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Article

Split-Belt Treadmill Training Improves Mechanical Energetics and Metabolic Cost in Women with Unilateral Hip Osteoarthritis: A Proof-of-Concept Study

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Abstract: We have shown that step length asymmetry seen in hip osteoarthritis (OA) is associated with poorer mechanical energy exchange and higher metabolic cost. Thus, we conducted this proof-of-concept study to investigate whether modifying step length through split-belt treadmill training can improve walking energetics. We conducted split-belt treadmill training in four periods with simultaneous motion and metabolic analyses in 10 women with unilateral hip OA. Using repeated measures ANOVA, we evaluated changes across each period, in step length asymmetry, mechanical energy exchange, and O_2 rate. We also examined changes in hip range of motion and peak plantarflexor moment. We used Spearman correlations (rho) to assess the strength of associations between variables at baseline and after adaptation. We found that step length asymmetry and O_2 rate decreased ($p = 0.007$, $p < 0.001$) and mechanical energy exchange increased ($p < 0.001$). Reduced step length asymmetry was associated with reduced O_2 rate (rho = 0.732, $p = 0.016$). Hip range of motion increased ($p < 0.001$) and was associated with decreased step length asymmetry (rho = 0.818, $p = 0.004$), indicating a potential mechanism. These findings suggest that reducing step length asymmetry by split-belt treadmill training could improve walking energetics in hip OA people.

Keywords: gait asymmetry; mechanical energy exchange; metabolic energy expenditure; error augmentation; osteoarthritis

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1. Introduction

Regular physical activity is critical for healthy aging with benefits for cardiovascular health, cognitive health, and living independence [1–4]. Physical activity has additional benefits for people with hip osteoarthritis (OA), which affects almost 10% of adults over the age of 45 and can cause considerable pain and disability [5]. Physical activity decreases pain, improves physical function, and improves health-related quality of life in people with OA [6]. Unfortunately, many people who have hip OA do not achieve recommended levels of physical activity [7]. The "Pain Energy Model of Mobility Limitation in the Older Adult" [8] posits that older adults with chronic pain have a higher energy cost during walking, and that this impairment leads to lower levels of physical activity. Indeed, we have previously demonstrated that greater energy used during walking was associated with lower self-reported physical activity, more sedentary time, and less light activity time in women with hip OA [9]. Based on this cross-sectional work, we speculated that improving walking energetics in hip OA could be a strategy for improving physical activity and overall function.

Gait alterations associated with hip OA affect walking energetics. For example, we have recently shown that step length asymmetry is associated with higher metabolic cost of gait and less mechanical energy exchange [10]. Others have noted that pain is associated with reduced hip extension and external rotation during walking in women with hip OA [11]. These gait alterations may contribute to step length asymmetry, which is often observed in people with hip OA [12–15]. Therefore, we further speculated that modifying step length asymmetry could be a potential rehabilitation strategy to improve walking energetics. However, it is not known whether or not the gait deviations associated with walking energetics are modifiable in people with hip OA.

A rehabilitation intervention utilizing motor adaptation, which is a form of error-driven motor learning targeting specific gait deviations for people after stroke has emerged [16–18], is proposed. Error augmentation is a motor learning technique in which the motor error is amplified, driving the nervous system to make corrections. This technique can be applied to address step length asymmetry through split-belt treadmill training during which the step length asymmetry is magnified when the individual exposed walks on the dual-belts that are moving at different speeds. This increase in step length asymmetry (error) provides a prompt for the individual to recalibrate their motor commands in a feedback manner to reduce asymmetry. For example, a previous study found that a 15-min split-belt treadmill adaptation session temporarily induced step length symmetry in stroke patients who had step length asymmetry at baseline [17]. Additionally, step length asymmetry improved after eight-training sessions of treadmill-based error-augmentation gait training in people with non-traumatic transtibial amputation [19]. Moreover, when unequal step length gradually changes to equal step length in healthy participants, the net metabolic power is also reduced [20]. This novel rehabilitation strategy has not been explored in the hip OA population.

The purpose of this proof-of-concept study was to determine the immediate effect of modifying step length through split-belt treadmill training on walking energetics in people with hip OA. We hypothesized that in women with hip OA, split-belt treadmill training results in reduced step length asymmetry, increased mechanical energy exchange, and decreased oxygen consumption. Additionally, we also aimed to determine how participants adapted their gait during the training. To this end, we explored the effect of split-belt treadmill training on hip sagittal plane range of motion (ROM) and peak ankle plantarflexor moment during push off.

2. Materials and Methods

We recruited 10 community-dwelling women (Table 1) from an IRB-approved contact list of people with diagnoses of unilateral hip OA based on ICD-10 codes, confirmed by self-report. Exclusion criteria included other actively symptomatic joints, history of any total joint replacement within 2 years, inability to walk without assistive devices, and any medical condition that interfered with gait or the ability to safely complete the protocol. All participants provided written informed consent for this study which was approved by the Institutional Review Board of the University of Illinois at Chicago.

Table 1. Demographic data.

Variable	Mean	SD	Range	Number
Age (years)	64.7	6.2	56–76	-
Height (m)	1.59	0.09	1.50–1.73	-
Weight (kg)	81.33	19.59	56.7–119.29	-
BMI (kg/m^2)	31.95	5.97	24.22–42.27	-
Race White	-	-	-	3
Black or African American	-	-	-	7

We conducted split-belt treadmill training on a custom split-belt treadmill (Treadmetrix, Park City, UT, USA) in 4 periods—warm-up (3 min), baseline (1 min), adaptation (10 min), and post-adaptation (1 min)—with motion analysis and metabolic energy analysis

(Figure 1). We instructed participants to avoid holding the handrail if at all possible. All participants wore a safety harness that would engage in the case of a fall; however, no body weight support was provided. The self-selected walking speed was determined during the warm-up period; treadmill speed was adjusted until the participant reports that she felt comfortable. During the adaptation period, the involved limb (OA-side) was assigned to the slow speed belt (half of the self-selected walking speed), and the uninvolved limb was assigned to the fast speed belt (self-selected walking speed) [17,21,22].

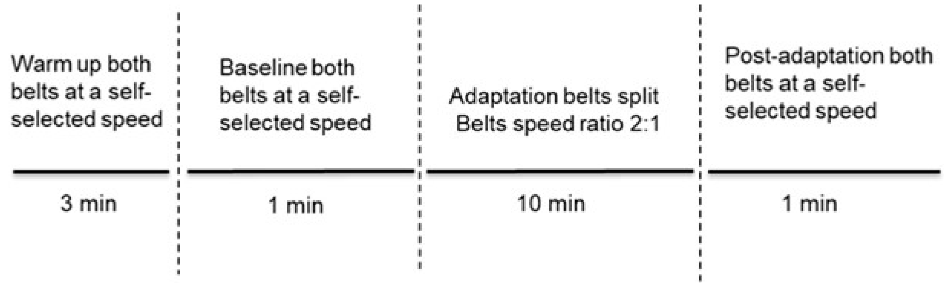

Figure 1. Split-belt treadmill training protocol.

Gait analysis was conducted using a standard (modified Helen Hayes) marker set and conventional methods previously described in detail [23]. Briefly, marker positions were recorded at a sampling rate of 120 Hz using an eight-camera motion analysis system (Motion Analysis Corporation, Santa Rosa, CA), while ground reaction forces were collected with two embedded force plates (AMTI, Watertown, MA, USA) under the belts of a custom split-belt treadmill. Data were filtered by using a low-pass Butterworth filter at a 6-Hz cutoff frequency for kinematics data and 30 Hz cutoff frequency for the kinetic data. Joint angles and moments were calculated according to standard methods previously described in detail using Visual 3D software (C-Motion, Germantown, MD, USA). Joint moments were normalized to body weight times height and were reported as N m/kg*m [24].

Step length was defined as the distance between the heel markers of each limb at their respective heel strikes. Step length asymmetry was evaluated using the symmetry index (SI) [25] as in our previous work [10].

$$SI = [\,|X_{uninvolved} - X_{involved}|\,/X_{uninvolved}] \times 100 \quad (1)$$

$X_{uninvolved}$ = the step length of the uninvolved limb; $X_{involved}$ = the step length of the involved limb. An SI value of 0 indicates full symmetry between steps with each leg; a higher SI value indicates a greater degree of step length asymmetry. Step length asymmetry was analyzed at baseline (1 min), beginning of adaptation (2 min), end of adaptation (2 min), and post-adaptation (1 min).

Mechanical energy exchange measures the energy transfer between the potential and kinetic energy of the inverted pendulum movement of the COM during gait and is typically reported as %Recovery. First, using MATLAB R2019a software (MathWorks, Natick, MA, USA) [26], potential (E_p) and kinetic (E_k) energy were calculated according to the equations [27],

$$E_p = M_{tot} \times 9.81 \times COM\ (z),\ E_k = 1/2 \times M_{tot} \times (V_x{}^2 + V_y{}^2 + V_z{}^2), \quad (2)$$

where M_{tot} = body mass; COM (z) = the vertical position (z) of the COM; andV_x, V_y, and V_z = the linear velocity of the COM in each direction. Next, %Recovery was calculated through the equation [28],

$$\%Recovery = [\Delta^+ E_p + \Delta^+ E_k - \Delta^+ E_{tot}]/[\Delta^+ E_p + \Delta^+ E_k], \quad (3)$$

as in our previous work [10].

Oxygen consumption was measured using indirect calorimetry with a Cosmed K5 (COSMED, Rome, Italy) portable gas exchange system that warmed up for >15 min before data collection and was calibrated to manufacturer specifications. We sampled oxygen consumption and carbon dioxide production breath-by-breath. Data were collected simultaneously during the previously described split-belt treadmill training protocol. Steady-state VO_2 (breath to breath change <5% for 2 min) was monitored and recorded. O_2 rate was extracted from the Omnia cardiopulmonary diagnostic software (COSMED, Rome, Italy). O_2 rate (ml/kg/min) indicates the intensity of physical effort during exercise and is a time-dependent parameter.

We used SPSS version 26 (IBM Corp, Armonk, NY, USA) for all analyses. Departures from normality among continuous variables were evaluated using Shapiro–Wilk test [29]. Next, we used median absolute deviation to identify outliers. Median plus or minus 2.5 times the median absolute deviation was used for outlier detection [30].

Repeated measures ANOVA was used to compare changes in SI for step length, mechanical energy exchange, O_2 rate, hip sagittal plane ROM, and peak ankle plantarflexor during push off across training periods. A Bonferroni post hoc test was used to compare each condition (period). The key comparison was the baseline period to the end of adaptation period. Cohen's d was used to assess the effect size of the change between the periods. Cohen's d was measured by taking the difference between two means of the variable in each period and dividing by the pooled standard deviation. Spearman correlations (rho) were used to assess the relationships between the baseline variables and the change of variables in different periods. An α level of 0.05 was used to indicate statistical significance for all tests.

3. Results

Step length asymmetry, mechanical energy exchange, and O_2 rate were normally distributed ($W \geq 0.842$, $p \geq 0.184$). There were no outliers for step length asymmetry, mechanical energy exchange, O_2 rate, hip sagittal plane ROM, or peak ankle plantarflexor moment.

3.1. Changes in Step Length Asymmetry

Participants showed asymmetry in step length (higher SI value) during baseline walking (SI: 10.4 ± 4.6%) with a longer step length of the involved limb (52.5 ± 11.0 cm) compared to the uninvolved limb (48.8 ± 9.2 cm). The step length of the involved limb at the baseline period (52.5 ± 11.0 cm) was longer than the end of adaptation period (43.42 ± 6.07 cm). There was a significant association between SI for step length and mechanical energy exchange during baseline walking (rho = −0.661, $p = 0.038$). However, SI for step length and mechanical energy exchange were not associated with O_2 rate during baseline walking (SI for step length: rho = 0.382, $p = 0.276$; mechanical energy exchange: rho = −0.285, $p = 0.425$).

There was a significant effect of training period for SI for step length ($p = 0.003$) (Figure 2). Post hoc testing revealed that SI for step length significantly increased from the baseline period to the beginning of adaptation (46.2 ± 17.6%) ($p = 0.002$, Cohen's d = 2.75). At the end of the adaptation period there was a more symmetrical step length on the two limbs. Post hoc testing further revealed that SI for step length significantly decreased from the baseline period to the end of adaptation period (3.1 ± 1.5%) ($p = 0.007$, Cohen's d = 2.23), and significantly decreased from the beginning of adaptation to the end of adaptation period ($p = 0.001$). Additionally, the step length of the involved limb (43.2 ± 6.1) was not significantly greater than that of the uninvolved limb (42.45 ± 6.2) at the end of adaptation period.

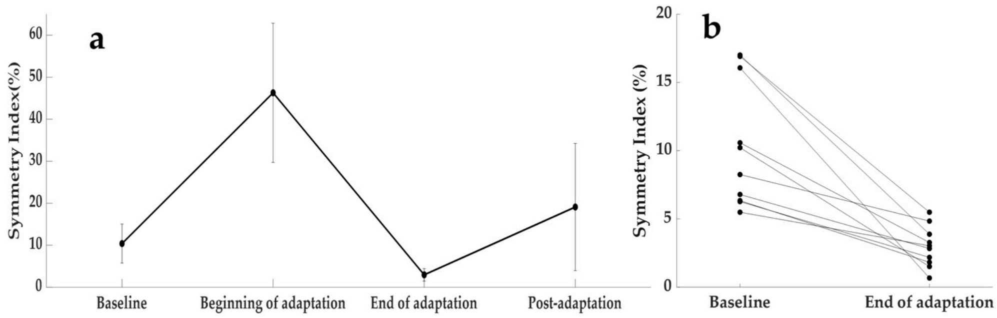

Figure 2. Changes in step length asymmetry. (**a**) Average of step length asymmetry across the different periods of split-belt treadmill training. The error bars represent the standard deviation. (**b**) Step length asymmetry was improved for all participants from the baseline to the end of adaptation periods.

3.2. Changes in Mechanical Energy Exchange

There was a significant effect of training period for mechanical energy exchange ($p < 0.001$) (Figure 3). Post hoc testing revealed that mechanical energy exchange significantly increased from the baseline period (22.0 ± 3.9%) to the end of adaptation period (29.3 ± 4.4%) ($p < 0.001$, Cohen's d =1.75). Additionally, mechanical energy exchange significantly decreased from the end of adaptation to the post-adaptation period (21.6 ± 5.2%) ($p = 0.002$, Cohen's d = 1.60). However, the change in mechanical energy exchange was not significantly associated with any change in step length asymmetry (rho = 0.261, $p = 0.467$) and O_2 rate (rho = 0.055, $p = 0.881$).

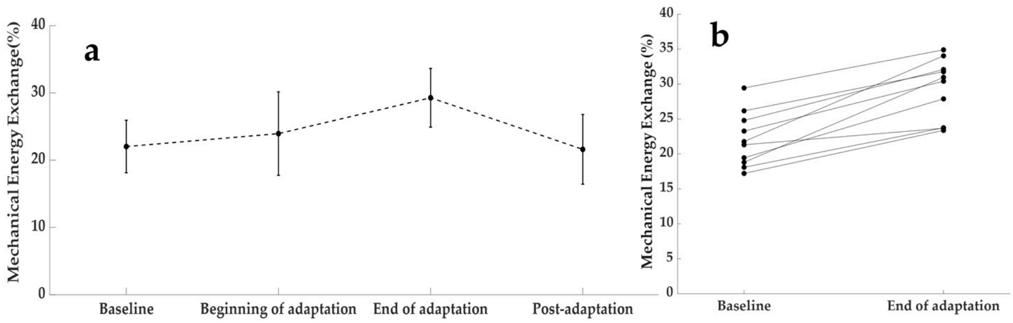

Figure 3. Changes in mechanical energy exchange. (**a**) Average of mechanical energy exchange across different periods of split-belt treadmill training. The error bars represent the standard deviation. (**b**) Mechanical energy exchange improved for all participants from the baseline to the end of adaptation periods.

3.3. Changes in Oxygen Consumption

There was a significant effect of training period for O_2 rate ($p < 0.001$) (Figure 4). Post hoc testing revealed that O_2 rate significantly decreased from the baseline period (8.8 ± 2.0 mL/kg/min) to the end of adaptation period (6.7 ± 1.5 mL/kg/min) ($p < 0.001$). Additionally, O_2 rate significantly decreased from the beginning of adaptation (8.7 ± 1.7 mL/kg/min) to the end of adaptation period ($p < 0.001$, Cohen's d = 1.17), but significantly increased from the end of adaptation period to the post-adaptation period (8.9 ± 1.3 mL/kg/min) ($p = 0.001$, Cohen's d = 1.52). Moreover, the decreasing SI for step length was significantly associated with the decreasing O_2 rate from baseline to the end of adaptation period (rho = 0.732, $p = 0.016$) (Figure 5). However, there was no association between step length asymmetry and O_2 rate at the end of adaptation period (rho = 0.467, $p = 0.174$).

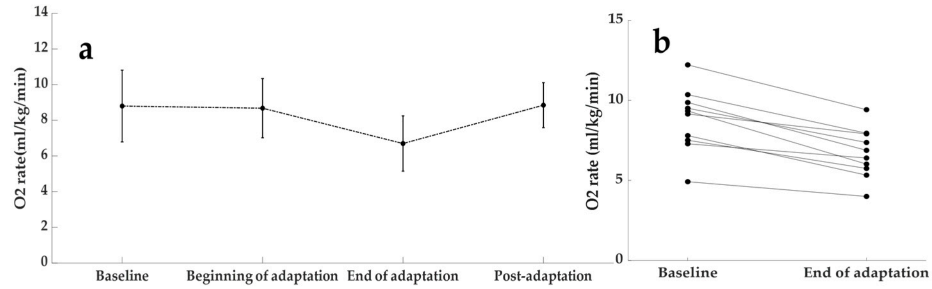

Figure 4. Changes in oxygen consumption. (**a**) Average of O_2 rate across different periods of split-belt treadmill training. The error bars represent the standard deviation. (**b**) O_2 rate decreased for all participants during the baseline and the end of adaptation periods.

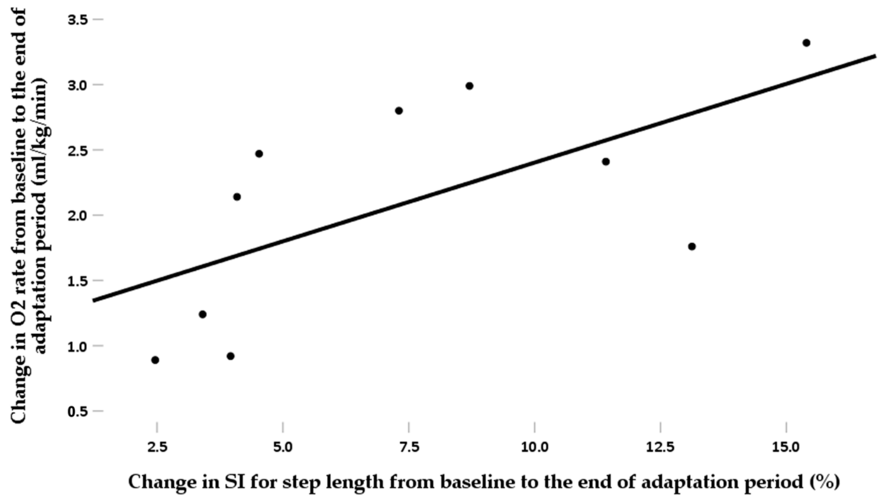

Figure 5. Association between change in step length asymmetry and change in oxygen consumption. A larger decrease in step length asymmetry from baseline to the end of adaptation period was associated with a larger decrease in O_2 rate from baseline to the end of adaptation period (rho = 0.732, p = 0.016). Black dots represent each participant's data. Black line represents the regression line.

3.4. Changes in Hip Sagittal Plane ROM

There was a significant effect of training period for hip sagittal plane ROM ($p < 0.001$) (Figure 6). Hip sagittal plane ROM significantly increased from the baseline period (26.19 ± 8.12) to the end of adaptation period (33.65 ± 7.89) (p = 0.006, Cohen's d = 0.93). Hip sagittal plane ROM increase was associated with step length asymmetry reduction (rho = 0.818, p = 0.004) (Figure 7).

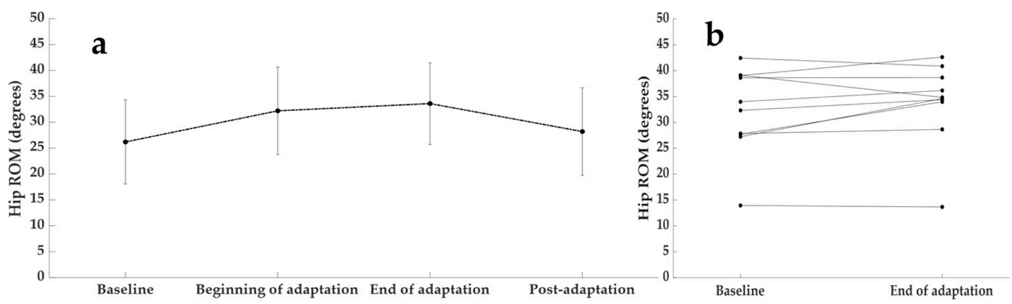

Figure 6. Changes in hip sagittal plane ROM. (**a**)Average of hip sagittal plane ROM across different periods of split-belt treadmill training. The error bars represent the standard deviation. (**b**) Hip ROM increased for all participants during the baseline and the end of adaptation periods.

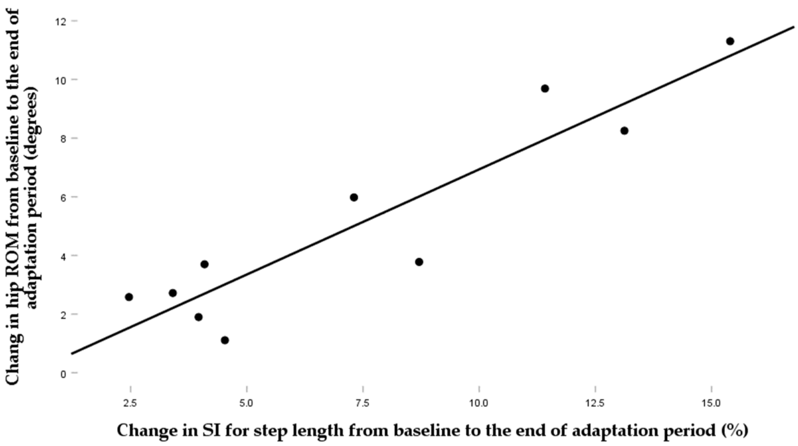

Figure 7. Association between change in step length asymmetry and change in hip ROM. A larger decrease in step length asymmetry from baseline to the end of adaptation period was associated with a larger increase in hip sagittal plane ROM from baseline to the end of adaptation period (rho = 0.818, $p = 0.004$). Black dots represent each participant's data. Black line represents the regression line.

3.5. Changes in Peak Ankle Plantarflexor Moment during Push Off

There was a significant effect of training period for peak ankle plantarflexor moment during push off ($p = 0.007$) (Figure 8). The difference in peak ankle plantarflexor moment between the baseline period and the end of adaptation period was not statistically significant ($p = 0.083$). There was no association between step length asymmetry and peak ankle plantarflexor moments (Rho = 0.167, $p = 0.693$).

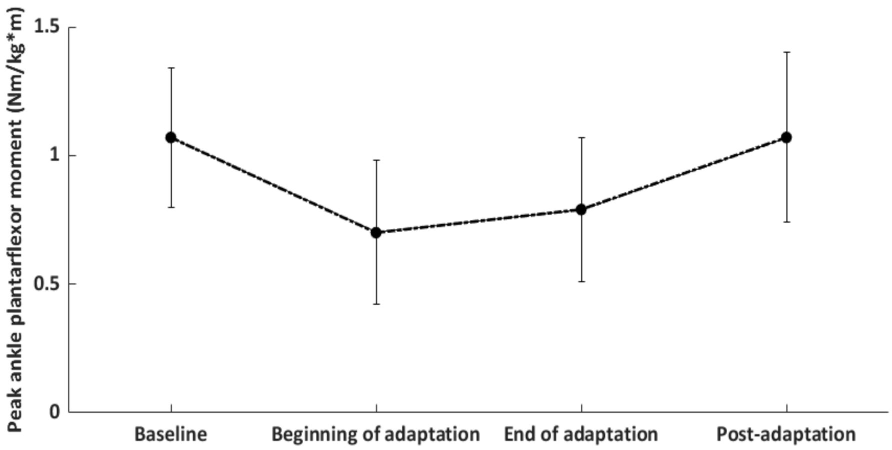

Figure 8. Changes in peak ankle plantarflexor moment during push off. Average peak ankle plantarflexor moment during push off across different periods of split-belt treadmill training. The error bars represent the standard deviation.

4. Discussion

The purpose of this study was to determine the effect of split-belt treadmill training, modifying step length, on walking energetics in women with hip OA. We found that one session of split-belt treadmill training successfully reduced step length asymmetry. This was accompanied by the hypothesized increased mechanical energy exchange and decreased O_2 rate during walking. Further, the magnitude of the reduction in step length asymmetry was significantly correlated with the magnitude of the reduction in O_2 rate. Finally, while split-belt treadmill training altered both the sagittal plane hip ROM and the peak ankle plantarflexor moment, only the change in sagittal plane ROM was associated with the reduction in step length asymmetry.

Our protocol presents a situation that drives the adaptation of motor commands to ultimately reduce step-length asymmetry by effectively increasing asymmetry during the early adaptation period. Split-belt treadmill training has resulted in improvements in step length asymmetry in people post stroke and with nontraumatic transtibial amputation [17,19,21]. However, to our knowledge, this was the first time split-belt treadmill training to improve step length asymmetry has been applied to people with hip OA. We did not know whether people whose limitations are thought to be primarily musculoskeletal would be able to respond to this training. This proof-of-concept study establishes that error augmentation training can be effective for women with hip OA.

Women with hip OA showed decreased O_2 rate after split-belt treadmill training. Additionally, decreased O_2 rate was associated with decreased step length asymmetry. This is in line with other studies. For example, in a study of healthy participants, the net metabolic power was reduced when unequal step length gradually changed to an equal step length [20]. In a study of people post stroke, participants began to step more symmetrically than they preferred to walk in daily life if it saved energy [31]. However, it should be noted that having an equal step length does not necessarily minimize the metabolic cost [32,33]. For example, in another study of healthy participants who walked on a split-belt treadmill for 45 min, even after step length change plateaued and became symmetric, energetic cost continued to decrease [34]. This suggests that there might be more room to improve energy costs, beyond only altering step length, perhaps with a longer adaptation period. There is a need to further investigate the optimal time for adaptation in people with hip OA to minimize their energetic cost.

Hip sagittal plane ROM was improved in women with hip OA, significantly increasing from the baseline to the end of adaptation period. Moreover, the change in hip sagittal plane ROM was significantly associated with the change in step length asymmetry during split-belt treadmill training. This association was not seen with ankle plantarflexion moments. The implications of this finding are two-fold: first, it suggests that altering hip ROM may be the mechanism by which these participants were able to increase their step lengths on the unaffected side, thereby reducing asymmetry; second, this finding indicates that modifying step length asymmetry through split-belt treadmill training could improve hip ROM during gait in women with hip OA. This is an important finding because reduced hip ROM is a hallmark of gait changes in hip OA [35] and is associated with poorer function [36]. Thus split-belt treadmill training in women with hip OA could have multiple benefits.

Our study was not without limitations. First, there was a risk of selection bias as participants needed to be able to tolerate and complete the evaluations and be able to walk on a treadmill without assistive devices. More impaired individuals may not be good candidates for this type of intervention. Second, it is important to note that %Recovery as a measure of mechanical energetics is a simplification as it only considers energy fluctuation of the center of mass and does not consider the role of limb segments or other aspects of recovery such as the phase relationships between the potential and kinetic energy fluctuation that may be relevant in this patient population. Third, we did not systematically document participants' pain levels. Anecdotally, we can state that none of the participants informally commented on worsening pain during or after the training. Nevertheless, it is important for future studies to monitor pain during and after the testing period to establish tolerability and because of any mechanistic link between pain and hip extension. Finally, we limited our participants to women at this proof-of-concept stage. We and others have previously reported sex differences in gait kinematics and kinetics in people with hip OA [37,38]. Further, there have been reports of sex-specific differences in vertical COM displacements that could potentially influence mechanical energy exchange [39]. Thus, future studies are needed to determine whether these findings are generalizable to men with hip OA. Despite these limitations, this proof-of-concept study successfully demonstrated that step length asymmetry is responsive to split-belt training in women with hip OA. As expected, the effects wash out (de-adaptation) during the early post-adaptation period due to the relatively short adaptation period and only a single exposure to the intervention. However, others have demonstrated a persistence of the training effect over a three-week period [40]. Identifying the optimal duration and number of sessions required for a lasting change in people with hip OA will be an important area for future study and is warranted by the promising results of this proof-of-concept study.

In conclusion, we found that split-belt treadmill training successfully reduced step length asymmetry and that this reduction was associated with increased mechanical energy exchange and decreased O_2 rate during walking, indicating more efficient gait. Increased hip sagittal plane ROM, also seen, could be a mechanism, a secondary benefit, or both. The findings from this proof-of-concept study suggest that modifying step length asymmetry through split-belt treadmill training with the error augmentation method could be a potential rehabilitation strategy to improve walking energetics in women with hip OA. Further developing this intervention will involve identifying the optimal time for each phase of training and assessing whether the results transfer to overground conditions and the extent to which the skill is retained.

Author Contributions: Conceptualization, C.-H.H. and K.C.F.; methodology, C.-H.H. and K.C.F.; formal analysis, C.-H.H.; investigation, C.-H.H. and B.A.; resources, K.C.F.; data curation, C.-H.H. and B.A.; writing—original draft preparation, C.-H.H.; writing—review and editing, C.-H.H., B.A., and K.C.F.; visualization, C.-H.H.; supervision, K.C.F.; project administration, C.-H.H. and B.A.; funding acquisition, C.-H.H. and K.C.F. 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 of University of Illinois at Chicago (protocol code 2019-0958 and date of approval 10/11/2019).

Informed Consent Statement: Written informed consent has been obtained from the patients 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 privacy concerns.

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

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