Changes in interlimb coordination induced by within-stride changes in treadmill speed

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ABSTRACT

During walking, interlimb coordination involves the right and left legs working together to achieve a desired movement. Previously, dynamic treadmill walking has been shown to drive asymmetric gait changes in healthy young adults through selectively changing the speed of the whole treadmill. Currently, the coordination demands of this novel walking environment are unknown and must be understood prior to assessing dynamic treadmill walking in clinical populations. We investigated the interlimb coordination requirements of dynamic treadmill walking in ten healthy young adults. We quantified interlimb coordination changes as phase shift (timing of maximum cross-correlation between limb angle trajectories of the left and right legs), center of oscillation (limb angle at midstance), and center of oscillation difference (oscillation angle difference between legs). We found that phase shift in the Fast trial (i.e., 1.0m/s treadmill speed in first 50% of gait cycle, 0.5m/s in latter 50%) was significantly more positive (i.e., the right leg oscillates ahead of the left leg in time) than in the Slow, Accelerate, and Decelerate trials (all $p<0.01$). The Fast trial produced significantly positive center of oscillation values on the right leg, indicating that the right leg is oscillating about a more flexed axis than the left. Center of oscillation difference was similarly more positive during the Fast trial than in the Decelerate ($p<0.01$) and Slow ($p<0.01$) trials. These results exemplify that some forms of dynamic treadmill walking change interlimb coordination to a greater extent than others. After several minutes of dynamic treadmill walking, interlimb coordination is changed relative to baseline walking in the spatial domain (Fast and Decelerate conditions) and the temporal domain (Fast and Slow). Therefore, dynamic treadmill walking is tunable in both biomechanical and interlimb coordination parameters, creating a variety of options for restoring gait symmetry in asymmetric populations.

INTRODUCTION

Many clinical populations – e.g., persons with stroke[1], Parkinson's disease[2], or cerebral palsy[3] – walk with gait patterns characterized by disrupted interlimb coordination, or the coordinated movements of the left and right legs. Unimpaired gait is characterized by oscillating, anti-phase movements between the two legs where one leg generally moves forward as the other extends backward and vice versa in a bilaterally coordinated manner[4,5]. Damage to the nervous system can affect these well-coordinated movements between the legs such that the oscillations deviate from their typical anti-phase relationship and become asymmetric[4,6]. Restoration of anti-phase interlimb coordination then becomes important because deviations from symmetric, coordinated gait can lead to increased fall risk[7,8] and elevated energy expenditure[9–11] that can decrease mobility and community engagement[12].

Interlimb coordination can be quantified in a variety of ways, but locomotion literature often uses a combination of temporal (e.g., limb phasing) and spatial (e.g., axis of limb oscillations, or "center of oscillation") metrics to measure and understand how the legs are controlled in synchrony[5,13–15]. In the temporal domain, "phasing" can be used to capture the degree to which the leg oscillations are anti-phase, or whether one limb lags or leads the other in time. It is often quantified by calculating the cross-correlation between limb angle trajectories[16]. In the spatial domain, center of oscillation is a common metric for measuring spatial interlimb coordination and describes the axis around which each leg rotates as a person walks. A center of oscillation difference near zero is expected for symmetric walking, indicating that both legs are rotating about a similar horizontal axis. However, both phasing and center of oscillation are often altered in persons with asymmetric gait patterns or when walking under perturbed conditions[16].

Ability to drive changes in interlimb coordination by perturbing gait offers an opportunity to leverage perturbations to improve interlimb coordination in persons with gait impairment. Our laboratory recently developed a 'dynamic treadmill walking' approach that can drive selective changes in gait symmetry by changing the speed of a conventional treadmill within a single stride while pacing the walker's heel-strikes with a metronome[17]. Our previous study in young adults without gait impairment revealed that the treadmill speed changes could be delivered at different timepoints within the gait cycle to induce customizable asymmetries in several clinically relevant gait parameters[17]. For example, slowing the treadmill immediately after right heel-strike induced asymmetries in step length, trailing limb angle, and peak propulsion whereas slowing the treadmill late in stance induced asymmetries in step time, leading limb angle, and peak braking force[17].

It is likely that different patterns of changes in interlimb coordination underlie these various gait asymmetries induced by dynamic treadmill walking. However, given that only one limb is paced by the metronome and the other is unconstrained, it is not yet clear how the coordination patterns between the limbs change with treadmill belt speed change at four different timings throughout the gait cycle. We anticipate that a better understanding of how the dynamic treadmill can affect interlimb coordination patterns could be useful for providing customizable rehabilitation approaches aimed at restoring proper interlimb coordination in persons with asymmetric gait deficits.

This study aimed to investigate interlimb coordination during dynamic treadmill walking in adults without gait impairment. We hypothesized that interlimb coordination would be changed during dynamic treadmill walking as demonstrated by an increased magnitude of center of oscillation difference and decreased anti-phase movement relative to normal walking. More

specifically, we hypothesized that these changes in interlimb coordination would differ depending on the timing of the speed change within a gait cycle, expecting that, in the trials where the paced (right) leg steps onto a fast treadmill, the right leg will have a center of oscillation about a more flexed axis when compared to that of the left leg and vice versa when the right leg steps onto a slow treadmill. Similarly, we expect that the limb angles while participants step onto a fast treadmill with their paced (right) leg will show the right leg leading the left in phase and the opposite being observed when the right leg steps onto a slow treadmill.

METHODS

Ten young adults without gait impairment were recruited from the greater Baltimore region to participa in this study (2 M, 8 F, age: 25.1 ± 3.0 years). These participants composed one group from a larger experiment (16 M, 24 F, age: 25.6 ± 3.5 years, randomly assigned to four groups) and were chosen because they walked under the slowest dynamic treadmill conditions, for the purpose of understanding potential translational implications to neurologic populations. All participants reported no current neurological, musculoskeletal, or cardiovascular conditions and provided written, informed consent in accordance with the Declaration of Helsinki. The Johns Hopkins University Institutional Review Board approved all study procedures, and participants all received monetary compensation for their participation.

Data collection

All participants walked on an instrumented split-belt treadmill (Motek Medical, Houten, The Netherlands), but we emphasize that the treadmill belts were tied for all trials (i.e., participants did not walk under split-belt treadmill conditions where the belts moved at different speeds simultaneously; the split-belt treadmill allowed us to collect ground reaction force data from each individual leg). We collected kinematic data using an eight-camera motion capture

system (Vicon Motion Systems, Centennial, CO; 100 Hz) with 30 passive retroreflective markers on the seventh cervical vertebrae, jugular notch, tenth thoracic vertebrae, xiphoid process, bilaterally over the iliac crest, anterior superior iliac spine, posterior superior iliac spine, trochanter, thigh, lateral femoral epicondyle, medial femoral epicondyle, shank, lateral malleolus, medial malleolus, calcaneus, second metatarsal head, and fifth metatarsal head. We collected triaxial ground reaction forces using force plates embedded independently under each treadmill belt (1000 Hz). We executed dynamic treadmill walking on our instrumented split-belt treadmill with a custom D-Flow script (Motek Medical BV, Houten, The Netherlands). The dynamic treadmill controller changes between a slow and fast speed within a single stride at an acceleration rate of 6.0 m/s^2. For each of the dynamic treadmill trials (See Figure 1), 50% of the gait cycle was spent at the fast speed (1.0 m/s) and 50% at the slow speed (0.5 m/s).

Experimental protocol

The experimental protocol is outlined in Figure 1. All participants completed three baseline trials at slow (0.5 m/s), intermediate (0.75 m/s), and fast speeds (1.0 m/s) for two minutes each. The baseline trials were followed by the four dynamic treadmill walking trials (Slow, Fast, Accelerate, and Decelerate; greater detail on each trial is included below), each five minutes in duration. This is the same set of conditions that were used in our previous work, but here we tested at slower treadmill speeds (previous: slow=0.75m/s, intermediate=1.125m/s, fast=1.5m/s)[17]. The order of the dynamic treadmill trials was randomized for each participant. We instructed participants to synchronize each right heel-strike with a metronome tone that was aligned with the treadmill speed changes. The timing of the metronome tone was determined by each participant's average stride time across the intermediate baseline trial calculated by dividing the trial duration (120 seconds) by the total number of strides in the trial.

The treadmill speed changes at different points in the gait cycle for each dynamic treadmill trial (Figure 1). The metronome sounded to guide the desired timing pattern set by each dynamic treadmill trial: Slow (pacing a right heel-strike to occur when the treadmill moved at the slow speed), Fast (right heel-strike at the fast speed), Accelerate (right heel-strike at the intermediate speed while accelerating to the fast speed), and Decelerate (right heel-strike at the intermediate speed while decelerating to the slow speed). During the Fast trial, the treadmill moved at the fast speed over the first and last ~25% of the gait cycle and slow during the middle ~50% of the gait cycle. The Slow trial was the inverse of the Fast trial: the treadmill moved slow over the first and last ~25% of the gait cycle and fast over the middle ~50% of the gait cycle. During the Accelerate trial, the treadmill accelerated to the fast speed during the right heel-strike and then decelerated to the slow speed for the last ~50% of the gait cycle. The Decelerate trial was the inverse of the Accelerate trial, and thus the treadmill decelerated from the fast speed to the slow speed during right heel-strike and accelerated to the fast speed for the last 50% of the gait cycle.

Data analysis

We used custom MATLAB software for data processing (The Mathworks [R2023b], Natick, MA). We used R [version 4.3.3] and RStudio[18] [version 2023.12.1] for data analysis and visualization[19–24]. We filtered the marker and ground reaction force data using a fourth-order low-pass Butterworth filter with cutoff frequencies of 6 Hz and 28 Hz, respectively. We determined heel-strikes as the timepoints where the limb angle shifted from positive to negative, and toe-offs as the opposite[17]. We calculated step length, step time, limb angles, peak propulsion and braking forces as in our previous work[17]. We also recorded the treadmill belt speeds within

each trial to assess how well participants synchronized their right heel-strikes with the metronome tone to assess adherence to the desired heel-strike/speed change pairings.

We calculated phase shift and center of oscillation (as well as center of oscillation difference) as temporal and spatial measures of interlimb coordination, respectively. We calculated limb phasing as stride-by-stride maximum cross-correlation value between right and left limb angle trajectories (we calculated limb angles as the sagittal vectors between the iliac crest and second metatarsal head markers bilaterally). We subtracted limb phasing during dynamic treadmill walking from limb phasing during intermediate baseline walking to calculate phase shift (e.g., a phase shift of zero would indicate that the participant is walking in anti-phase similar to baseline). We calculated center of oscillation as the limb angle at midstance (or at the timepoint midway between heel-strike and toe-off). We then calculated the center of oscillation difference as the difference between center of oscillation measured for the left and right legs. To assess how well the participants synchronized their right heel-strikes with the metronome tone, we also measured the percentage of the strides where the right heel-strike occurred within ±200ms of the metronome tone.

Statistical analysis

We compared phase shift between early (mean of first 30 strides) and late (mean of last 30 strides) epochs within each dynamic treadmill trial, compared across the four dynamic treadmill trials, and assessed Time*Trial interactions using a 2 (Time) x 4 (Trial) repeated measures ANOVA. We performed a similar analysis on center of oscillation difference. Finally, we analyzed leg-specific centers of oscillations using a 2 (Leg) x 2 (Time) x 4 (Trial) repeated measures ANOVA. We set $\alpha<0.05$ for all analyses. To understand how the timing of gait events (left heel-strike, left toe-off, and right toe-off) changed between the four dynamic treadmill

walking trials within participants, we ran a 2 (Time) x 4 (Trial) repeated measures ANOVA. All post-hoc analyses were pairwise comparisons with Bonferroni correction to assess any significant main effects and interactions. Given that we paced everyone to a prescribed cadence linked to their stride time during the intermediate baseline trial, we used a one-way repeated measures ANOVA to understand if stride time was consistent across the four trials within participants.

RESULTS

Participants stepped in synchrony with the metronome during dynamic treadmill walking

Participants synchronized their right heel-strikes with the metronome with group mean success rates ranging from 89% to 94% across the four dynamic treadmill trials. Because we constrained the right heel-strike to a prescribed cadence individualized to each participant's stride time during the intermediate baseline trial, we verified that participants walked with similar stride times across all four dynamic treadmill walking conditions using a one-way repeated measures ANOVA that revealed no significant main effect of trial on stride time ($F(3,67)=2.73$, $p=0.05$). We also confirmed that our spatiotemporal, kinematic, and kinetic measures (e.g., step length, step time, leading and trailing limb angle, ground reaction forces, etc.) aligned with the biomechanical results of our previous work[17]. Given the present study was aimed at understanding the interlimb coordination demands of dynamic treadmill walking, these data are depicted in the Supplementary Material.

Timing of heel-strikes and toe-offs within the gait cycle changed across the different dynamic treadmill walking trials

In Figure 2, we show the mean timings of the unconstrained gait events (i.e., left toe-off, left heel-strike, right toe-off) within the gait cycle across all four dynamic treadmill walking

trials relative to the treadmill speed changes that occurred during each trial (black lines indicate group mean treadmill speeds, gray lines indicate individual participant mean treadmill speeds).

Left toe-off

A 2 (Time) x 4 (Trial) repeated measures ANOVA comparing the timing of left toe-offs within each gait cycle revealed a significant main effect of Trial ($F(3,27)=10.62$, $p<0.01$) and a significant Time*Trial interaction ($F(3,27)=5.22$, $p<0.01$) but no significant main effect of Time ($F(1,9)=0.41$, $p=0.54$). Post-hoc analyses showed that left toe-off timing was significantly different between the early and late epochs of the Accelerate ($p=0.03$) and Fast ($p=0.03$) trials but not the Slow ($p=0.24$) or Decelerate ($p=0.06$) trials. Left toe-off timings during the early epochs of the Accelerate and Fast trials were significantly different ($p=0.02$), as the left toe-off occurred later in the gait cycle in the early epoch of the Accelerate trial when compared to the Fast trial. Left toe-off timing was significantly different between the Fast and Slow trials during both the early and late epochs ($p<0.01$ and $p=0.04$, respectively), as the left toe-off occurred later in the gait cycle in the Slow trial as compared to the Fast trial. During the late epoch, left toe-off timing was significantly different between the Accelerate and Slow trials ($p<0.01$) and between the Decelerate and Fast trials ($p=0.02$). Left toe-off occurred later in the gait cycle over the late epoch of the Slow trial when compared to the Accelerate trial; similarly, left toe-off occurred later in the Decelerate trial when compared to the Fast trial.

Left heel-strike

A 2 (Time) x 4 (Trial) repeated measures ANOVA comparing the timing of left heel-strikes within each gait cycle revealed no significant main effects of Time ($F(1,9)=0.06$, $p=0.81$) or Trial ($F(3,27)=2.20$, $p=0.11$) but did reveal a significant Time*Trial interaction ($F(3,27)=3.85$, $p=0.02$). Post-hoc analyses revealed that the timing of the left heel-strike during the early epoch

of the Fast trial was significantly earlier in the gait cycle than the timing of the left heel-strike during the late epoch of the Fast trial ($p<0.01$). The timing of the left heel-strike was also significantly later during the early ($p=0.02$) and late ($p=0.02$) epochs of the Slow trial than those of the Accelerate trial. The timing of the left heel-strike during the late epoch of the Decelerate trial was significantly later as compared to the late epoch of the Accelerate trial ($p<0.01$).

Right toe-off

A 2 (Time) x 4 (Trial) repeated measures ANOVA comparing the timing of right toe-offs within each gait cycle revealed no significant main effects of Time ($F(1,9)=1.03$, $p=0.34$) or Trial ($F(3,27)=0.56$, $p=0.64$) and no significant Time*Trial interaction ($F(3,27)=1.23$, $p=0.32$).

Changes in temporal and spatial measures of interlimb coordination depend on the timing of the speed change within the gait cycle

Temporal interlimb coordination: phase shift

Briefly, a phase shift value of zero indicates that the limbs are in anti-phase, similar to baseline walking. A positive phase shift indicates that the right leg oscillations are advanced in time relative to those of the left and vice versa. Phase shift time series values are depicted in Figure 3A.

A 2 (Time) x 4 (Trial) repeated measures ANOVA revealed a significant main effect of Trial ($F(3,27)=19.85$, $p<0.01$) on phase shift and a significant Time*Trial interaction ($F(3,27)=7.63$, $p<0.01$) but no significant main effect of Time ($F(1,9)=0.370$, $p=0.56$). Post-hoc analyses (depicted in Figure 3B) revealed that phase shift in the Fast trial was significantly more positive (i.e., right leg oscillates advanced in time relative to the left) than in the Slow ($p<0.01$), Accelerate ($p<0.01$), and Decelerate ($p<0.01$) trials. Phase shift in the Slow trial was significantly more negative (i.e., left leg oscillates advanced in time relative to the right) than in

229 the Accelerate trial ($p<0.01$). During the early epoch of the Fast trial, phase shift was
230 significantly more positive than during the Accelerate ($p<0.01$), Decelerate ($p<0.01$), and Slow
231 ($p<0.01$) trials. During the late epoch of the Slow trial, phase shift was significantly more
232 negative than in the Accelerate trial ($p=0.01$). During both the early and late epochs of the trial,
233 phase shift was significantly more positive during the Fast trial as compared to the Decelerate
234 and Slow trials ($p=0.01$ and $p<0.01$, respectively). This indicates that the right leg oscillated
235 advanced in time relative to the left, and to a greater extent in the Fast trial than in Decelerate
236 and Slow.

237 Spatial interlimb coordination: center of oscillation and center of oscillation difference

238 Briefly, a positive value of center of oscillation indicates that the right leg is rotating
239 about a flexed axis whereas a negative value indicates rotation about an extended axis. A positive
240 value of center of oscillation *difference* indicates that the right leg is rotating about a more flexed
241 axis than the left and vice versa. Center of oscillation difference time series data are depicted in
242 Figure 4A.

243 A 2 (Leg) x 2 (Time) x 4 (Trial) repeated measures ANOVA revealed a significant main
244 effect of Time ($F(1,9)=10.64$, $p=0.01$) on center of oscillation but no significant main effects of
245 Leg ($F(1,9)=1.72$, $p=0.22$) or Trial ($F(3,27)=1.15$, $p=0.35$). The repeated measures ANOVA also
246 revealed significant Leg*Trial ($F(3,27)=4.21$, $p=0.02$) and Leg*Time ($F(1,9)=10.93$, $p=0.01$)
247 interactions but no significant Time*Trial($F3,27)=0.43$, $p=0.73$) or Leg*Time*Trial
248 ($F(3,27)=1.46$, $p=0.25$) interactions. Post-hoc analyses revealed that the center of oscillation
249 during the Fast trial was significantly more positive on the right leg than the left ($p<0.01$). The
250 left leg oscillated about a significantly more extended axis during the Fast trial as compared to
251 the Decelerate ($p=0.02$) and Slow ($p<0.01$) trials. Conversely, the right leg oscillated about a

significantly more flexed axis during the Fast trial as compared to the Decelerate ($p<0.01$) and Slow ($p<0.01$) trials.

When considering the significant Leg*Time interaction, post-hoc analyses revealed that the centers of oscillation for the left and right legs during the early epochs were significantly different than those during the late epochs ($p<0.01$). To expand further, the axis about which the right and left limbs oscillated during the early epoch of each trial was significantly different from the late epoch of each trial for both the Slow ($p=0.02$) and Decelerate ($p=0.02$) trials, but not Fast ($p=0.96$) or Accelerate ($p=0.82$).

Asymmetry in center oscillation can be captured by the center of oscillation difference, or the bilateral difference in the axis about which each leg rotates in the sagittal plane. A 2 (Time) x 4 (Trial) repeated measures ANOVA revealed a significant main effect of Time ($F(1,9)=10.93$, $p=0.01$) and Trial ($F(3,27)=4.21$, $p=0.02$) on center of oscillation difference. There was no significant Time*Trial interaction effect ($F(3,27)=1.46$, $p=0.25$). Post-hoc analyses (shown in Figure 4B) revealed that the Fast trial displayed significantly greater center of oscillation difference than the Slow ($p<0.01$) and Decelerate ($p<0.01$) trials. Additionally, the center of oscillation difference was greater in the early epochs as compared to the late ($p<0.01$).

DISCUSSION

In this study, we showed that dynamic treadmill walking can be leveraged to drive interlimb coordination changes that are dependent on the timing of the speed change within the gait cycle (i.e., trial type). Additionally, we show that asymmetric gait changes selectively driven during dynamic treadmill walking are finely tuned with the timing of the constrained right heel-strike. The unconstrained left leg gait events shift in time across trials, which may drive the interlimb coordination changes shown above. Our hypotheses were supported in the Fast trial,

which was the most perturbing trial to interlimb coordination. The Fast trial caused the limbs to be more in-phase and have a more flexed or forward center of oscillation when compared to any of the three other dynamic treadmill trials and to normal walking. The remaining trials showed lower magnitude interlimb coordination changes than originally hypothesized. Here, we will discuss potential implications of the different dynamic treadmill walking patterns in driving gait changes in populations with gait asymmetry, and future work to translate the dynamic treadmill controller for clinical use.

During the Slow trial, the metronome sounds to align each right heel-strike with the slow speed (0.5 m/s). Then as the right limb enters single support, the treadmill accelerates to the fast speed (1.0 m/s), remains there through double support, and decelerates at the beginning of swing phase. The opposite is true of the left limb, despite both left heel-strike and toe-off being unconstrained. Given the timings of these speed changes and the general adherence to the metronome, the gait asymmetries this trial creates are fairly predictable and agree with our previous work[17]. For example, step length on the left leg was larger than that on the right given the faster speed at heel-strike for the left leg. In this study, the data show that the left and right limbs oscillate about the same axis during the Slow trial. At the start of the Slow trial, the limbs are more in-phase than normal walking, and they shift toward but never truly reach anti-phase by the end of five minutes of walking. Altogether, this shows that the Slow trial does not require spatial interlimb coordination changes, but it does create temporal changes from normal walking, especially at the start of the walking bout.

The Fast trial was designed to induce equal and opposite gait changes to the Slow trial. In our previous study, this was generally the case with a few caveats. For example, Fast trial trailing limb angle asymmetry was largest at the beginning of the trial and decreased throughout the five

minutes of walking, while Slow trial trailing limb angle was consistently asymmetric with equivalent magnitude to the end of the Fast trial[17]. The change over time indicates some level of motor learning, but the effects are quite transient, especially when comparing to a task like split-belt treadmill walking. During the Fast trial, the timing of the speed changes relative to the unconstrained gait events are the opposite of the slow trial, with more consistency across individuals. In general, the biomechanical changes observed during this trial were opposite to that of the Slow trial. Given the opposite nature of the Fast and Slow trials, it can be assumed that the interlimb coordination change requirements of the Fast trial would mirror those of the Slow. However, we found that interlimb coordination demands were greater during the Fast trial in both center of oscillation and phasing. Center of oscillation moves through a greater range between the right and left legs, creating a significant center of oscillation difference in comparison to the other trials. In terms of phasing, the limbs are more in-phase than the other trials, with opposite directionality. The Fast trial offers the greatest magnitude of interlimb coordination change from normal walking, as well as from the other dynamic treadmill conditions.

The Accelerate and Decelerate trials were designed to be opposites of one another and more accurately reflect this design than the Slow versus Fast comparison. Accelerate involves the treadmill accelerating to the fast speed at right heel-strike, remaining fast until late stance, and then decelerating to the slow speed until late swing phase of the right limb. The Decelerate trial is the opposite but slightly shifted in time, with the treadmill almost achieving the slow speed at right heel-strike, accelerating to the fast speed for the latter 50% of the gait cycle, then decelerating during late swing of the right limb. Similar to the previous trials, Accelerate and Decelerate produced biomechanical results that we expected given previous work in dynamic

treadmill walking[17]. The Accelerate trial requires the least amount of change in interlimb coordination from normal walking, while the Decelerate trial involves some degree of temporal shift (i.e., the limbs are more in-phase than normal walking).

Across the four dynamic treadmill walking trials, two created the greatest temporal shifts in interlimb coordination (Fast and Decelerate), while two created shifts in spatial coordination (Fast and Slow). Because it shifts both temporal and spatial components, the Fast trial requires the greatest coordination adjustments to meet the needs of the novel gait pattern.

While dynamic treadmill walking was developed to simulate a split-belt walking environment with a conventional, single-belt treadmill, the two walking patterns have clear differences. The interlimb coordination demands of split-belt treadmill walking are significantly greater than those observed here in dynamic treadmill walking. During split-belt walking, the slow leg (i.e., the leg on the slow belt) lags the fast leg (i.e., the leg on the fast belt) in timing, creating a more in-phase gait pattern than normal walking[16]. Additionally, the slow leg oscillates about a more forward axis than the fast leg during split-belt walking[16]. Fast dynamic treadmill walking drives a similar pattern of temporal and spatial changes, but the other conditions produce changes in neither or only one domain of coordination. The magnitude of interlimb coordination change created in the Fast trial is like that of gradually introduced spl it-belt walking, but about half the magnitude of abruptly introduced split-belt walking[16]. We hypothesize that this lower magnitude of interlimb coordination change in the Fast trial, and smaller deviations in the remaining trials, play a role in dynamic treadmill walking not following the characteristics of gait adaptation that are seen so well in split-belt walking. Additionally, the explicit task of pacing the right limb to a metronome provides a different kind of stimulus for gait pattern change.

The ability to selectively target asymmetric gait using dynamic treadmill walking, which can be executed on a conventional treadmill, offers opportunity for use in traditional rehabilitation settings. To understand how people with a neurologic impairment or injury will respond to dynamic treadmill walking, it is important to first understand the interlimb coordination demands of this pattern. We have shown that this pattern can be leveraged to drive significant interlimb coordination changes when using the Fast condition but does not require the same magnitude of changes as other methods (i.e., split-belt walking). For people with gait impairment, it is currently unknown whether perturbing interlimb coordination is necessary for creating a long-term change in gait symmetry. Additionally, we cannot assume that people with asymmetric gait patterns, and especially those with neurologic conditions, respond to dynamic treadmill walking in the same way as healthy young adults. Therefore, ongoing work is assessing the feasibility of using dynamic treadmill walking to normalize asymmetry patterns after stroke, as well as the potential impact of repeated exposure on changing overground gait asymmetry.

Limitations

There are limitations to this study that should be noted when considering the findings. Young adults with intact neurologic systems tend to walk at speeds around 1.5 m/s ± 0.17 m/s[25], but in our study, we had our participants walk at 0.5 m/s and 1.0 m/s. These slower speeds are advantageous from a clinical perspective because clinical populations tend to walk more slowly, though there is potential that these slower speeds may have simultaneously disrupted the walking of our control participants. Another limitation of the current study is that we only used two measures of interlimb coordination, center of oscillation and phase shift. There are other measures that we could have used to gain a deeper understanding of interlimb coordination changes driven by dynamic treadmill walking (e.g., percent double limb support time[5], limb

orientation at weight shift[5], etc.). Similarly, we also operationally defined interlimb coordination as the coordination between the left and right legs. We did not assess movement of the upper limbs or how they interact with the legs in this analysis.

CONCLUSION

In this study, we investigated the interlimb coordination changes that dynamic treadmill walking may require. We found that only the Fast trial generates significant interlimb coordination differences from baseline walking in both the spatial and temporal domains. The Slow and Decelerate conditions required interlimb coordination changes in only one domain, while the Accelerate condition does not require altered coordination from normal walking. As a potential clinical tool, this finding is encouraging because it offers additional flexibility to remediate gait asymmetry while choosing whether to challenge interlimb coordination. Given that we tested interlimb coordination changes driven by this tool in slower-than-average walking for control participants, there is potential for implementation into clinical populations that present with gait asymmetry.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, RTR, upon reasonable request.

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459 **FIGURE CAPTIONS**

460 **Figure 1.** Experimental paradigm: All participants completed three baseline trials at slow (0.5
461 m/s), intermediate (*inter*, 0.75 m/s), and fast (1.0 m/s) treadmill speeds for two minutes each.
462 Participants then completed the four five-minute dynamic treadmill walking trials in a
463 randomized order. The shaded, gray box depicts the target speed profiles of each trial over a gait
464 cycle. We used a metronome to pace the right heel-strike, so all gait cycles are depicted for the
465 right leg and begin at right heel-strike. Each trial is named according to treadmill speed at heel-
466 strike.

467 **Figure 2.** Group speed profiles: Group average treadmill speed traces are shown as solid black
468 lines with standard error of the mean represented with gray fill. Participants generally adjusted to
469 the target speed profiles depicted in Figure 1, showing overall success with metronome
470 synchrony. Individual participant speed profiles are layered behind the group traces in light gray.
471 The group average gait event timings (LTO, LHS, RTO) are represented by the vertical dashed
472 lines shown in each profile. *RHS*: right heel-strike; *LTO:* left toe-off; *LHS:* left heel-strike; *RTO:*
473 right toe-off.

474 **Figure 3.** Phase shift: **A)** Time-series plots of the temporal shift of the left and right leg limb
475 angles through the duration of each dynamic treadmill walking condition. Each phasing value
476 was subtracted from baseline walking at the intermediate speed to understand phase shift from
477 baseline walking. Plots depict group mean (thick, dark colored line) ± standard error of the mean
478 (lighter colored fill). On the far-right side of each plot, group mean ± standard error over the last
479 30 strides is depicted by a solid dot with error bar. **B)** Boxplots of early (first 30 stride, darker
480 color) and late (last 30 stride, lighter color) phase shift from each trial. Bars display the group
481 median ± interquartile range of phase shift values. Individual participant data are represented as

gray scatter points. Solid black scatter points indicate outlier values. Asterisks indicate statistical significance within a repeated measures analysis of variance: *: $p<0.05$, **: $p<0.001$, ***: $p<0.0001$.

Figure 4. Center of oscillation difference: **A)** Time-series plots of the spatial shift between the left and right leg limb angles through the duration of each dynamic treadmill walking condition. Plots depict group mean (thick, dark colored line) ± standard error of the mean (lighter colored fill). On the far-right side of each plot, group mean ± standard error over the last 30 strides is depicted by a solid dot with error bar. **B)** Boxplots of early (first 30 stride, darker color) and late (last 30 stride, lighter color) center of oscillation difference from each trial. Bars display the group median ± interquartile range of phase shift values. Individual participant data are represented as gray scatter points. Solid black scatter points indicate outlier values. Asterisks indicate statistical significance within a repeated measures analysis of variance: *: $p<0.05$, **: $p<0.001$, ***: $p<0.0001$.

Figure 1

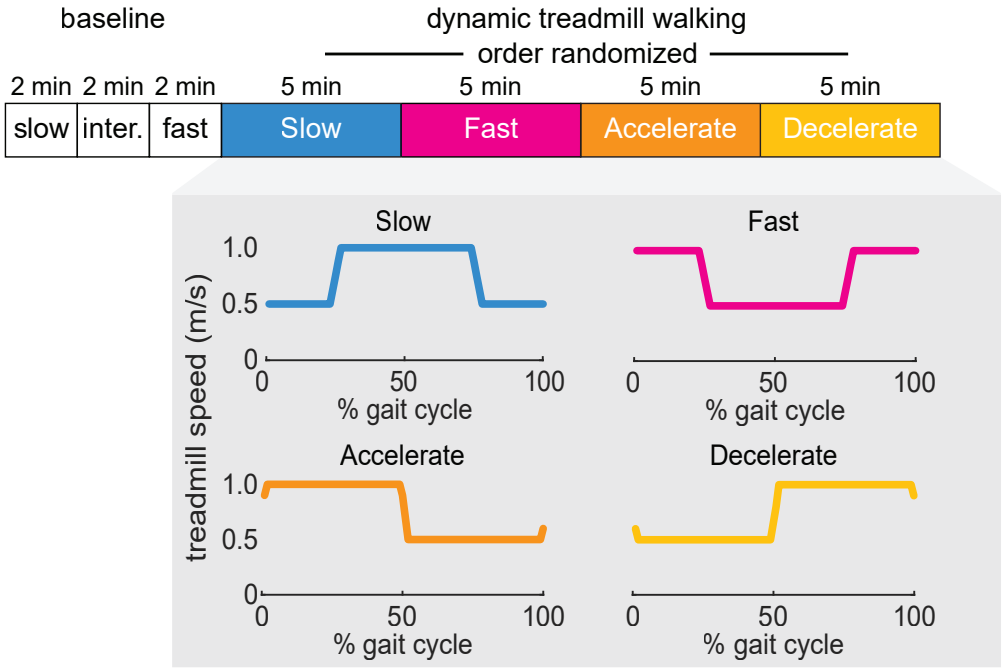

baseline
dynamic treadmill walking
order randomized
2 min
2 min
2 min
5 min
5 min
5 min
5 min
slow
inter.
fast
Slow
Fast
Accelerate
Decelerate
treadmill speed (m/s)
1.0
0.5
0
0
50
100
% gait cycle

Figure 2

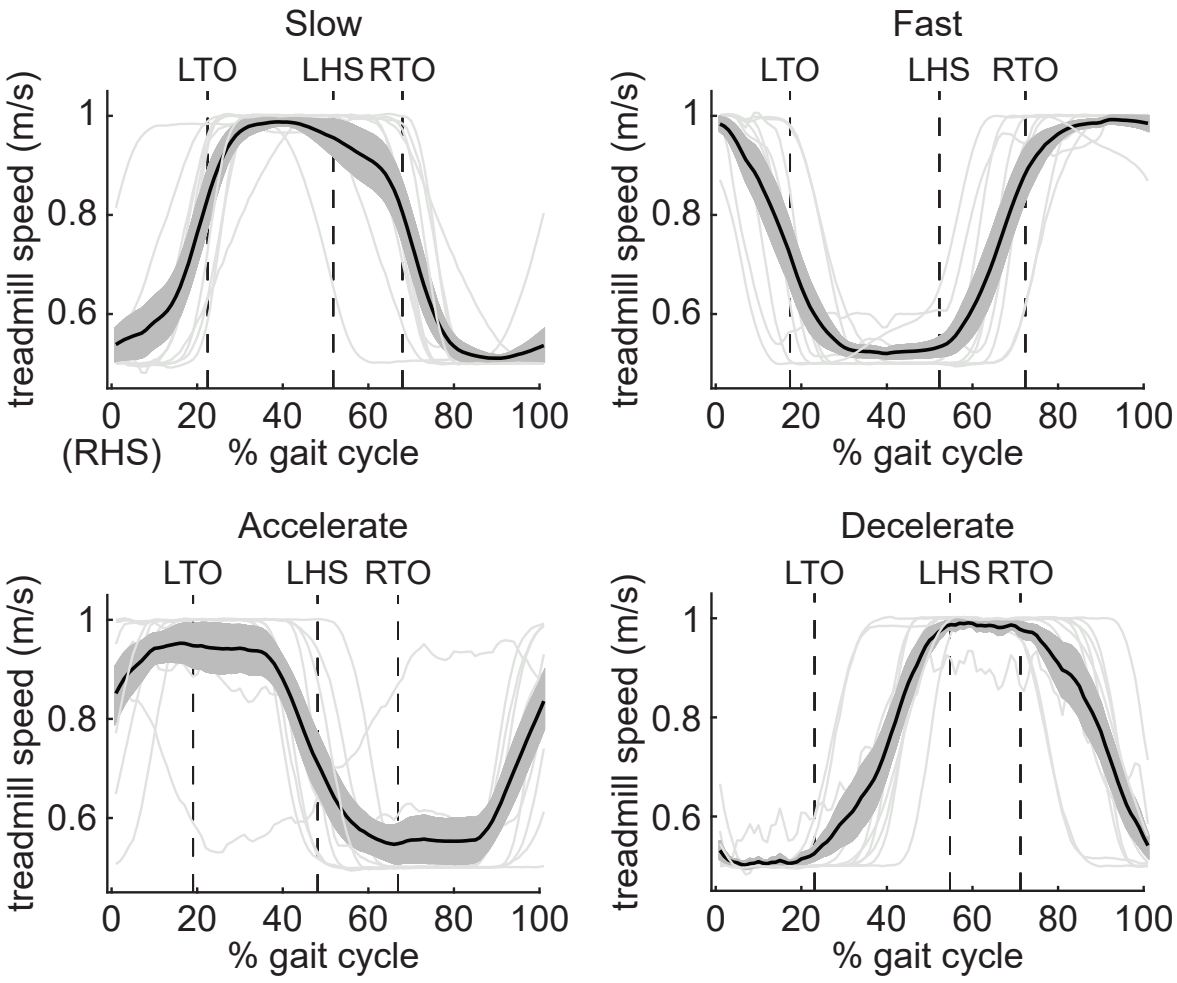

Slow
LTO
LHS
RTO
treadmill speed (m/s)
1
0.8
0.6
0
20
40
60
80
100
(RHS)
% gait cycle
Fast
LTO
LHS
RTO
treadmill speed (m/s)
1
0.8
0.6
0
20
40
60
80
100
% gait cycle
Accelerate
LTO
LHS
RTO
treadmill speed (m/s)
1
0.8
0.6
0
20
40
60
80
100
% gait cycle
Decelerate
LTO
LHS
RTO
treadmill speed (m/s)
1
0.8
0.6
0
20
40
60
80
100
% gait cycle

Figure 3

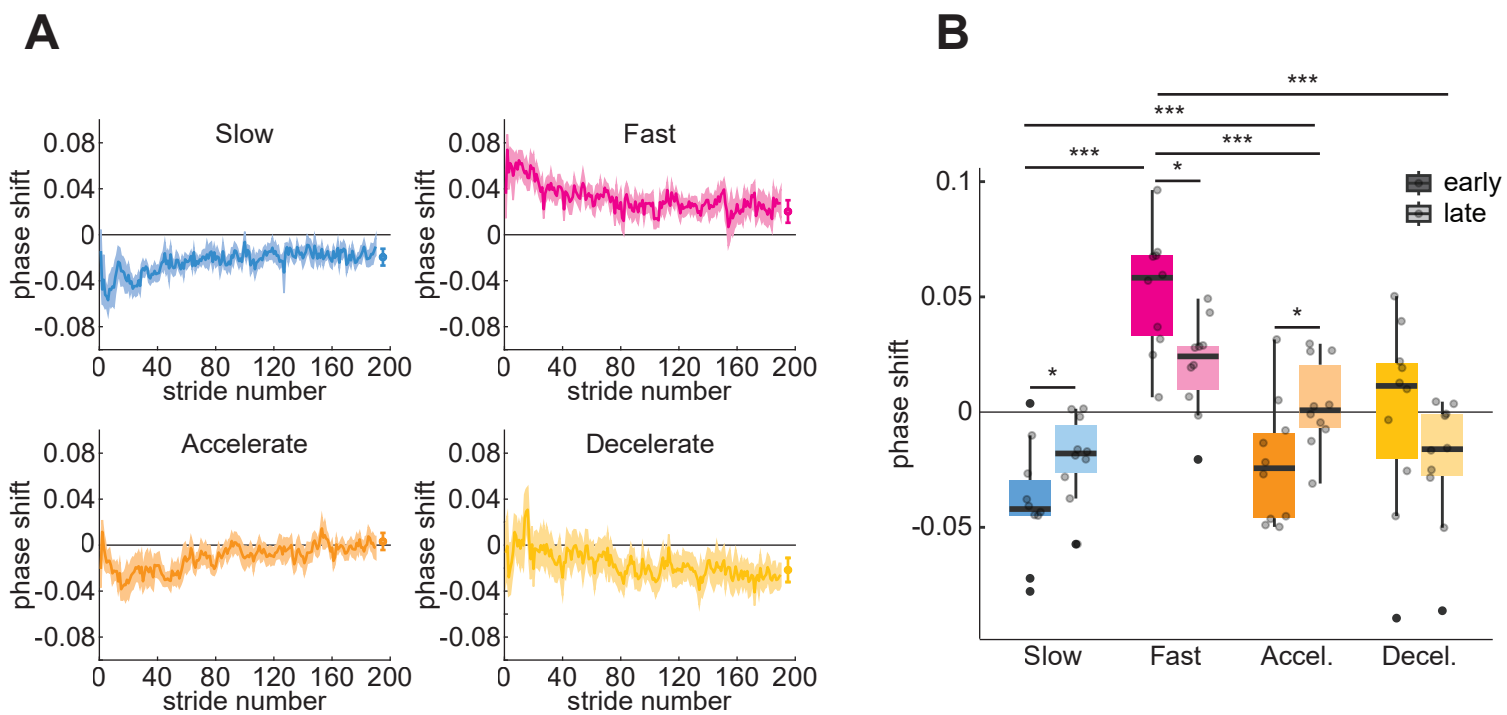
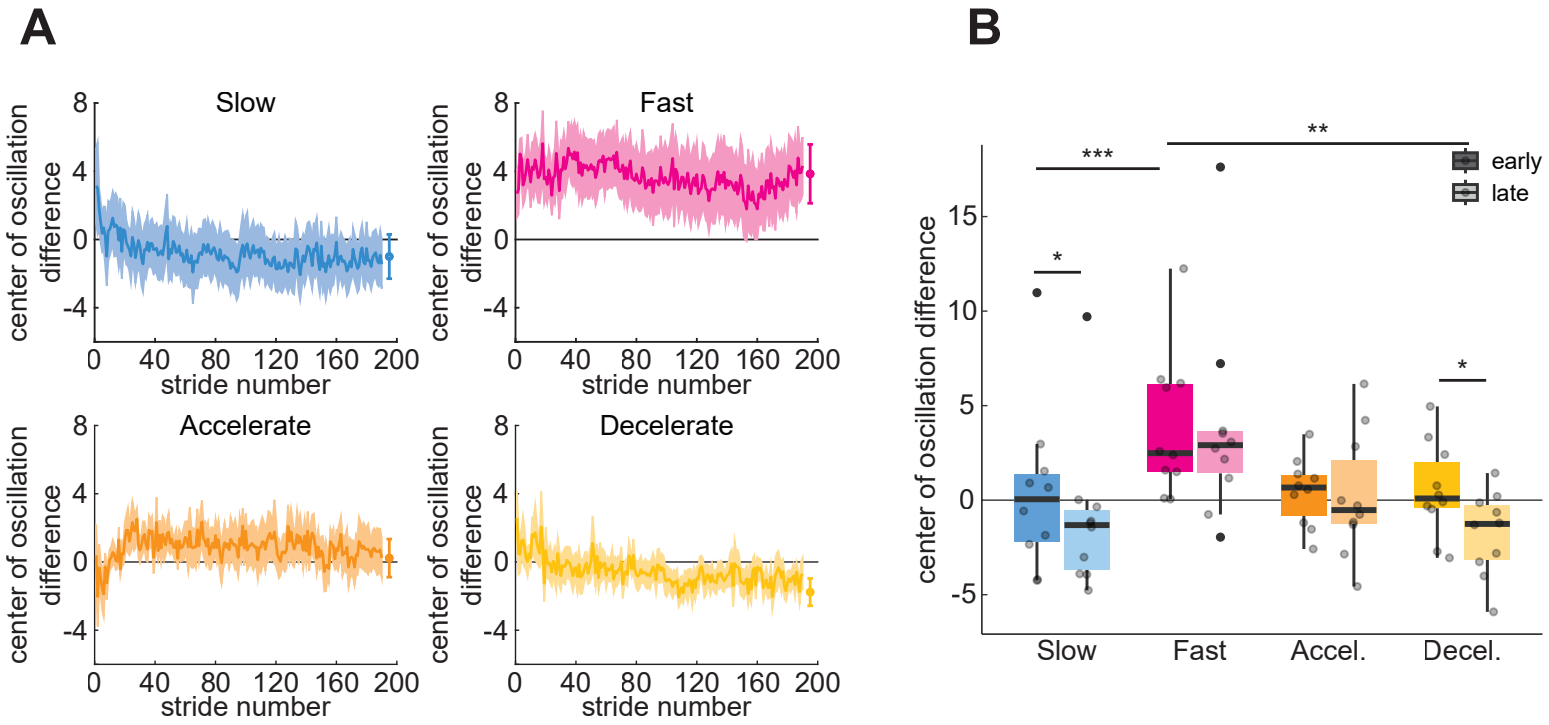

A
Slow
Fast
Accelerate
Decelerate
phase shift
0.08
0.04
0
-0.04
-0.08
0
40
80
120
160
200
stride number
B
early
late
0.1
0.05
0
-0.05
Slow
Fast
Accel.
Decel.
***
*

Figure 4


A
Slow
Fast
Accelerate
Decelerate
center of oscillation difference
stride number
8
4
0
-4
0
40
80
120
160
200
B
early
late
***
**
*
*
15
10
5
0
-5
Slow
Fast
Accel.
Decel.