Published in final edited form as:
Gait Posture. 2012 February ; 35(2): 287–291. doi:10.1016/j.gaitpost.2011.09.101.

A Kinematic Comparison of Split-belt and Single-belt Treadmill Walking and the Effects of Accommodation

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Abstract

INTRODUCTION—Instrumented treadmills are becoming increasingly more common in gait laboratories. Instrumented side-split treadmills allow the collection of forces under each foot during walking. However, there may be a tendency to increase the base of support when walking on these treadmills, influencing other frontal plane mechanics as well. Therefore, the purpose of this study was to examine the effect of walking on a side-split instrumented treadmill on base of gait and frontal plane kinematics of the lower extremity.

METHODS—Twenty subjects walked on both a split and a single-belt treadmill. Base of gait and frontal plane kinematic angles and variability data were recorded. A one-way ANOVA was used to determine differences between the single and split-belt conditions at baseline and following a 10 minute accommodation on the split-belt. The relationships between the change in base of gait and change in each kinematic variable were also determined.

RESULTS—On average, the base of gait was 3.7 cm wider on the split-belt treadmill with a 4 mm gap between belts. No significant differences were observed in the mean values of lower extremity kinematics or kinematic variability at baseline or following the 10 minute accommodation. However, the increase in base of gait was significantly related to a decrease in peak knee and hip adduction angles.

CONCLUSION—The 4 mm gap between the treadmill belts significantly increased the mean base of gait in all subjects. This did not alter mean frontal plane kinematics. However, as base of gait increased, the tendency towards hip and knee abduction also increased.

INTRODUCTION

Walking mechanics are often studied to obtain a better understanding of human locomotion. Many of these studies have been conducted overground in labs with embedded force platforms [1]. This set-up typically allows the analysis of only one or two consecutive steps. Treadmills provide the ability to collect multiple, sequential steps in a small volume. In addition, treadmills provide the opportunity to study walking patterns over a prolonged period of time to assess the effect of fatigue or training.

The advent of instrumented force treadmills has expanded our ability to include kinetic analyses during treadmill ambulation. For walking analyses, an instrumented treadmill must have two belts in order to record forces from the right and left feet independently. These two belts can be positioned in either a front-to-back or side-by-side arrangement. In a front-to-back split treadmill, one belt is placed in front of the other with a narrow horizontal gap between them. Typically, the foot moves from one belt to the other without the individual perceiving the gap. However, the subject must remain centered, so that each heel strike occurs on the front plate, moving to the back plate in time for the contralateral heel strike.

The side-split treadmill has two side-by-side belts, separated by a narrow gap ranging from 4 mm to 2.5 cm, depending upon the make and model of the device. While a side-split treadmill eliminates the problem of anterior-posterior drift, there may be an increased tendency to widen the base of gait in order to avoid walking on the gap. A widened base of gait may cause reduced hip adduction, increasing the tendency towards hip abduction. This may, in turn, lead to a reduction in the knee adduction angle or a tendency to increase knee valgus . Increased knee valgus increases the tendency for excessive foot pronation [2]. To compensate for this, the rearfoot may invert more at footstrike in order to maintain a plantigrade foot. As a result, a reduction in peak rearfoot eversion may also be seen. A schematic of these compensations is shown in Figure 1.

If kinematic alterations do occur with split-belt treadmill walking, it is possible that they may resolve after an accommodation period. Studies of single-belt treadmill walking suggest that gait mechanics do stabilize within a 10 minute period of accommodation. Matsas et al. [3] determined that it took six minutes of treadmill walking before knee kinematics and temporal-distance measurements correlated well with overground walking. Using variability as an indicator, Van de Putte et al. [4] determined that 10 minutes of walking were necessary before kinematic and spatio-temporal variability stabilized.

Only one study has examined the accommodation period for split-belt treadmill walking. In a group of young, healthy subjects, Zeni et al. [5] found that variability of ground reaction forces and sagittal plane kinematics decreased with time, and stabilized after 5 minutes. The authors attributed the increased variability at the onset to a lack of familiarity with split-belt treadmill walking. The authors noted that the base of gait reduced from 17.2 to 16.0 cm after 5 minutes of walking. While they did not make a comparison to single-belt or overground walking, this base of gait was still much larger than the reported range of 8 to 10 cm that is typically seen in overground walking [6-8].

In summary, side-split treadmill walking may lead to a wider base of gait and other kinematic alterations. There are no studies to date that have compared the lower extremity kinematics between split-belt and single-belt treadmill walking. This information would be helpful when designing studies involving a split-belt treadmill. Therefore, the aim of this study was to examine kinematic differences between split-belt and single-belt treadmill walking. It was expected that base of gait would be increased in the split-belt versus single belt condition at baseline. It was also expected that hip adduction, knee adduction, and rearfoot eversion would be reduced in the split-belt condition as a result of the widened base of gait. Additionally, these reductions in frontal plane kinematics were expected to be significantly correlated with the increase in base of gait on the split-belt treadmill. The variability of movement was hypothesized to be greater on the less familiar split-belt treadmill. Finally, we hypothesized that hip adduction, knee adduction and rearfoot eversion will increase and their associated variability will be reduced from the baseline measures following a 10 minute accommodation period on the split-belt treadmill.

METHODS

Subjects

An a priori power assessment based on preliminary data, $\alpha = 0.05$, $\beta = 0.8$, indicated 20 subjects were necessary for this study (10 male, 10 female, age 26.5 (±7.0) years, weight 64.7 (±13.5) kg, height 1.68 (±0.072) m). Subjects were healthy and comfortable walking on a treadmill. Comfort was rated on a 10 point scale where 10 means completely comfortable [9]. Inclusion required subjects rated their comfort greater or equal to 8/10, subjects averaged 9.5(±0.5). No subjects were removed due to insufficient comfort ratings. For all subjects, split-belt treadmill walking was a novel task. All subjects signed informed consent forms approved by the Human Subjects Review Board of the University of Delaware.

Protocol

Fifty-one reflective markers were placed on the shoe, rearfoot, shank, thigh and pelvic segments of both lower extremities. In order to place the rearfoot tracking markers directly on the calcaneus, shoes (Nike Air Pegasus, Nike, Inc, Beaverton, OR) with holes cut out of the posterior and lateral heel counter were used. Standing calibration and hip functional joint center [10] trials were performed using anatomical and tracking markers, then the anatomical markers were removed.

The custom AMTI (Watertown, MA) treadmill used in this study had two belts, one narrow (0.33 m) and one wide (0.66 m). There was a small, 4 mm gap between the two belts. This treadmill was designed to accommodate both walking studies (using both the wide and narrow belts) and running studies (using just the wide belt). An eight camera VICON (Oxford, UK) Motion Analysis System was used to capture marker trajectory data.

The subject first warmed up by walking for three minutes at a self selected speed on the wide treadmill belt (single-belt condition). The treadmill speed was then adjusted to 1.3 m/s and data were collected. All subjects were familiar with single-belt walking, but not with split-belt walking. Therefore, we chose to have them perform the familiar task first in all cases. Pilot studies were performed where the order was reversed and no difference was observed. Marker trajectory data were collected at 200 Hz for five gait cycles. Following a 5-minute rest period, the subject walked at 1.3 m/s with one foot on each belt (split-belt condition) for 10 minutes. The same data were collected initially (time 0) and after 10 minutes of walking on the split-belt (time 10). Subjects were instructed not to look down at their feet, but to instead pick a point on the wall to focus on to maintain the balance between the two belts. Data were collected for both extremities so that base of gait could be analyzed. However, the angular kinematics of only the right side were analyzed for this study since pilot work showed no kinematic differences between limbs.

Analysis

The 3D coordinate data were processed using Vicon Nexus software. The 3D coordinates were filtered at 8 Hz using a fourth order, phase corrected, low-pass Butterworth filter. Three-dimensional joint angles for the rearfoot, knee, and hip were then calculated with Visual 3D (CMotion, Bethesda, MD). Segments were modeled as frustra of right cones, and joint angles were calculated using an x-y-z Cardan angle rotation sequence, where z is vertical, y is anterior and x is medial-lateral.

A kinematic method of stance determination was needed since both feet were on the same forceplate during double stance of the single-belt treadmill condition. Therefore, footstrike was identified as the time when the forward distance of the heel marker from the sacral marker is at a maximum. Toe-off was identified as the time when the toe marker is at its furthest posterior distance from the sacral marker. This method was demonstrated to be reliable and valid for treadmill walking [11].

The variables of interest were extracted from the kinematic time series curves. For each angle, the initial position at footstrike and the peak (within the first 75% of stance) were calculated. The base of gait was calculated as the medio-lateral distance between the distal shoe markers at 50% of stance for a consecutive left and right footstrike (Figure 2). Each variable was averaged over five consecutive stance phases collected for each subject. To formulate ensemble average curves, each individual stance phase was normalized between footstrike and toe off and then averaged with the other curves. Variability was calculated from the standard deviation between the five peak values for a given subject.

A series of repeated measures, mixed, one-way ANOVAs were used to compare the variables of interest. First, comparisons were made between the belt conditions at baseline. The variables assessed were base of gait, frontal plane angles of the rearfoot, knee and hip at footstrike and at the peak value. The variability associated with each of these was also compared across belt conditions and over time on the split-belt. Tukey's post-hoc tests were performed when a significant ANOVA was present, between the split and single-belt at time 0, and between time 0 and time 10 on the split-belt condition. Additionally, we correlated the change in each frontal plane measure between belt conditions to the change in base of gait. An alpha level of 0.05 was used to determine significance for all statistical tests.

RESULTS

The ANOVA for base of gait was significant, so post hoc testing was conducted. Results revealed that base of gait was wider during the split-belt walking than single-belt walking at baseline (Table 1). This was true for all but one subject, with differences ranging from −1 to 7 cm wider on the split-belt condition. However, on the split-belt condition, base of gait did not change over time.

Despite the significant difference in base of gait, all kinematic variables were statistically similar between belt conditions at baseline. (Figure 3 and Table 1). Mean group differences were all less than 1°. However, individual differences ranged from 0.1° to 4°. While no mean group differences were observed, the increase in base of gait from the single to split-belt was significantly correlated to reductions in both peak knee adduction and peak hip adduction (Figure 4). The other correlations ranged between 0.1-0.4 and were not statistically significant.

There were also no accommodation effects of time in the split-belt condition. In terms of variability, measures were similar between conditions. A trend towards greater base of gait variability in the single-belt condition was noted. No differences were identified between time 0 and time 10 on the split-belt condition.

DISCUSSION

The purpose of this study was to identify differences in lower extremity kinematics between split and single-belt treadmill walking. In addition, we were interested in whether any differences in split-belt walking would resolve over time. We found that the base of gait was widened 3.7 cm, on a split-belt treadmill with a gap between the belts of only 4 mm. This change was correlated with peak knee and hip adduction angle changes. All other variables remained similar between conditions. Base of gait was not reduced over the 10 minute period, suggesting that accommodation does not occur.

A large change was observed in the base of gait from the single to split-belt conditions. The base of gait values on the split-belt ranged from 14 to 22 cm, with a mean of 17.7 cm. This was similar to the 17.2 cm base of gait found previously [5]. Additionally, the 14.0 cm base of gait value we found during single-belt walking was still wider than the 8-10 cm base of gait values typically reported for overground walking [6-8]. This may have been due to differences in the method of measurement. The base of gait in the previous overground studies was measured from the center of pressure rather than the distal heel. The center of pressure moves medially immediately after footstrike. Therefore, it is possible that using center of pressure would result in a systematic decrease in base of gait compared with markers placed on the center of the heel counter. Another explanation is that individuals may use a wider stance during treadmill walking to lower their center of gravity to increase stability on the moving surface.

The large increase in base of gait was not associated with changes in the mean values of the frontal plane angles. While mean differences were not significant, some subjects exhibited up to a 4° difference between conditions. A 4° reduction over a total range of 8° of knee adduction represents a 50% change in this motion. This suggests that some subjects may exhibit differences that may be clinically meaningful. Most individuals did display the decreased adduction in the hip and knee that we had expected. However the majority of these changes were small and the mean group differences were not statistically different. It is possible that it may require some threshold base of gait value, above which kinematics become altered.

The increase in base of gait from single-belt to split-belt walking was significantly correlated with reductions in peak hip and knee adduction. It should be noted that the 4 mm gap between the belts on the treadmill used in this study is quite narrow compared to the 1-2 cm gaps of most other split-belt treadmills. With gaps 3 to 4 times as wide, the effect on base of gait is likely to be even greater, which will have a more significant effect on kinematics. It does appear from the linear model that, with narrow belt gaps and changes in the base of gait less than 2-3 cm, knee adduction and hip adduction may be relatively unchanged. However, once base of gait widens more than 3 cm, both knee and hip adduction will be reduced, which may be problematic. We do not know if these relationships are truly linear, and further studies of treadmills with wider gaps are needed to verify these results. In addition, the effect of these kinematic changes on the calculation of joint kinetics also needs to be examined.

The base of gait was slightly less variable on the split-belt condition, contrary to our hypothesis. This may have resulted from the more constrained foot placement required as subjects attempted to keep one foot on each belt. It may also be possible that on the split-belt, little side to side drift occurred, while on the single-belt, subjects may have moved more freely from side to side, making their base of gait measure, more variable on this condition. No significant difference in variability was seen in the kinematic measures between conditions or post accommodation.

While previous studies have demonstrated an accommodation to treadmill walking over time [3-5], [12], no changes were noted on the split-belt in this study. Given the lack of change in the base of gait over time, it is not surprising that the kinematic variables remained stable as well. However, Zeni and colleagues did find a 1.2 cm reduction in the base of gait over time [5]. The lack of accommodation seen in our study may have been due to the fact that all of our subjects were very comfortable with treadmill walking necessitating very little accommodation. This may also explain the lack of change in variability that we found over time. One alternate explanation for the lack of findings in the variability measures may be due to limitations in the measure. Only 5 trials were analyzed to assess within-subject variability, while typically 10 or more are used for this type of measure. Preliminary comparisons did not indicate differences between variability assessed with 5 versus 10 trials.

CONCLUSION

The results of this study suggest that walking on a split-belt treadmill results in a significantly wider base of gait. This widened base of gait was not sufficient to significantly alter mean frontal plane kinematics. However, base of gait during split-belt walking was moderately correlated to frontal plane kinematic variables. This suggests that larger gaps may further increase the base of gait and may have a significant effect on frontal plane kinematics. These changes seen during split-belt walking did not resolve following a 10 minute accommodation period.

Acknowledgments

Funding: Drayer Physical Therapy Institute, DOD W911NF-05-1-0097, and NIH 1 S10 RR022396.

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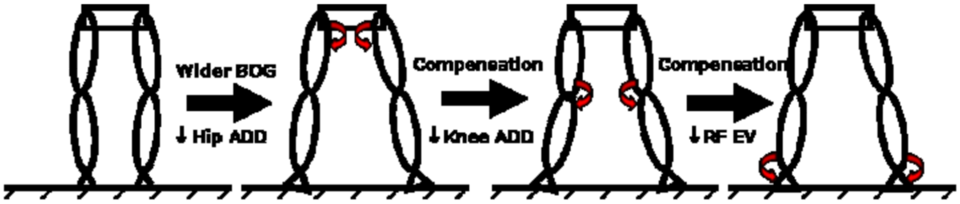

Figure 1.
Compensation strategies expected with a widened base of gait.

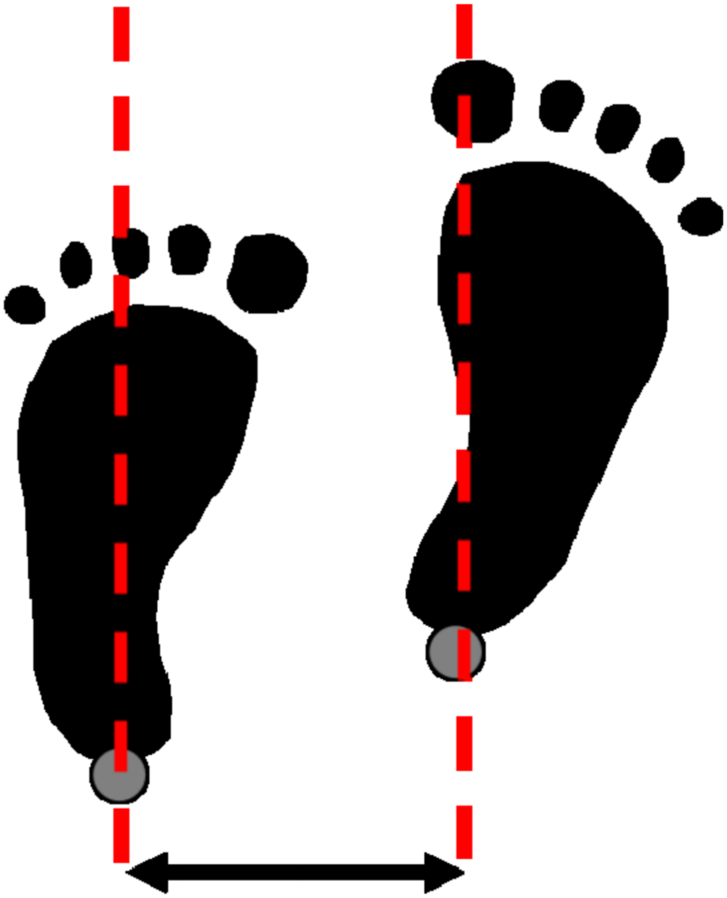

Figure 2.
Base of gait. This was measured as the mediolateral distance between the heel markers during a right and left consecutive midstance.

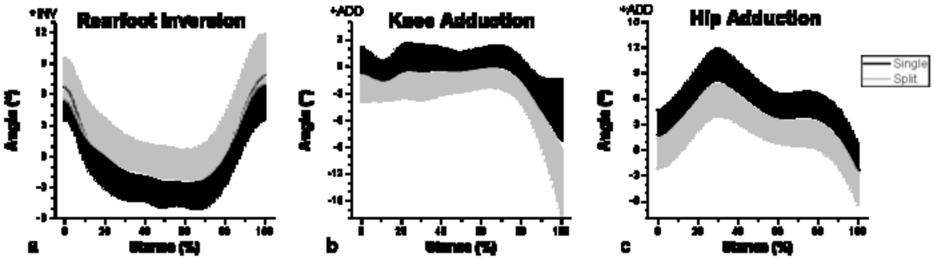

Figure 3.

Comparison of frontal plane kinematic patterns between the single-belt and split-belt conditions for the a) rearfoot b) knee c) hip. Shown as mean ±1 SD.

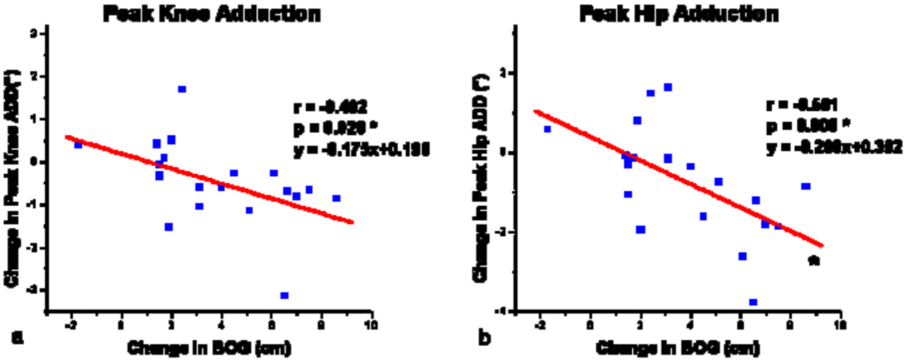

Figure 4.

Scatter plots for change in base of gait from single to split-belt conditions versus change in knee (a) and hip (b) adduction. * Indicates p<0.05.

Table 1

Comparison of variables of interest (mean (sd)).

	ANOVA *p-value*	Time 0			Time 10	
		Single-belt, (SD)	Split-belt (SD)	Split(0)-Single(0) Difference *p-value*	Split-belt (SD)	Split(10)-Split(0) Difference *p-value*
Kinematics						
BOG (cm)	*0.000* *	14.0 (2.4)	17.7 (2.6)	3.7 0.000 *	17.2 (2.8)	−0.5 0.831
RFINVFS (°)	*0.491*	6.7 (3.2)	5.9 (3.7)	−0.8	5.5 (4.1)	−0.4
RFEV PK (°)	*0.703*	3.3 (2.2)	3.3 (2.5)	0.0	2.6 (2.6)	−0.7
Knee ADD FS (°)	*0.830*	−0.7 (3.0)	−1.0 (2.9)	−0.3	−1.3 (2.8)	−0.3
Knee ADD PK (°)	*0.774*	1.6 (2.5)	1.2 (2.0)	−0.4	1.2 (2.4)	0.0
Hip ADD FS (°)	*0.891*	1.8 (2.9)	1.3 (3.5)	−0.5	1.3 (3.5)	0.0
Hip ADD PK (°)	*0.806*	8.6 (3.4)	7.9 (5.5)	−0.7	8.4 (3.8)	0.5
Variability				0.0		
BOG var (cm)	*0.055*	2.3 (0.8)	1.6 (0.9)	−0.7	1.8 (0.9)	0.2
RFEV var (°)	*0.577*	1.1 (0.7)	1.2 (1.2)	0.1	1.3 (1.0)	0.1
Knee ADD var (°)	*0.519*	0.4 (0.2)	0.4 (0.2)	0.0	0.4 (0.2)	0.0
Hip ADD var (°)	*0.151*	0.6 (0.4)	0.8 (0.4)	0.2	0.8 (0.4)	0.0

* Indicates the difference is statistically significant, p<0.05.