± 0.04	6	0.410
	R	8	0.91 ± 0.04			6	0.93 ± 0.04			2	0.86 ± 0.09		
Stride Length (m)	NR	17	1.06 ± 0.03	65	0.887	6	1.04 ± 0.07	19	1.000	11	1.08 ± 0.04	9	0.769
	R	8	1.06 ± 0.03			6	1.06 ± 0.04			2	1.06 ± 0.05		
Stride Time (s)	NR	17	1.12 ± 0.02	85	0.344	6	1.09 ± 0.03	23	0.485	11	1.14 ± 0.03	19	0.154
	R	8	1.17 ± 0.03			6	1.14 ± 0.02			2	1.24 ± 0.07		
Stride Length Variability (m)	NR	17	0.04 ± 0.01	94	0.140	6	0.04 ± 0	22	0.589	11	0.05 ± 0.01	20	0.103
	R	8	0.05 ± 0			6	0.04 ± 0			2	0.05 ± 0.00		
Stride Time Variability (s)	NR	17	0.04 ± 0.01	76	0.669	6	0.03 ± 0	17	0.937	11	0.04 ± 0.01	16	0.410
	R	8	0.04 ± 0.01			6	0.03 ± 0			2	0.05 ± 0.02		

Bolding indicates significance at $p < 0.05$.

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