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Lower extremity sagittal joint moment production during split-belt treadmill walking

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Abstract

The split-belt treadmill (SBT) has recently been used to rehabilitate locomotor asymmetries in clinical populations. However, the joint mechanics produced while walking on a SBT are not well-understood. The purpose of this study was to investigate the lower extremity sagittal joint moments produced by each limb during SBT walking and provide insight as to how these joint moment patterns may be useful in rehabilitating unilateral gait deficits. Thirteen healthy young volunteers walked on the SBT with the belts tied and in a "SPLIT" session in which one belt moved twice as fast as the other. Sagittal lower extremity joint moment and ground reaction force impulses were then calculated over the braking and propulsive phases of the gait cycle. Paired t-tests were performed to analyze magnitude differences between conditions (i.e. the fast and slow limbs during SPLIT vs. the same limb during tied-belt walking) and between the fast and slow limbs during SPLIT. During the SPLIT session, the fast limb produced higher ground reaction force and ankle moment impulses during the propulsive and braking phases, and lower knee moment impulses during the propulsive phase when compared to the slow limb. The knee moment impulse was also significantly higher during braking in the slow limb than in the fast limb. The mechanics of each limb during the SPLIT session also differed from the mechanics observed when the belt speeds were tied. Based on these findings, we suggest that each belt may have intrinsic value in rehabilitating specific unilateral locomotor deficits.

Introduction

Locomotor asymmetry is an important cause of motor impairment in many aging and clinical populations such as osteoarthritis, stroke, and Parkinson's disease (PD). Recently, locomotor training protocols using split-belt treadmills (SBT) have been used to target this deficit (Reisman, 2007; Reisman, 2009; Reisman, 2010). During SBT walking, the treadmill belt under one leg moves faster than the other, inducing an asymmetric locomotor task. This external perturbation challenges the motor control system to reorganize the gait pattern to adapt to the novel walking condition. Acutely, SBT walking produces changes in interlimb coordination that are reliant on both feedback and feedforward control (Dietz, 1995; Morton, 2006). The spatiotemporal characteristics of gait are readily adapted, leading to increases in stride length and swing/stance ratio in the faster limb and similar decreases in the slower

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Conflict of Interest Statement
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limb (Dietz, 1994). With chronic training, Reisman and colleagues reported restorative effects on step length symmetry in a person post-stroke when the limb initially producing shorter steps trained by walking on the faster belt (Reisman, 2010). However, the mechanical considerations driving these changes are not well-understood.

Asymmetries in spatiotemporal gait parameters are driven by alterations in lower-extremity joint mechanics. Allen and colleagues (2011) reported that a variety of lower extremity sagittal joint torque production patterns can produce step length asymmetry in persons post-stroke. Moreover, asymmetries in external knee flexion moments observed during loading response and at opposite foot-off strongly relate to step time asymmetry in persons with PD (Johnsen, 2009). Thus, several potential targets exist for tailoring interventions to improve gait symmetry. Conventional treadmill training improves gait symmetry in persons post-stroke, but the improvements do not exceed established minimal detectable change values (Tyrell, 2011). Similarly, Pohl and colleagues (2003) did not find any positive effect of conventional treadmill walking on gait symmetry in PD. However, previous research by Reisman and colleagues and preliminary data from our lab suggest that interventions using SBT may improve gait symmetry in these populations (Reisman, 2009; Reisman, 2010). Thus, an understanding of the mechanical demands of the limbs walking on each belt during SBT walking may provide knowledge necessary to improve rehabilitation and better refine training protocols in order to address various patterns of gait asymmetry.

We sought to investigate the mechanical demands induced by each belt during a SBT walking task in which one limb walked twice as fast as the other as commonly observed in SBT walking investigations. We hypothesized that the limb walking on the faster belt would produce 1) higher ground reaction force (GRF) impulses during the braking and propulsive phases, 2) higher internal ankle moment impulses during the braking and propulsive phases, 3) lower internal knee moment impulses during the propulsive phase, and 4) higher internal hip and knee moment impulses during the braking phase when compared to the limb on the slower belt. These hypotheses were based on previous research outlining changes in lower extremity joint mechanics during speed manipulation of conventional walking (Orendurff, 2008; Peterson, 2011).

Methods

Thirteen volunteers (age 22.4 ± 3.5 yr, 169.0 ± 9.2 cm, 64.2 ± 10.49 kg, 7 males, 6 females) participated. None of the participants had walked on a SBT prior to participation nor had they experienced any lower-extremity orthopedic injury for at least one year. All participants provided written informed consent before participating in the study as approved by the University Institutional Review Board. Sixteen passive reflective markers were attached to the lower body in accordance with the Vicon Plug-in-Gait lower body marker system. Kinematic data, time-synchronized to the kinetic collection, were collected using a 7-camera motion capture system (120 Hz; Vicon Nexus, Oxford, UK). Kinetic data were collected as the participants walked on an instrumented SBT (960 Hz; Bertec Corporation, Columbus, OH).

Initially, participants began by walking on the SBT while both belts moved together at the same speed for five minutes in order to accommodate to walking on the treadmill. The speed of both belts was then gradually increased until the participants reported being at the “fastest speed they felt comfortable walking for 15 minutes”. This speed was set as the “fast” walking speed (mean fast walking speed = 1.60 ± .19 m/s), while 50% of this speed was designated as the “slow” walking speed (mean slow walking speed = .80 ± .10 m/s). Participants then walked for two minutes at the slow speed (TIED-SLOW) and two minutes at the fast speed (TIED-FAST), followed by a two-minute washout period at the slow speed

(Reisman, 2005). Then, the belt under the nondominant leg was sped up to the fast speed while the belt under the dominant leg remained at the slow speed. Participants walked under these conditions (SPLIT) for 10 minutes. Leg dominance was determined based on "which leg the participant would use to kick a soccer ball?" (Alexander, 2011) Herein, the nondominant leg will be referred to as the "fast" leg while the dominant leg will be referred to as the "slow" leg. Data were collected during the last 30 seconds of the TIED-SLOW, TIED-FAST, and SPLIT conditions.

Sagittal joint moments at the hip, knee, and ankle were calculated using inverse dynamics techniques. The moments and GRFs were subsequently normalized to participant body mass and temporally to 100% of the gait cycle. Each gait cycle was then divided into swing and stance phases, with the stance phases being particularly relevant to the current study. The stance phase of each gait cycle was calculated as the percentage of the temporally-normalized gait cycle occurring from heel-strike to toe-off of the same limb. The stance phase was then further divided into braking and propulsive phases. The braking phase was defined as the percentage of the gait cycle from heel-strike through the first 50% of single-limb stance and the propulsive phase was defined as the percentage of the gait cycle from the second 50% of single-limb stance until toe-off (Turns, 2007). Braking and propulsive GRF impulses were calculated as the time integrals of the antero-posterior (AP) GRFs over the braking and propulsive phases, respectively, after temporal normalization. Sagittal joint moment impulses were calculated in similar fashion for the ankle, knee, and hip over the braking and propulsive phases (Figure 1). All variables were averaged across all strides for each participant within each 30-second trial. Paired t-tests were performed to compare the AP-GRF impulses and the sagittal ankle, knee, and hip moment impulses during the braking and propulsive phases of gait between the following pairs of conditions: slow limb during TIED-SLOW vs. slow limb during SPLIT, fast limb during TIED-FAST vs. fast limb during SPLIT, and slow limb vs. fast limb during SPLIT. Pearson's correlation analyses were performed to analyze relationships between bilateral difference in belt speed magnitude during the split condition and all AP-GRF and sagittal joint moment impulses. Level of significance for the t-tests and Pearson's correlation was set at $\alpha = .05$.

Results

Ensemble AP-GRF curves and sagittal joint moments are shown in Figure 2. Means and standard errors are shown for all braking and propulsive AP-GRF impulses for each limb and condition in Figure 3.

Slow limb during TIED-SLOW condition vs. slow limb during SPLIT condition

No significant differences were observed between the braking or propulsive AP-GRF impulses in the slow limb during the SPLIT condition and the TIED-SLOW condition. The ankle moment impulses in the slow limb, however, were significantly larger during braking in the TIED-SLOW condition than in the SPLIT condition (p=.002). The knee moment impulses in the slow limb were significantly smaller during braking in the TIED-SLOW condition than in the SPLIT condition (p<.001). For the hip during braking in the TIED-SLOW condition, the slow limb produced significantly more negative (i.e. toward flexion) hip moment impulses when compared to the SPLIT condition (p=.001). The ankle moment impulses in the slow limb during propulsion in the TIED-SLOW condition were larger but not significantly different from those during the propulsion in the SPLIT condition. The knee and hip moment impulses in the slow limb were significantly smaller during propulsion in the TIED-SLOW condition than in the SPLIT condition (both p<.001).

Fast limb during TIED-FAST condition vs. fast limb during SPLIT condition

In the fast limb, the braking and propulsive AP-GRF impulses were significantly larger during the TIED-FAST condition when compared to the SPLIT condition (p=.012 and p=.003, respectively). The ankle moment impulses in the fast limb were significantly smaller during braking in the TIED-FAST condition than in the SPLIT condition (p<.001). The knee moment impulses in the fast limb were significantly larger during braking in the TIED-FAST condition than in the SPLIT condition (p=.001). Hip moment impulses were significantly different in the fast limb during braking in the TIED-FAST condition when compared to the SPLIT condition, as hip moment impulses became significantly more negative (i.e. toward flexion) during SPLIT (p<.001). The ankle moment impulses in the fast limb were significantly larger during propulsion in the TIED-FAST condition than in the SPLIT condition (p<.001). The knee moment impulses in the fast limb were significantly smaller during propulsion in the TIED-FAST condition than in the SPLIT condition (p=.012). The hip moment impulses in the fast limb were significantly larger during propulsion in the TIED-FAST condition than in the SPLIT condition (p<.001).

Slow limb vs. fast limb during SPLIT condition

The AP-GRF and joint moment impulses were asymmetric during the SPLIT condition (Figure 3). The AP-GRF impulses were significantly smaller during braking and propulsion in the slow limb than the fast limb (p<.001 and p=.013, respectively). The ankle moment impulses were significantly smaller during braking and propulsion in the slow limb than in the fast limb (p<.001 and p=.038, respectively). The knee moment impulses were significantly greater during braking and propulsion in the slow limb than in the fast limb (p=.030 and p=.003, respectively). The hip moment impulses were not significantly different bilaterally during braking, but they were significantly greater during propulsion in the slow limb than in the fast limb (p=.003).

Relationships between belt speed difference and impulses

During the SPLIT condition, the ankle moment impulses during braking and propulsion in the fast limb were inversely related to belt speed difference between the fast and slow belts (Figure 4) (r=−.624 and −.563, p=.023 and .045, respectively). There were no significant relationships between any of the other AP-GRF or sagittal joint moment impulses and belt speed difference.

Discussion

The primary goal of this study was to investigate changes in mechanical demands created by SBT walking as compared to conventional treadmill walking. In keeping with previous research on walking speed manipulation (Orendurff, 2008; Peterson, 2011), we found that many of the mechanical adjustments made bilaterally to alter walking speed during conventional treadmill walking were also made unilaterally during SBT walking. For instance, the fast limb produced 1) higher propulsive and braking AP-GRF impulses, 2) higher ankle moment impulses during the propulsive and braking phases, and 3) lower knee moment impulses during the propulsive phase when compared to the slow limb during the SPLIT condition. However, contrary to our hypotheses, we did not detect higher hip or knee moment impulses in the fast limb during the braking phase. In fact, we observed that the knee moment impulse was significantly higher in the slow limb during braking than in the fast limb. Further, a negative association was found only between the ankle moment impulses in the fast limb and the difference in magnitude of the belt speeds during the SPLIT condition, while no other impulses showed any relationship to the difference in belt speeds.

The mechanics of each limb are markedly different during SBT walking, not only when compared bilaterally but also when compared to the ipsilateral limb mechanics during speed-matched conventional walking. For example, participants produced lower braking and propulsive AP-GRF impulses in the fast limb during the SPLIT condition when compared to the TIED-FAST condition. Further, the slow limb demonstrated reduced ankle and increased knee and hip moment impulses during braking and increased knee and hip moment impulses during propulsion in the SPLIT condition when compared to the TIED-SLOW condition. Our data suggest that the altered joint mechanics involved with each limb during SBT walking certainly are not independent of one another nor do they result simply from unilateral speed changes. They appear to constitute an entirely new gait pattern and demonstrate potential for altering gait symmetry.

As we have shown the kinetics of SBT walking to be profoundly asymmetric, we postulate that the fast and slow belts may each have intrinsic value in rehabilitation of populations characterized by gait asymmetry. Indeed, intervention strategies should consider the kinetics generated in both limbs during training. For instance, previous research has suggested that persons post-stroke with longer paretic limb step length exhibit increased ankle plantarflexor and knee extensor moments in the non-paretic limb (Allen, 2011) and that the paretic limb may step further due to compensatory propulsion of the non-paretic limb (Balasubramanian, 2007). Our results suggest that training the paretic limb on the slow belt may increase the knee moment impulses, potentially resulting in longer non-paretic limb steps and greater step length symmetry. However, we may simultaneously increase propulsion in the non-paretic limb by increasing ankle and knee moment impulses while training on the fast belt. Thus, one could actually hinder complete step length symmetry restoration by further lengthening the paretic step. Indeed, longer steps were observed bilaterally after 4 weeks of SBT training in which the limb taking the longer step (the paretic limb, in this case) trained on the slow belt and the limb taking the shorter step on the fast belt in one person post-stroke (Reisman, 2010). While step length symmetry certainly improved by training the paretic limb on the slow belt in this case study, further lengthening of the paretic step appeared to limit symmetry restoration.

Neural mechanisms involving error augmentation have been postulated to account for locomotor adaptation during SBT walking (Reisman 2009, Reisman 2010). We propose that the mechanics of SBT walking also contribute to (and potentially hinder optimization of) the restoration of spatiotemporal gait symmetry observed after SBT training. As the limb with the shortest step length has previously been trained on the faster belt, we hypothesize that not only does the central nervous system perhaps play a role in changing step length unilaterally by way of error-correction mechanisms during adaptation to SBT walking, but it is also likely that a new gait pattern resulted from adaptation to the mechanical requirements. Indeed, Kahn and Hornby (2009) have shown that unilateral stepping with the non-paretic limb, which facilitates mechanical changes in gait but requires no error correction between limbs, leads to diminished overground step length asymmetry. However, the degree to which gait kinetics transfer to overground walking after SBT training remains unknown and certainly requires further research.

Future research on physiological changes resulting from SBT training should be considered in order to further investigate how SBT training may influence gait kinetics in pathological populations. Gait asymmetry is frequently multifactorial in nature among various pathological populations, and physiological origins of these asymmetric gait patterns are often highly variable even within certain populations. A better understanding of the physiological mechanisms underlying the gait kinetics observed during SBT walking may enhance our ability to design effective, patient-specific gait rehabilitation protocols using the SBT.

Conclusion

Split-belt treadmill walking produces asymmetric patterns in gait mechanics when compared to conventional treadmill walking. In this study, we found that the limb walking on the faster belt generated higher propulsive and braking AP-GRF impulses, higher ankle and lower knee moment impulses during the propulsive phase, and higher ankle moment impulses during the braking phase when compared to the limb walking on the slow belt. Surprisingly, we also found that the knee moment impulse was significantly higher during braking in the slow limb when compared to the fast limb. We suggest that these findings provide valuable insight into the mechanical demands of each belt during SBT walking and should certainly be taken into consideration when designing maximally-effective SBT-based rehabilitation protocols in which unilateral gait deficits are targeted.

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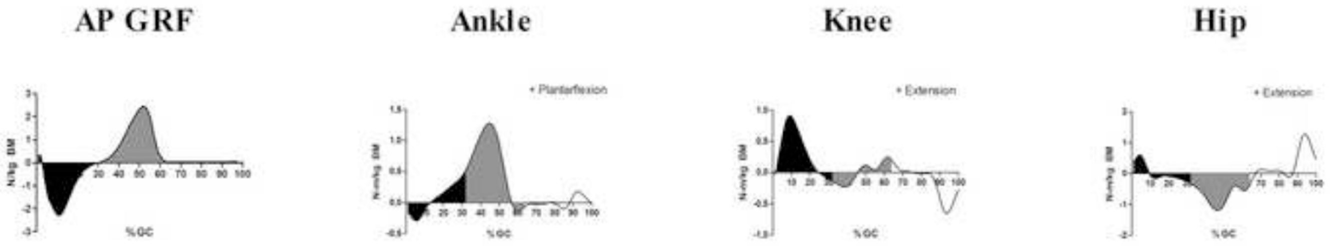

Figure 1.

Braking (black) and propulsive (gray) moment impulse classification for representative antero-posterior ground reaction force (AP GRF) and sagittal joint moment profiles.

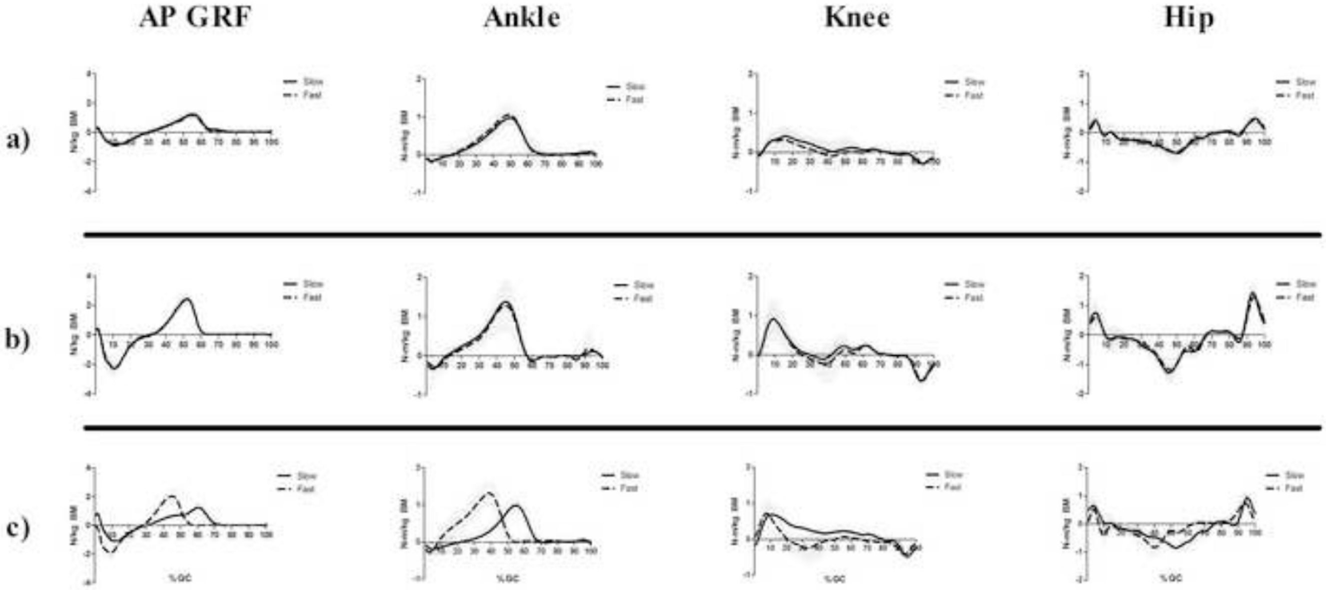

Figure 2.
Ensemble antero-posterior ground reaction force (AP GRF) and sagittal ankle, knee, and hip moment profiles. All forces and moments were normalized to body mass (kg) and 100% of the gait cycle (GC) and then averaged across all subjects during the a) TIED-SLOW condition, b) TIED-FAST condition, and c) SPLIT condition. The fast limb and slow limb walked at the same speed during the TIED-SLOW and TIED-FAST conditions (a, b) and the fast limb walked twice as quickly as the slow limb during the SPLIT condition (c).

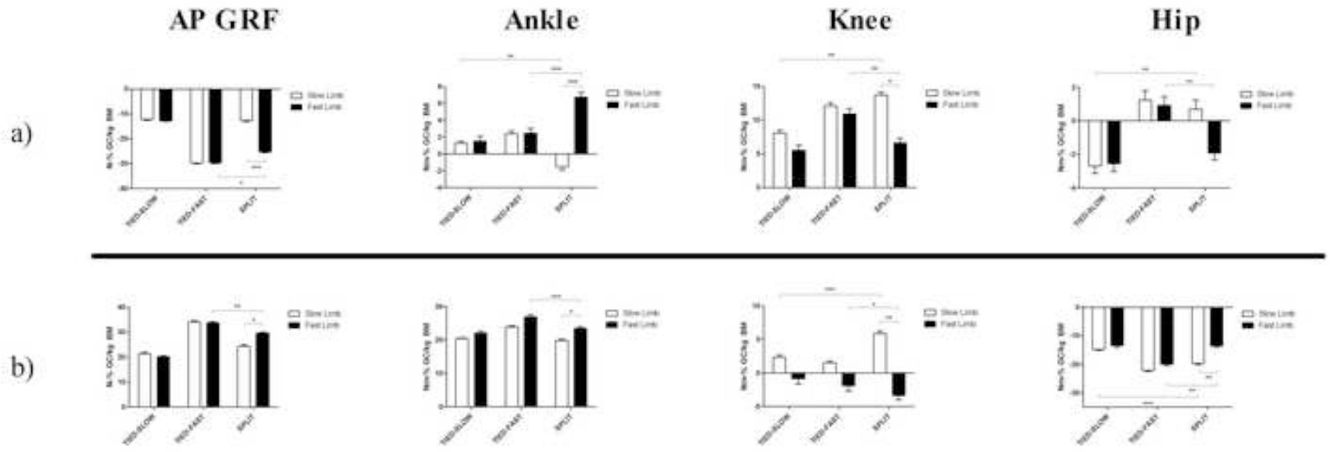

Figure 3.

Mean and standard error for antero-posterior ground reaction force (AP GRF) and sagittal ankle, knee, and hip moment impulses for the slow and fast limbs during the braking (a) and propulsive (b) phases across the TIED-SLOW, TIED-FAST, and SPLIT conditions. *** indicates a p-value <.001, ** indicates p <.01, and * indicates p <.05.

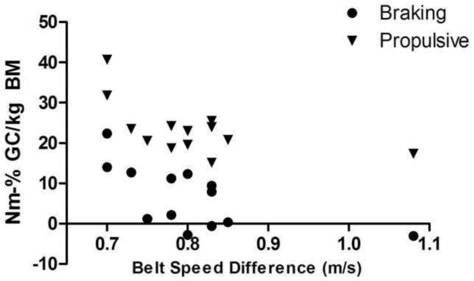

Figure 4.

Mean ankle moment impulses in the fast limb for each subject plotted against difference in magnitude of the belt speeds during the SPLIT condition.