



Article

Effects of Obesity on Adaptation Transfer from Treadmill to Over-Ground Walking

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Abstract: Discerning whether individuals with obesity transfer walking adaptation from treadmill to over-ground walking is critical to advancing our understanding of walking adaptation and its usefulness in rehabilitating obese populations. We examined whether the aftereffects following split-belt treadmill adaptation transferred to over-ground walking in adults with normal-weight body mass index (BMI) and obese BMI. Nineteen young adults with obesity and 19 age-matched adults with normal weight walked on flat ground at their preferred speed before and after walking on a treadmill with tied belts (preferred speed) and with the split-belt at their preferred speed and at a speed 50% slower than their preferred speed. The adaptation and aftereffects in step length and double-limb support time symmetry were calculated. We found that the amount of temporal adaptation was similar for adults with obesity and with normal weight ($p > 0.05$). However, adults with obesity showed greater asymmetry for double-limb support time following split-belt treadmill walking compared to adults with normal weight ($p < 0.05$). Furthermore, the transfer of asymmetry for double-limb support time from the treadmill to over-ground walking was less in adults with obesity than in adults with normal weight ($p < 0.05$). The transfer of adapted gait following split-belt treadmill walking provides insight into how atypical walking patterns in individuals with obesity could be remediated using long-term gait training.

Keywords: obesity; gait; adaptation; rehabilitation



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1. Introduction

Obesity is a public health epidemic, elevating the risk of numerous comorbid conditions, including heart disease, stroke, type 2 diabetes, and certain cancers that may cause premature death [1]. The prevalence of obesity in the United States is 42.4% among adults over 20 years old and has increased 12% over the past 20 years [2]. To combat obesity, increasing energy expenditure via increasing physical activity has been strongly recommended; physical activity promotes weight loss and can help maintain cardiovascular and metabolic health [3]. Unfortunately, individuals with obesity fall short of physical activity recommendations [4]. Although walking is a recommended and cost-effective intervention used to increase overall physical activity, walking may be harmful to individuals with obesity [5]. Common characteristics of individuals with obesity include altered spatiotemporal gait parameters (slower speed and shorter and wider steps) and joint kinematics (less flexed lower extremity joints) compared to adults with normal weight [6–8], which likely serve as ways to compensate for a lack of postural stability [9].

Obesity is associated with the abnormal distribution of body fat in the abdominal area and greater thigh and trunk girth [5,10,11], which could hinder the ability to adapt walking patterns to changes caused by environmental constraints, such as surfaces with obstacles or slopes [12]. A failure to quickly and effectively adapt to change while walking can lead to injuries and poses a safety risk [13]. For example, compared to normal-weight adults, adults with obesity demonstrate poor strategies during obstacle avoidance, with higher toe

clearance to cross low versus high obstacles [14]. Additionally, adults with obesity have difficulty matching steps to an audio metronome beat while walking; they step later than the metronome beat regardless of the BPM (beats per minute) [12]. Adults with obesity also walk slower after a slow metronome pace and faster after a fast metronome pace, thus demonstrating aftereffects. Taken together, the evidence shows that these challenges with adaptation may make it difficult to safely complete walking and activities of daily living, such as walking to the grocery store and crossing the street in accordance with traffic signals. This raises a question; how do individuals with obesity change the ways in which they walk when posed with a disruption in their typical patterns of walking?

A split-belt treadmill training paradigm has been used to examine walking adaptation. In a split-belt treadmill paradigm, two separate belts moving beneath each leg can be independently controlled [15,16]. This paradigm allows for repeated practice of walking in which each leg moves at a different speed. Previous research on split-belt treadmill walking adaptation in healthy adults has demonstrated that step length and double-limb support time are asymmetric during an initial adaptation period when the belt speed is changed so that one belt moves faster than the other [16]. Consequently, the limb on the slow belt takes a longer step than the limb walking on the fast belt. Over time, walkers gradually adapt to re-establish step symmetry during split-belt walking. After only 10–15 min of split-belt treadmill walking, walkers exhibit aftereffects [16,17]. These findings have led to the suggestion that the adaptive strategies observed during split-belt treadmill walking may have the potential to be used as a rehabilitative technique for individuals post-stroke [16,18], with Parkinson's disease [19], and who have had amputations [20]. However, whether the same would be true for adults with obesity is unknown. Using split-belt treadmill training as a rehabilitative tool might spur faster adaptation to future perturbations experienced in everyday life and facilitate increased physical activity; short-term changes in walking could be capitalized upon with repeated practice to produce long-term changes in walking [21].

Critical to advancing our understanding of gait adaptation and its usefulness in rehabilitating obese populations is discerning whether the adaptive effects observed on a treadmill transfer to over-ground walking. Previous studies demonstrated the transfer of split-belt treadmill walking adaptation to over-ground walking [21]. The results revealed that the adapted walking pattern following split-belt treadmill walking partially transfers to over-ground in healthy young adults, suggesting that the treadmill walking adaptation influenced some aspects of over-ground walking. Examining whether adults with obesity transfer walking from the treadmill to over-ground walking could provide support for the usefulness of treadmill walking as a rehabilitative tool.

Therefore, the current study investigated the effects of obesity on adaptation and transfer from the treadmill to over-ground walking. We hypothesized that normal and obese BMI groups would successfully adapt both spatial and temporal parameters following split-belt perturbations and would transfer adapted walking patterns from the split-belt treadmill to over-ground walking. We also hypothesized that the extent of the adaptation and transfer would be less in adults with obesity than in adults with normal weight [12–14].

2. Materials and Methods

2.1. Participants

Thirty-eight young adults (19 normal weight BMI and 19 obese BMI) participated in this study (Table 1). The study eligibility criteria included being between 18–35 years old, having no weight loss surgery, having no significant cardiovascular, vestibular, or other neurologic disorders, having no hip, knee, or foot pain on most days during the past 90 days, and having the ability to walk independently on a treadmill for over 40 min. All the participants gave informed written consent before participating. The Boston University Institutional Review Board approved the protocols (4922E).

Table 1. Demographics and anthropometric information. Means are listed with standard deviations in parentheses.

	BMI Groups	
	¹ NW (N = 19; ³ F = 10)	² OB (N = 19; ³ F = 12)
Age (years)	23.21 (5.46)	28.27 (4.03)
Height (m)	1.71 (0.09)	1.69 (0.08)
Weight (kg)	66.83 (12.46)	119.74 (29.08)
BMI (kg/m ²)	22.37 (2.49)	42.62 (8.01)
Waist Circumference (cm)	78.93 (9.01)	123.56 (18.42)
Gait Velocity (m/s)	1.24 (0.12)	1.05 (0.12)

¹ NW: normal weight; ² OB: obesity; ³ F: female.

2.2. Experimental Protocol

Spatiotemporal walking data were collected at the Motor Development Lab and the Human Adaptation Lab in Sargent College, Boston University, Boston, MA, from July 2019 through to November 2019. Walking adaptation was characterized using a 6.10 m long × 0.89 m wide pressure-sensitive gait carpet (Protokinetics, LLC; Peekskill, NY, USA; 120 Hz sampling frequency) and a split-belt treadmill with two independent belts and full-length force plates (Bertec Corporation, Columbus, OH; 1000 Hz sampling frequency). As these data were collected as part of a larger study evaluating navicular drop, the participants walked barefoot with stick-on foot pads throughout the experiment. The experimental paradigm is shown in Figure 1. The walking task involved six conditions. In the first condition, participants walked on the carpet at their own pace for two minutes. Participants began the trials standing 2 m before the edge of the carpet and ended the trials 2 m after walking off the carpet. Trials began and ended the walking with verbal prompts from the experimenter (i.e., “Go” and “Stop”). After that, they turned around and walked again. The participants’ comfortable over-ground walking speeds were calculated by the total step length divided by the total step time (m/s) in the first over-ground condition. This was used to set the preferred walking speed in the following treadmill conditions. The participants then moved to the treadmill and performed four treadmill walking conditions (Figure 1). As the treadmill speed was constant within each of the four treadmill walking conditions, the transition phases between tied-belt and split-belt were discarded for the analysis. All the participants reported that their dominant leg was the right leg. During treadmill walking conditions, participants were positioned in the middle of the treadmill with their dominant leg on the right-side belt (the slow belt was always on the dominant leg). Participants were instructed to refrain from looking down at the belts. The treadmill had rails on the front, left, and right sides to grab in case they lost balance, but participants were instructed not to grab the rails unless they felt unbalanced. Before testing, all participants walked on a treadmill at their comfortable walking speed until they felt comfortable with treadmill walking and ready for testing. Participants initially performed a tied-belt walking condition for five minutes. During the tied-belt condition, the treadmill belt speeds were set at each participant’s preferred over-ground walking speed. Following this, the participants underwent a split-belt condition for 10 min. During the split-belt condition, the belt under the left leg moved at the participant’s preferred speed while the belt under the right leg moved at a speed 50% slower than their preferred speed. As has been demonstrated previously [15,17,22], this split-belt perturbation typically causes spatial and temporal gait asymmetries (i.e., visible interlimb difference); however, with 10 min of practice with ‘split-belts’, gait symmetry is typically restored and the asymmetric stepping goes away. Following this split-belt condition, the participants walked on tied-belts for 5 min to wash out the perturbation. At the beginning of the washout condition, the participants typically exhibit the opposite asymmetry in their gait (i.e., they walk with an inter-limb difference in the opposite direction). Thus, we assessed the storage and retention of the novel walking pattern in the washout condition. By the end of the washout condition, the participants returned to symmetrical walking on the tied-belts. Participants

then performed a second split-belt perturbation condition for five minutes to examine how quickly they re-adapted during split-belt walking. Following this, the participants completed an over-ground walking condition again at their own pace for two minutes (Figure 1).

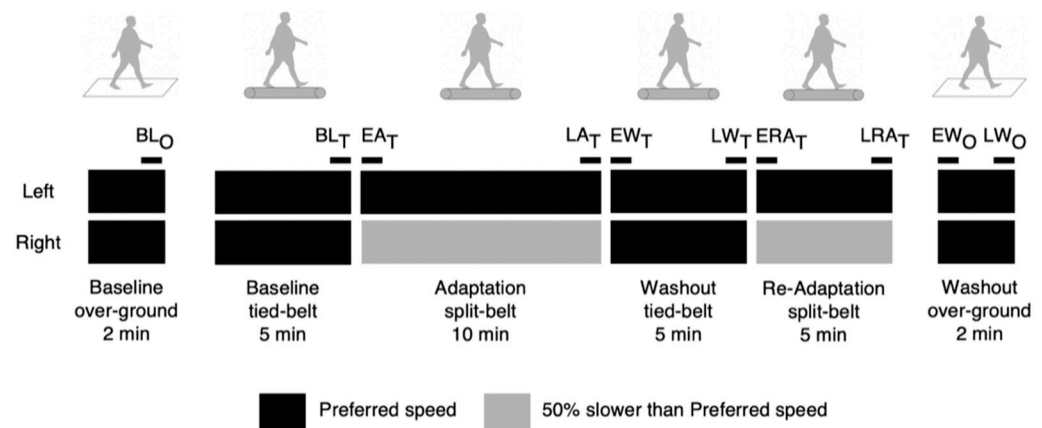


Figure 1. Time course for the experimental paradigm showing the over-ground baseline (BL_O), treadmill baseline (BL_T), split-belt treadmill adaptation (EA_T & LA_T), tied-belt treadmill washout (EW_T & LW_T), split-belt treadmill re-adaptation (ERA_T & LRA_T), and over-ground washout conditions (EW_O & LW_O). For split-belt treadmill walking, the upper bar shows fast (left, black) belt speed and the lower bar shows slow (right, gray) belt speed.

2.3. Data Analysis

We examined where the participants placed their feet (spatial coordination) and when participants placed their feet as they walked (temporal coordination) during all of the testing conditions. Center of pressure (COP) data were determined using the pressure-sensitive gait carpet for over-ground walking and the force plates for treadmill walking. COP consisted of a time series of the x and y coordinates. Gait events, such as heel strike and toe-off, were independently determined for each leg from the pressure data for over-ground walking and the force data for treadmill walking. The step length (m) was calculated by the absolute difference in the anteroposterior center of pressure (COP) position between the right and left foot at the heel strike. Double-limb support time (s) was measured by the period between the heel strike and the contralateral toe-off for each step. Step length symmetry was calculated as the ratio of the slow (right; dominant leg) step length to the fast (left; non-dominant leg) step length. Double-limb support symmetry was calculated as the ratio of the initial double-limb support time of the slow (right) leg to that of the fast (left) leg over the gait cycle. Positive symmetry values indicate a longer left step length and initial double-limb support time, while negative values indicate a shorter right step length and initial double-limb support time. A value of 0 indicates perfect symmetry, and with a greater symmetry value, the gait is more asymmetric. To determine the transfer of aftereffects observed on the treadmill to over-ground walking, we calculated a transfer index [21]:

$$\text{Transfer Index} = \frac{EW_O - BL_O}{EW_T - BL_T},$$

where EW_O is the mean of the first ten strides in the over-ground washout condition, BL_O is the mean of the first 10 strides in the over-ground baseline condition, EW_T is the mean of the first 10 strides in the tied-belt treadmill washout, and BL_T is the mean of the first 10 strides in the tied-belt treadmill baseline condition.

2.4. Statistical Analysis

Two-way repeated measures analysis of variance (ANOVA) was used to identify statistically significant interactions in the gait symmetry (i.e., step length symmetry and

double-limb support time symmetry) between groups (i.e., adults with obesity vs. adults with normal weight) across testing conditions. To test the degree of adaptation during the split-belt treadmill walking, we compared gait symmetry between groups and between adaptation conditions (tied-belt treadmill baseline (BL_T) vs. early split-belt treadmill adaptation (EA_T)). To test storage (what participants learned) during the adaptation period, we compared gait symmetry between groups and between the washout condition (tied-belt treadmill baseline (BL_T) vs. the early tied-belt treadmill washout (EW_T)). To test the memory of the adapted walking pattern when re-exposed to the same perturbation, we compared gait symmetry between groups and between the re-adaptation condition (early split-belt treadmill adaptation (EA_T) vs. the early split-belt treadmill re-adaptation (ERA_T)). When the ANOVA yielded significant results, post hoc analyses were performed using a Bonferroni correction. Lastly, to test the transfer of aftereffect (i.e., how split-belt training influenced participants' abilities to store a new walking pattern) from the treadmill to over-ground walking, we used a t-test to compare the transfer index between the groups. The values for each outcome variable were averaged over the first 10 strides in EA_T , EW_T , ERA_T , and EW_O , as well as the last 10 steps in BL_O , BL_T , LA_T , LW_T , LRA_T , and LW_O . The effect sizes for the ANOVA were reported via partial eta squared (ηp^2) after p-values, giving 0.01 (small), 0.09 (medium), and 0.25 (large) effects. Effect sizes for the t-test were reported via Cohen's d considering 0.2 (small), 0.5 (medium), and 0.8 (large) effects [23]. For all tests, the statistical significance was set at 0.05 (two-tailed). All the statistical analyses were performed using SPSS (Version 26.0, SPSS Inc., Chicago, IL, USA).

3. Results

Figure 2 shows changes in double-limb support time symmetry (Figure 2a) and step length symmetry (Figure 2c) over the course of over-ground and split-belt treadmill walking. There was no statistically significant interaction between the groups and the adaptation conditions on double-limb support time symmetry ($F(1, 72) = 0.01, p = 0.94, \eta p^2 < 0.01$; Figure 2b) and step length symmetry ($F(1, 72) = 0.17, p = 0.68, \eta p^2 < 0.01$; Figure 2d). The main effect of the groups showed no significant difference in double-limb support time symmetry ($F(1, 72) = 0.66, p = 0.42, \eta p^2 < 0.01$) and step length symmetry ($F(1, 72) = 0.30, p = 0.59, \eta p^2 < 0.01$). The main effect of the adaptation condition showed that there were significant differences in double-limb support time symmetry ($F(1, 72) = 197.59, p < 0.01, \eta p^2 = 0.70$) and step length symmetry ($F(1, 72) = 961.74, p < 0.01, \eta p^2 = 0.92$) between the tied-belt treadmill baseline (BL_T) and early split-belt treadmill adaptation (EA_T), indicating that both groups were perturbed when the belts were first split (i.e., walking asymmetrically with inter-limb difference).

There was a statistically significant interaction between the groups and washout conditions on double-limb support time symmetry ($F(1, 72) = 5.68, p = 0.02, \eta p^2 = 0.10$; Figure 2b). The symmetry value for the double-limb support time was significantly greater in adults with obesity than in adults with normal weight during the early tied-belt washout period (when the split-belt perturbation is removed). The symmetry value for the double-limb support time was similar between adults with obesity and adults with normal weight during tied-belt baseline. There was no significant interaction between the groups and washout conditions regarding step length symmetry ($F(1, 72) = 2.91, p = 0.09, \eta p^2 = 0.03$; Figure 2d). The main effect of the group showed no significant difference in step length symmetry between adults with obesity and adults with normal weight ($F(1, 72) = 2.39, p = 0.13, \eta p^2 = 0.02$). The main effect of the washout condition showed that there was a significant difference in step length symmetry between the tied-belt treadmill baseline (BL_T) and the early tied-belt treadmill washout (EW_T) ($F(1, 72) = 241.95, p < 0.01, \eta p^2 = 0.74$), indicating that both groups showed aftereffects (i.e., walking asymmetrically with inter-limb difference in the opposite direction).

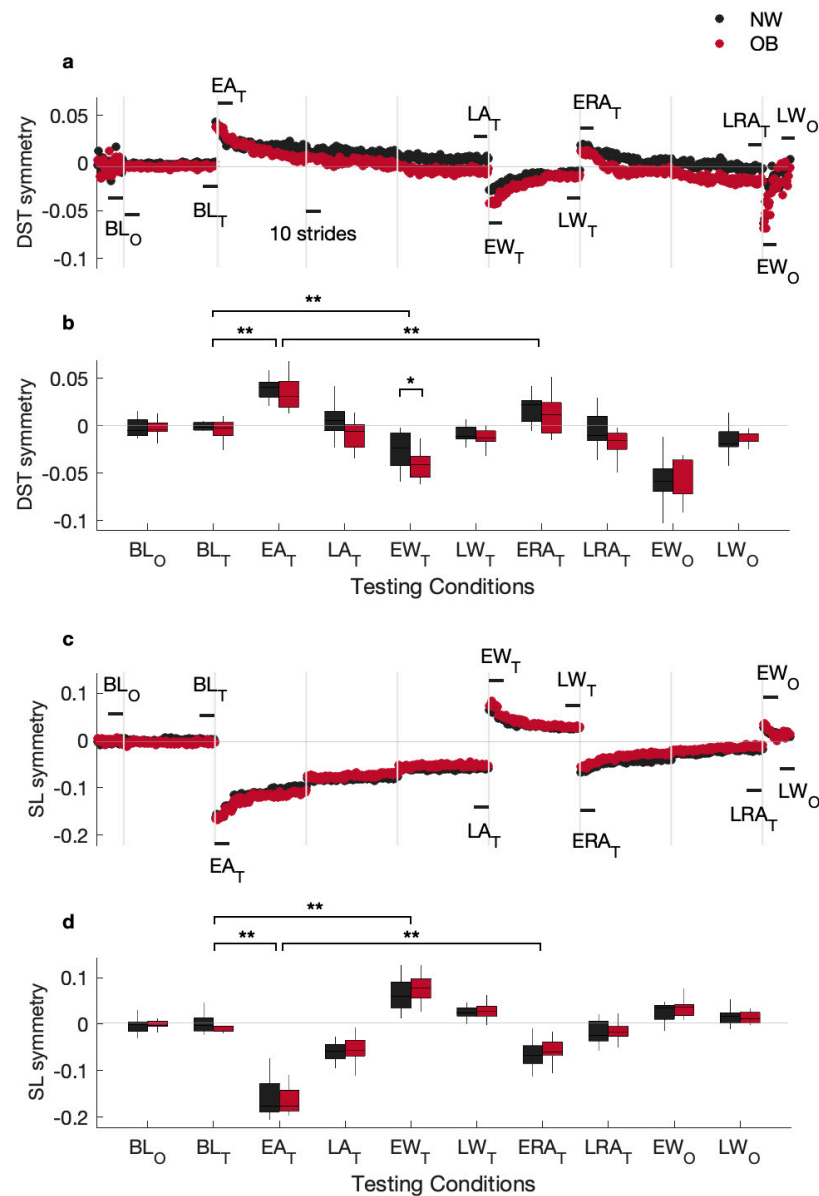


Figure 2. Experimental paradigm showing the periods of testing conditions in a light gray vertical line: over-ground baseline (BL_O), treadmill baseline (BL_T), early treadmill adaptation (EA_T), late treadmill adaptation (LA_T), early treadmill washout (EW_T), late treadmill washout (LW_T), early treadmill re-adaptation (ERA_T), late treadmill re-adaptation (LRA_T), early over-ground washout (EW_O), late over-ground washout (LW_O). Double-limb support time (DST) symmetry (a) and step length (SL) symmetry (c) values for sequential strides over the ground and on the treadmill between adults with normal weight (dark grey) and obesity (dark brown) across all testing conditions. A value of 0, represented as a light gray horizontal axis, indicates perfect symmetry. Means and standard errors for DST symmetry (b) and SL symmetry (d) are shown between the body mass index (BMI) groups (NW: normal weight; OB: obesity) across testing conditions. ** $p < 0.01$; * $p < 0.05$.

There was no statistically significant interaction between the groups and re-adaptation conditions on double-limb support time symmetry ($F(1, 72) = 0.62, p = 0.43, \eta p^2 < 0.01$; Figure 2b) and step length symmetry ($F(1, 72) = 1.01, p = 0.32, \eta p^2 = 0.01$; Figure 2d). The main effect of the group showed no significant difference in double-limb support time symmetry ($F(1, 72) = 0.18, p = 0.19, \eta p^2 = 0.02$) and step length symmetry ($F(1, 72) = 0.06, p = 0.81, \eta p^2 < 0.01$). The main effect of the adaptation condition showed that there were significant differences in double-limb support time symmetry ($F(1, 72) = 37.10, p < 0.01, \eta p^2 = 0.31$)

and step length symmetry ($F(1, 72) = 250.91, p < 0.01, \eta p^2 = 0.75$) between the early split-belt treadmill adaptation (EA_T) and the early split-belt treadmill re-adaptation (ERA_T), indicating that both groups experienced smaller errors early in the re-adaptation period rather than early in the initial adaptation period (i.e., participants were less perturbed by the split-belts).

Figure 3 shows that there was a significant difference in the transfer of double-limb support time symmetry (from the treadmill to over-ground walking) between groups. The transfer index for double-limb support time symmetry was less in adults with obesity than in adults with normal weight ($t(36) = 3.49, p < 0.01, d = 0.75$; Figure 3b). However, the transfer index for step length symmetry was not statistically different in adults with obesity compared to adults with normal weight ($t(36) = 0.58, p = 0.15, d = 0.17$; Figure 3a).

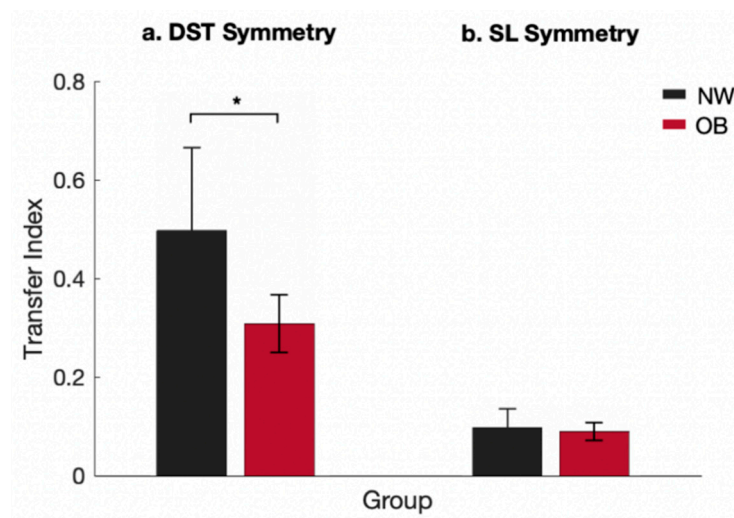


Figure 3. Transfer Index for adults with normal weight (dark grey) and obesity (dark brown) for double-limb support time (DST) symmetry (a) and step length (SL) symmetry (b). The transfer index indicates the amount of adaptation transfer from the treadmill to over-ground walking in each BMI group. For both adapted parameters, the transfer index is greater in adults with normal weight than in adults with obesity. Error bars indicate the standard deviation. Asterisk indicates a significant difference between groups. * $p < 0.05$.

4. Discussion

In the current study, we demonstrated that the temporal gait adaptation following split-belt treadmill walking was greater in adults with obesity versus adults with normal weight. We also found that a temporal gait adaptation following split-belt treadmill walking transfers to over-ground walking in both adults with obesity and adults with normal weight. The adaptation transfer of double-limb support time was smaller in adults with obesity when compared with the adults with normal weight. This provides additional support for the previous suggestion that gait characteristics such as lower step frequency and longer double-limb support phase exist in those with obesity.

Throughout the adaptation, we observed that both groups successfully adapted their walking patterns to split-belt perturbations (adaptation), showed aftereffects (washout), and saved the memory of adapted walking patterns (re-adaptation), which is supported by previous research focusing on healthy young adults [16,17,22]. This is the first study, however, to demonstrate that adults with obesity adapted their walking and transferred from the treadmill to a real-world task: in this case, over-ground walking. In the current study, step length and double support asymmetries following split-belt treadmill adaptation transferred to over-ground walking. Therefore, this study supports the possibility of using a treadmill to, for instance, lengthen or quicken stepping movements or manage new constraints in individuals with obesity.

Contrary to our hypothesis, however, we did not observe any differences in step length symmetry between normal-weight adults and adults with obesity throughout the testing conditions. One interpretation is that the amounts of adaptation, aftereffects, savings, and transfers for step length symmetry may depend on the imposed walking speed as a mediator of the effect of obesity on gait symmetry. In the current study, to maximize the effect of obesity on gait adaptation, treadmill belt speeds were set at each participant's preferred over-ground walking speed. Specifically, each participant's treadmill baseline walking speed was matched with their self-selected comfortable walking speed over the ground, which is more like everyday life where speed is sometimes imposed. However, we acknowledge that using a preferred speed for each participant may have limited the amount of variability in response to the split-belt perturbation. Given that each participant walked at a comfortable speed and adapted to the split-belt perturbation with a 2:1 speed ratio between the fast and slow belt, this explains how participants with obesity adapted and washed out at similar rates to participants with normal weight despite a slower walking speed. Future research may elucidate whether a fixed split-belt speed ratio may affect the rate of adaptation (split-belt) and de-adaptation (tied-belt) across BMI groups.

Interestingly, the initial double-limb support times of both the slow (right) leg and the fast (left) leg over the gait cycle were larger in adults with obesity versus adults with normal weight over all of the testing conditions. This finding suggests that temporal gait is affected by obesity, which is consistent with previous findings [5,6,12]. Researchers suggest that prioritizing postural stability is likely primary for adults who have less ability to recover from a loss of balance [24]. Considering that individuals with obesity have impaired postural control and stability [25], increasing double-limb support time, along with increasing step width and decreasing walking speed, could be a primary strategy to maximize postural stability, and to avoid asymmetric gait and falling after split-belt treadmill walking. Furthermore, it is reasonable to suppose that step length could be balanced by contributions from increased double-limb support time. When exposed to split-belt perturbation, the treadmill powers the legs, so more control is required for regulating the period of double-limb support (i.e., when both limbs are on the ground). This may have led to longer double-limb support times in adults with obesity compared with adults with normal weight.

Researchers have studied how human actions adapted to a specific environment are transferred to other environments and demonstrated that similarity of the movements can influence the transfer of action [26,27]. The transfer of adapted patterns is greatest when walking in a familiar environment [28–30]. The amount of transfer could be similar for adults with obesity and with normal weight if both groups have experience with treadmill walking. We suspect that the transfer of the adapted gait pattern observed in adults with obesity could be similar to that observed in normal weight adults, considering the fact that treadmills have been widely used for exercise. However, the altered temporal gait parameters (i.e., increased double-limb support times) observed in the obese population might reduce the ability to switch temporal patterns with the change in gait environment from the treadmill to over-ground walking (i.e., less transfer of aftereffects for the temporal gait parameter).

Previous studies on rehabilitative gait training have demonstrated that, although a little different, there are similarities observed between treadmill and over-ground walking in young adults [31–33]. An ideal rehabilitation intervention could include both treadmill and over-ground walking to maximize improvements in walking through task-specific training. In the current study, participants reduced step asymmetry in both treadmill and over-ground walking and transferred aftereffects for step symmetry from the treadmill to over-ground walking. Therefore, it could be beneficial for future studies to examine the use of split-belt treadmill walking paired with over-ground walking in interventions with those with obesity. One drawback of this approach, of course, would be the cost incurred by using a rehabilitation paradigm that necessitates the use of split-belt treadmill

technology. However, future findings may reveal whether there are rehabilitative benefits that outweigh the cost of the equipment.

We acknowledge that the present study has limitations. Firstly, we intentionally recruited participants without comorbidities, such as osteoarthritis, plantar fasciitis, or cardiovascular disease. Thus, the generalizability of our study is limited by the fact that our participants may not be representative of those with obesity and additional conditions. However, this reduced confounding variables that could have influenced the interpretation of our results. Secondly, the number of male participants with obesity that we tested was smaller than the number of females, which may reduce the ability to generalize the results to males. Third, we did not have the participants rate their perceived exertion during the walking task. Future studies should examine how perceived exertion affects walking adaptation in adults with obesity. Despite these limitations, our results provide important information about the effect of obesity on walking adaptation and transfer from treadmill to over-ground walking.

5. Conclusions

Our findings suggest that adults with obesity showed greater asymmetry for double-limb support time than adults with normal weight. The transfer of asymmetry for double-limb support time from the treadmill to over-ground walking was less in adults with obesity than in adults with normal weight. Understanding how individuals with obesity adapt their walking to a new environment and how adapted patterns transfer from treadmill to over-ground walking can be used to design interventions aimed at increasing physical activity.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patient(s) to publish this paper.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the consent provided by participants on the use of confidential data.

Conflicts of Interest: The authors declare no conflict of interest.

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