THE METABOLIC AND MECHANICAL COSTS

OF STEP ASYMMETRY IN WALKING

by

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The Metabolic and Mechanical Costs of Step Asymmetry in Walking

Thesis directed by Associate Professor Rodger Kram

Many gait pathologies (e.g. stroke, injury, joint replacement, amputation) result in both bilateral asymmetry and substantial metabolic and biomechanical costs. Despite this, the role of gait asymmetry during walking remains uncertain; gait asymmetry may either be caused by the pathology or may be adaptive, minimizing the costs associated with an already problematic situation. Here I asked, are there inherent costs to gait asymmetry independent of gait pathology and beyond that imposed by non-preferred step times? To answer this question, I measured the rate of metabolic energy expenditure and calculated mechanical power production while healthy adults walked symmetrically and asymmetrically at a range of step and stride times. I found that walking with asymmetric steps required more metabolic power than symmetric gait at corresponding step times. The positive mechanical power production increased with increasing asymmetry, paralleling the increases I observed in metabolic power. I suggest that the increased need for mechanical power may result from increased power absorption during double support and compensation through increased power production during single support. Overall, I identify an inherent metabolic and mechanical cost to gait asymmetry and find that symmetry is optimal in healthy, symmetric adults.

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THE METABOLIC AND MECHANICAL COSTS OF STEP ASYMMETRY IN WALKING

Richard Gregory Ellis

I. Introduction

Restoring gait symmetry remains a central clinical goal for people recovering from injury, stroke, joint replacement and amputation (Chow et al., 2006; Hopper et al., 2008; Kim and Eng, 2003; Wall et al., 1981), yet it remains to be shown that symmetry is optimal in pathological populations. Indeed, there remains debate as to whether bilateral symmetry is optimal even in healthy human walking. Recent modeling studies suggest that the costs of small asymmetries may be minimal (Srinivasan, 2011), functional or stable under some circumstances (Gregg et al., 2011; Seyfarth, 2011). In addition, some researchers have suggested that some asymmetry even in healthy adults may serve a functional purpose, differentiating the roles of the dominant and non-dominant lower limbs (Seeley et al., 2008).

The presence of some degree of gait asymmetry in healthy adults has been consistently reported, although its importance is uncertain. Researchers have found kinematic asymmetry in both spatial and temporal aspects of gait (Sadeghi et al., 2000b) as well as in important kinetic variables such as ground reaction force (GRF) (Seeley et al., 2008) and center of mass (CoM) velocity (Crowe et al., 1993). In most cases, however, identified gait asymmetries in healthy humans are relatively small, typically less than ~4% (e.g. Herzog et al., 1989). Studies examining healthy gait asymmetry have emphasized the role of the dominant and non-dominant lower limb. During healthy gait, it appears that the dominant limb contributes more to propulsion and power generation (Hirasawa, 1979; Hirokawa, 1989; Sadeghi et al., 2000a). In contrast, the non-dominant limb may be more involved in weight support and power absorption.

In contrast, substantial bilateral asymmetries are consistently reported for a range of gait pathologies. For example, Hesse et al. (1997) identified kinematic asymmetries of 14-42% during gait initiation in hemiparetic patients. Kim and Eng (2003) found swing and stance time asymmetries of 13-27% during walking in a similar subject population. In people with unilateral leg amputations, researchers have identified temporal and spatial asymmetries of 2 to 10%, (Dingwell et al., 1996; Isakov et al., 2000). Beyond this, Seliktar and Mizrahi (1986) found differences in affected/unaffected push-off and braking forces as high as 75%. Small but consistent asymmetry in both kinematic and kinetic variables have also been observed in individuals recovering from ACL surgery (Noyes et al., 1991), and knee and hip arthroplasty (McCrory et al., 2001; Yoshida et al., 2008).

Beyond observed asymmetries, gait pathology is also associated with clear physiological and biomechanical costs. Waters and Mulroy (1999) quantified the metabolic energy expenditure for a variety of pathological gaits, finding that walking in affected populations was consistently more metabolically expensive (up to 100%) even at slower walking speeds than in healthy controls. Biomechanical costs have also been observed. For example, amputees have noticeably higher risk for osteoarthritis than age-matched non-amputees, which many believe is tied to unequal power production and absorption patterns between the legs (Lloyd et al., 2010; Norvell et al., 2005). Asymmetric use may also result in higher chances of repeat ACL injury in the unaffected leg of those who have already undergone unilateral ACL reconstruction (Salmon et al., 2005).

Although gait pathology is associated with both increased asymmetry and distinct physiological costs, the relation between these remains unclear. Gait asymmetry may either be caused by the pathology or may be adaptive, minimizing the costs associated with an already problematic situation. Supporting this idea, Hof et al. (2007) suggested that gait asymmetry in unilateral amputees may help compensate for impaired balance. Here I asked, is there an inherent cost to gait asymmetry independent of that imposed by gait pathology? To answer this question, I investigated if symmetry is optimal in healthy, approximately symmetrical adults.

Before examining the mechanics of asymmetric gait, it is important to understand the mechanics of symmetric gait. During symmetric walking, the body repeatedly arcs over a rigid leg, exchanging kinetic energy and potential energy. Because of this exchange, walking is typically modeled as an inverted pendulum (Cavagna et al., 1977; Farley and Ferris, 1998). Significant, simultaneous positive and negative work must be performed to transition to the next leg, much of it during double support (Donelan et al., 2002b; Kuo et al., 2005). Strides deviating from preferred width, duration and length are both metabolically and mechanically more expensive than preferred strides (Donelan et al., 2002b; Maxwell Donelan et al., 2001; Umberger and Martin, 2007). An asymmetric stride is composed of two unequal steps, which necessitates that at least one step is not preferred. I must therefore be careful to appropriately compare an asymmetric, non-preferred stride to a symmetric, preferred stride.

Here, I examined the metabolic and mechanical costs of step-time asymmetry in healthy adults using visual and auditory feedback. I hypothesized that:

Hypothesis 1: The metabolic cost of walking with asymmetric steps will be greater than for walking with symmetric steps.

Hypothesis 2: This increased metabolic cost will be explained by greater mechanical power production.

Hypothesis 3: The majority of the additional positive and negative mechanical power required will be performed during double support.

II. Methods

Overview

10 healthy subjects (5M/5F) volunteered for this study (Height 1.74±0.20m, Mass 68±10kg, Age: 26±6yrs, Mean± SD). All subjects were informed as to the requirements and goals of the study and gave written consent prior to participation as per the Institutional Review Board of the University of Colorado.

During a single session, I measured the gait kinematics, metabolic rates and ground reaction forces of subjects as they walked both symmetrically and asymmetrically at different step and stride frequencies, and target asymmetries. All trials were at one walking speed (1.25 m/s) on a motorized dual-belt treadmill with a force plate under one treadmill (Kram et al., 1998). For all conditions, I instructed subjects to match an auditory metronome and gave them visual feedback of their symmetry as they walked. I measured subject's rates of metabolic energy expenditure via expired gas analysis and used the individual limbs method derived by Donelan et al. (2000) to calculate the external mechanical power production under each condition.

Subjects performed 5 symmetric trials (step times -25, -12.5, 0, +12.5 and +25% of preferred), 3 moderately asymmetric trials (R/L step times 0/-25, +12.5/-12.5, and +25/-0% of preferred) and 1 highly asymmetric trial (R/L step times +25/-25% of preferred) (Fig 1). Each asymmetric trial therefore had stride and step times comparable to one of the symmetric trials.

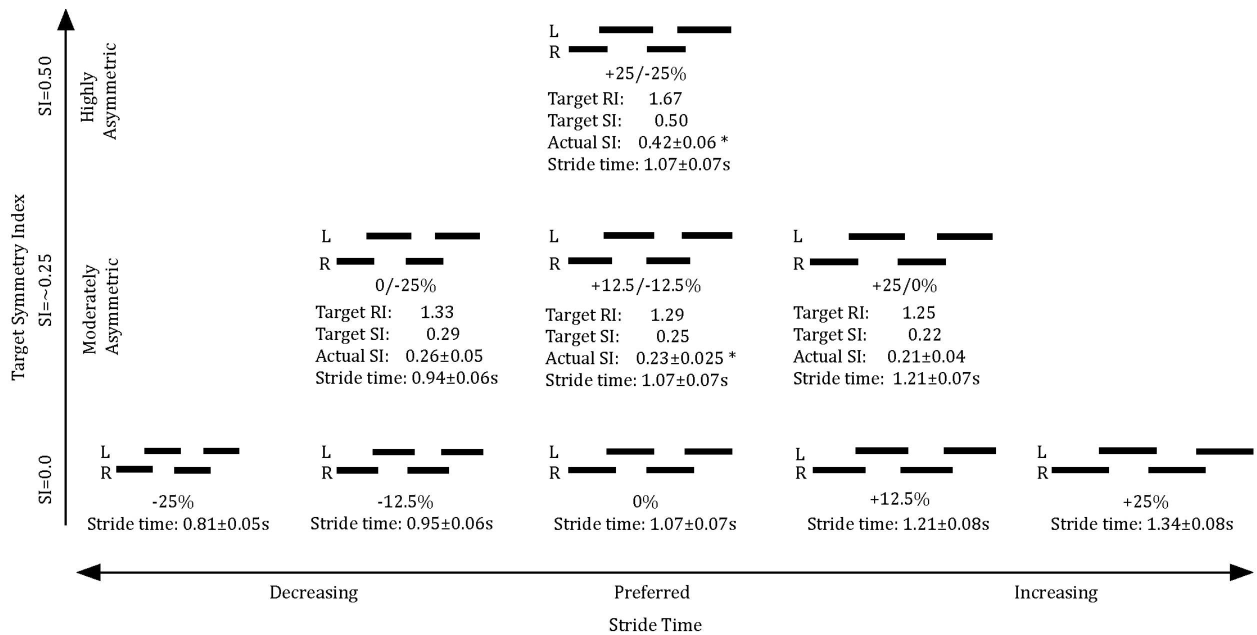

Fig 1. Step diagram of conditions. Subjects walked both symmetrically and asymmetrically at a range of target step and stride times. Subjects completed 5 symmetric trials (Target SI 0.0), 4 moderately symmetric trials (Target SI ~0.25), and 1 highly asymmetric trial (Target SI .50). Subjects were able to match the target stride time for all conditions, but did not walk as asymmetrically as the target for the +12.5/-12.5% and +25/-25% conditions. * Actual SI significantly different from target.

Symmetry Calculation

I define a step as being from heel strike of the contralateral foot to the heel strike of the ipsilateral foot (i.e. a right step is from left heel strike to right heel strike). After (Sadeghi et al., 2000b), I calculated ratio index (RI) as:

$$Ratio\ Index\ (RI) = \frac{Time_{Right}}{Time_{Left}} \qquad \text{Eq. 1}$$

Ratio index was given as feedback to the subjects because it provided a simple, easily understood metric and implies a clear directionality. I chose target RI's greater than 1.0 for each asymmetric condition. The right leg was therefore always the 'slow' leg, with a step time greater than the left leg and slower than or equal to preferred. Similarly, the left leg was the 'fast' leg for all subjects with a step time less than the right leg and faster than or equal to preferred. The use of RI's greater than 1.0 also helped to partially standardize how subjects could complete the task. I also calculated symmetry index (SI) (Herzog et al., 1989; Robinson et al., 1987) as:

$$Symmetry\ Index\ (SI) = \frac{Time_{Right} - Time_{Left}}{0.5*(Time_{Right} + Time_{Left})} \qquad \text{Eq. 2}$$

Although subjects received feedback of their ratio index, I present all results in terms of symmetry index to more easily compare my results with the work of others.

Experimental Protocol

Subjects first stood quietly on the treadmill for 5 minutes while I measured their standing metabolic rate. Although all subjects had previously experienced treadmill walking, I further familiarized all subjects to treadmill walking for 5 minutes at the experimental speed (1.25 m/s). During this time, I measured subjects preferred stride frequency by measuring the time it took to complete 20 strides twice and averaging the results. I used this in all subsequent data collection to determine relative step and stride times.

I then introduced subjects to the step time symmetry feedback that they used for the remainder of the study. A computer screen mounted in front of subjects at eye level presented their actual step time RI as well as a target RI for that trial. Subjects walked for 5 minutes at 1.25 m/s with verbal instructions to explore how to increase or decrease their RI. Subjects had visual feedback of their RI for the remainder of the protocol, including during the symmetric trials.

Subjects next walked to a symmetric auditory metronome for 5 trials. The symmetric trials were at preferred stride frequency, ±12.5 and ±25% of preferred, presented in a random order (target RI 1.00). Each trial was 5 minutes long. I measured metabolic data for the entire trial and collected ground reaction force (GRF) data for 30 seconds during the last two minutes of each trial.

Subjects then completed 4 asymmetric trials. I chose the asymmetric conditions such that stride time matched one of the symmetric conditions but with unequal step times. The target step time for each leg matched the step time experienced in one of the symmetrical conditions. The asymmetric conditions had right/left step times: +0/-25, +12.5/-12.5, +25/-0 and+25/-25 % faster or slower than preferred (semi-random order, target RI of 1.33, 1.29, 1.25 and 1.66 respectively). Because the target RI was always greater than 1.00, the right leg step always had a longer step time then the left leg.

In order to give subjects time to learn the to walk asymmetrically, all subjects first completed the +12.5/-12.5% for 20 minutes while attempting to both match the metronome and reach the target RI. Subjects first breathed into the mouthpiece for 1 minute while quietly standing and listening to the metronome. After the treadmill had reached the experimental speed (1 minute), I then recorded metabolic rate, step time and right foot ground reaction force continuously for the next 20 minutes of this trial. Finally, subjects completed the +0/-25, +25/-0 and +25/-25% conditions in a random order for 7 minutes each. I recorded metabolic data for the duration of each trial and force data from the right foot for 30 seconds during the last minute of each asymmetric trial. For each asymmetric condition, subjects then walked for 1 minute in the other direction (i.e. with their left foot on the force treadmill). I measured left foot GRF for 30 seconds during this window.

Metabolic Rate

I measured metabolic rate via expired gas analysis using a ParvoMedics TrueOne 2400 Metabolic Measurement system. Subjects remained seated for at least 10 minutes prior to measurement of their standing metabolic rate and rested for at least 3 minutes between all trials. I calculated the average rates of O_2 consumption and CO_2 production over the last 2 minutes of each trial. I calculated gross metabolic power (Brockway, 1987) and subtracted standing power from gross power to find net metabolic power.

Kinematics

Footswitches in each shoe measured heel-strike and toe-off times throughout the experiment. I used this data and Eq. 1 to provide subjects with RI feedback. For the asymmetric conditions, I used the heel strike times from each foot to determine right and left step time for each foot as the subject walked in each direction (measuring right and left GRF respectively). I took the average step times from these two trials and used them to synchronize the independently recorded ground reaction forces.

Mechanics

I measured the ground reaction forces and moments at 1000 Hz using a dual belt treadmill with an AMTI force platform under one treadmill (Kram et al., 1998). For all conditions, I low-pass filtered the data at 20 Hz and used an 80 N force threshold to determine stance onset and offset times. I then constructed an average force profile for the first 15 complete strides.

For the symmetric conditions, I duplicated and phase-shifted the right foot force profile by 50% of the gait cycle to create a complete stride cycle from only right-foot forces. For the asymmetric conditions, I used the average right and left step times observed in the footswitch data to find the percentage of the gait cycle taken up by the left step (39-45% depending on condition). I then phase shifted the left foot ground reaction force by the measured percentage to create a complete right and left combined force profile. In software, I enforced zero net impulse across a stride such that average vertical force equaled the subject's weight and average horizontal force equaled zero.

I then calculated the individual limb power after Donelan et al. (2002a). Briefly, I summed the force data from both feet and integrated the data to find CoM velocity and displacement. I then took the dot product of the force from each foot and the CoM velocity to find the individual limb power for both the right and left legs. Finally, I independently integrated the left and right leg positive and negative power to calculate the positive and negative work associated with each double and single-support phase for each leg. I added these components to find positive and negative work per stride and divided by stride time to find positive mechanical power. I performed all data processing using Matlab 7.11.0 (The MathWorks Inc., 2010).

Statistics

Because steps both faster and slower than preferred are metabolically and mechanically different from preferred steps, I believe that the costs of asymmetry are best understood by comparing an asymmetric slow/fast stride to the corresponding symmetric slow/slow and fast/fast conditions. For example, when possible, I compared the +12.5/-12.5% condition to the average of the symmetric +12.5% and -12.5% conditions rather than the same stride time, +0% condition. For each asymmetric condition, I normalized the average metabolic and mechanical power of each asymmetric trial to the average of these two relevant step time conditions. I then used a linear mixed effects model to investigate how increasing SI affected metabolic and mechanical power.

I also tested whether subjects met the target stride time and SI for each condition using a one sample t-test. Finally, I used a 1-factor repeated measures ANOVA to test for a change in positive or negative mechanical work across three symmetric or asymmetric conditions. I performed this test for each foot when that foot was the leading leg, during single support, and as the trailing leg. If I found a significant and substantial difference, I then followed up this comparison with 3 t-tests to identify specific within-comparison differences. I used R 2.13.1 (2011) for the regression analysis and Matlab 7.11.0 for all t-tests and ANOVA's.

III. Results

My symmetric results confirm previous findings on the metabolic cost of varying step time; slower and faster steps relative to preferred increased metabolic power (Umberger and Martin, 2007). Symmetric steps 25% slower than preferred cost resulted in a ~0.97 W kg^{-1} (+30%) increase in metabolic power, while steps 25% faster than preferred resulted in a 1.35 W kg^{-1} (+42%) increase. Similarly, mechanical power increased with increasing symmetric step time (i.e. longer steps). A 12.5% increase in symmetric step time resulted in a ~0.024 W kg^{-1} (+6%) increase in mechanical power output, consistent with previous findings that slow steps require greater external power production (Donelan et al., 2002b).

The moderately asymmetric conditions required 0.7-1.0 W/kg (21-29%) more metabolic power than symmetric steps at the same stride time (Fig. 2). Similarly, the +25/-25% condition required 2.5 W/kg (+80%) more metabolic power. Regression analysis revealed that asymmetric walking is also more expensive than the average cost of symmetric walking with corresponding fast and slow steps. I found that a 0.23 increase in SI (moderately asymmetric conditions) required a ~0.55 W/kg (17%) increase in metabolic power while a 0.42 increase in SI (highly asymmetric condition) required ~1.0 W/kg (31%) more metabolic power than corresponding symmetric walking ($p < 0.0001$).

I observed parallel increases in the demand for external mechanical power. Subjects produced 35% more positive power under the moderately asymmetric conditions and 64% more positive power for the highly asymmetric conditions (~0.13 and ~0.24 W/kg respectively, $p < 0.0001$). I next examined subject's kinematics and mechanics more closely to better understand how subjects responded to my specific perturbation.

For both the symmetric and asymmetric conditions, subjects were able to successfully walk at the target stride time, but did not walk as asymmetrically as the target SI for the +12.5/-12.5% and +25/-25% conditions (Fig. 1). Subjects were also more variable when completing the asymmetric trials (e.g. Fig. 2, error bars). One to two subjects were able to walk with less mechanical power production during each of the 3 moderately asymmetric conditions than during comparable symmetric walking.

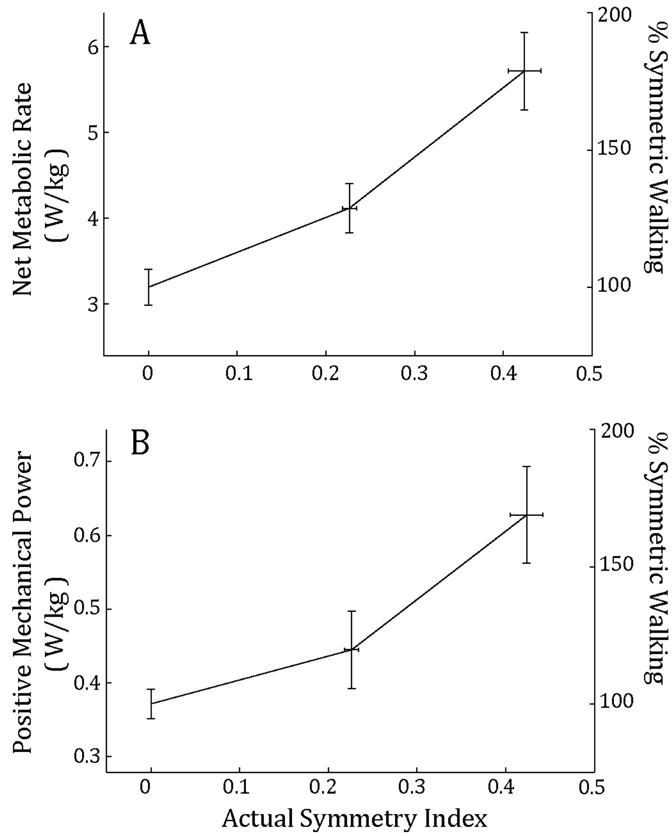

Fig. 2. Net metabolic power (A) and mechanical power (B) for the 0%, +12.5/-12.5% and +25/-25% conditions. % Symmetric walking reflects values normalized symmetric preferred (0% condition). There was variation in both power production and actual symmetry index for each subject. Vertical and horizontal error bars represent ±1 S.E.

Subjects adjusted both their stance and swing times to reach the target asymmetry. In order to increase step time with their right leg, subjects had correspondingly longer stance durations with their left leg. Similarly, a short step time with the left leg corresponded to a short stance time on their right leg. The right, ‘slow’ leg therefore had a longer swing duration and a shorter stance duration relative to symmetric walking while, the left, ‘fast’ leg had a longer stance duration and shorter swing duration. Increasing asymmetry resulted in a longer left stance time, a shorter right stance time and a faster left to right transition period relative to symmetric walking at the same stride time.

Interestingly, this means that stance duration was nearly constant for the right leg across the -25, +0/-25 and +25/-25% trials; In each, the left leg took a step 25% faster than preferred, resulting in similar ground contact times for the right foot (contact times of 0.49, 0.51 and 0.52s respectively). Correspondingly, left leg contact time was similar constant across the +25, +25/-0 and +25/-25% conditions (0.79, 0.77, and 0.72s).

I observed changes in the vertical and horizontal ground reaction force produced by each leg in response to the imposed asymmetry (Fig. 3 A,B). The right, ‘slow’ leg demonstrated reduced vertical force at the end of stance and produced less braking force in the horizontal. Increasing asymmetry therefore resulted in increasing reliance on the short step-time (and longer stance duration) left leg. With increasing asymmetry, the left leg produced more vertical force during early stance while also braking more.

Asymmetric forces also resulted in an asymmetric CoM velocity profile (Fig 3C). Consistent with symmetric walking, subjects generally were moving more quickly during double support and slower at mid-stance. Unlike symmetric walking, however, the CoM velocity was slower at left mid-stance than during right mid-stance.

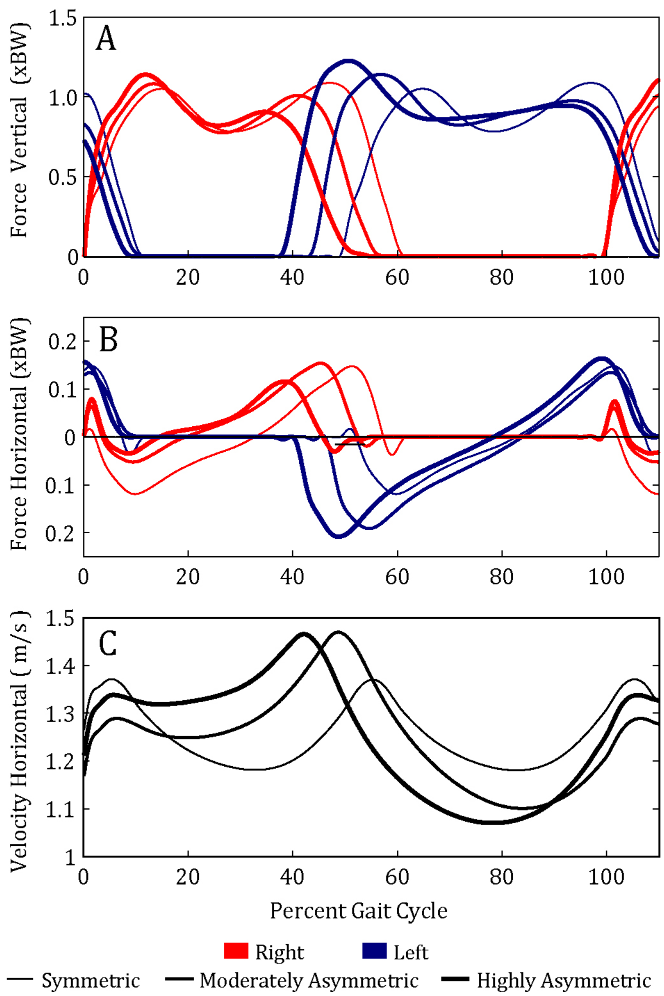

Fig. 3. Subject average vertical (A) and horizontal (B) GRF and horizontal velocity (C) profiles for the 0%, +12.5/-12.5% (moderately asymmetric) and +25/-25% (highly asymmetric) conditions.

I also observed a shift in when subjects were absorbing and producing power with each leg (Fig. 4). I then broke down the work performed by each leg as the leading leg, during single support and as the trailing leg (area under power curve, Fig. 5). To control for the effects of stance and step duration on mechanics, I made this comparison across the -25, 0/-25 and +25/-25% conditions for the right leg and across the +25, +25/0 and +25/-25% conditions for the left leg, as stance duration was relatively constant across these conditions.

Increasing asymmetry resulted in a redistribution of when during the gait cycle subjects performed both positive and negative work (Fig. 5). For the right, ‘slow’ leg, increasing asymmetry resulted in an increase in negative work performed during single support. The left, ‘fast’ leg performed substantially more negative work as the lead leg during the left-to-right transition and less positive work as the trailing leg during the right-to-left transition. Subjects then performed dramatically more positive work during left leg single support.

IV. Discussion

I accept my 1st hypothesis; walking with asymmetric step times required 0.7-2.5 W/kg (21-80%) more metabolic power than symmetric walking at a comparable stride time (Fig. 6A). Further, I find that my asymmetric conditions were also more expensive than walking with non-preferred step times; the moderately asymmetric conditions were ~0.55 W/kg (~17%) more expensive than the average of symmetric walking at comparable step times. I therefore suggest that gait asymmetry is inherently metabolically expensive beyond the costs imposed by non-preferred step times.

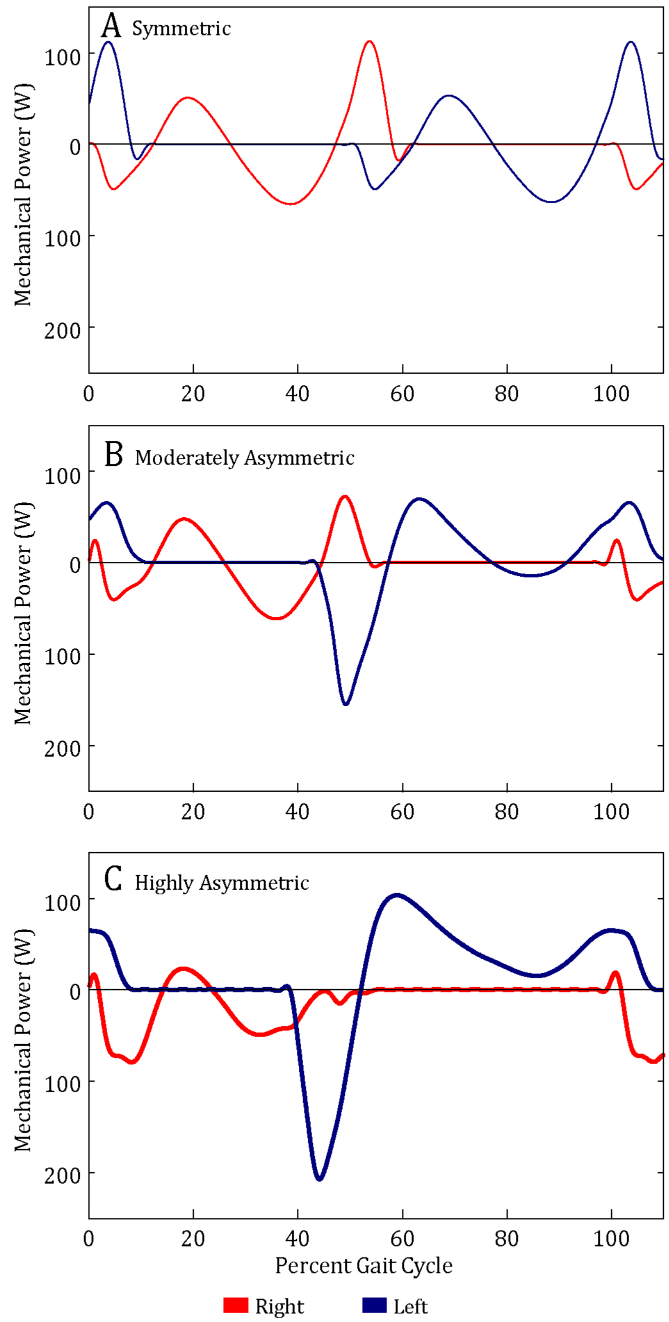

Fig. 4. Subject average power across a stride for the 0% (A), +12.5/-12.5% (B, moderately asymmetric) and +25/-25% (C, highly asymmetric) conditions.

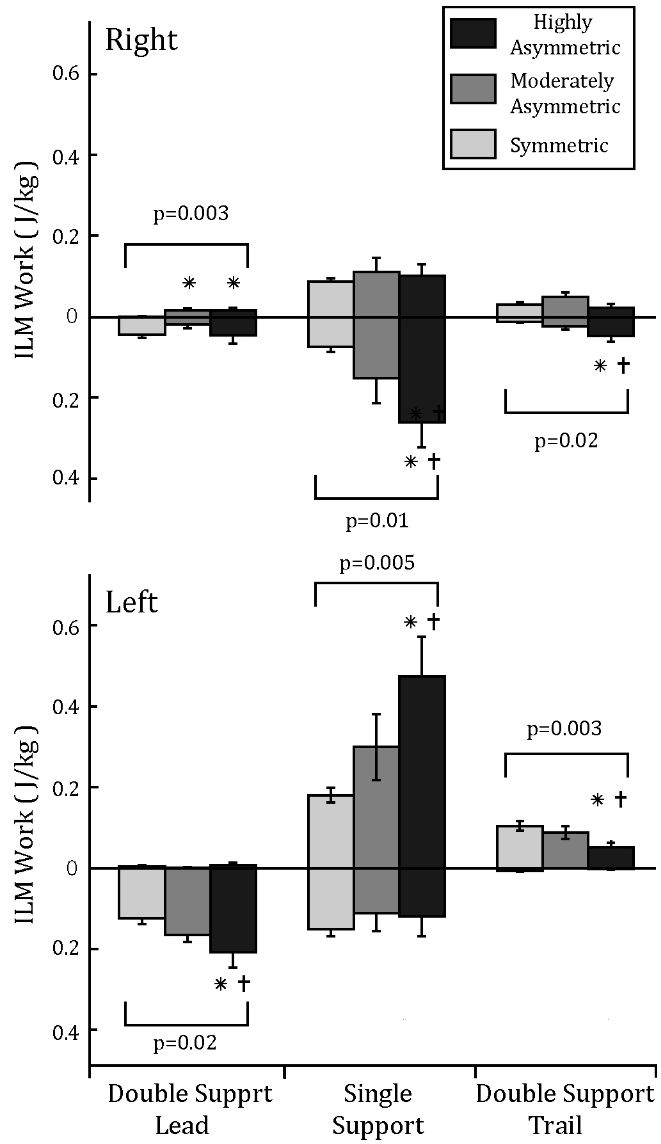

Fig. 5. Individual Limb Work for the right and left leg as the trailing leg, during single support and as the leading leg. For the right leg, I looked across the same-stance duration -25%, +25/0% and +25/-25% conditions. For the left leg, I examined the +25%, +25/0% and +25%/-25% conditions. Subjects performed increasing negative work with their right leg during single support, and with their left leg as the leading leg. Subjects performed more positive work during single support on the left leg. Error bars are ±1 S.E. * significantly different from symmetric. t significantly different from moderately asymmetric condition.

Previous studies have shown that preferred human gait involves combinations of step width, length and duration that minimize energy expenditure (Donelan et al., 2001; Umberger and Martin, 2007). I identify symmetry as another energy-minimizing criteria in healthy human gait. Interestingly, walking asymmetrically at non-preferred stride times required increased metabolic power parallel to the increases observed during symmetric walking (Fig 6A, moderately symmetric points). These results therefore clarify two separate metabolic costs in human walking; both step symmetry and stride time are independently optimized during normal, preferred walking.

I observed increases in the demand for mechanical power production and absorption across stride times that parallel the observed increase in metabolic power (Fig. 6B). A 0.23 increase in SI required 35% more positive mechanical power production than symmetric walking at comparable step times. I therefore accept my 2nd hypothesis and suggest that changes in external mechanical power production partially drive the observed differences in metabolic power.

I also identified shifts in when subjects performed positive and negative external mechanical work. With increasing asymmetry, subjects generally performed less positive push-off work and more collision work during double support. They also did more negative work during right leg single support. Potentially in compensation, subjects then performed dramatically more positive work during left leg single support. I therefore reject my 3rd hypothesis.

Although novel, these findings are generally consistent with those hypothesized by Soo and Donelan (2012), who suggest that the coordination of push off and collision plays an important role in minimizing the work of step-to-step collisions in human walking. Indeed, my

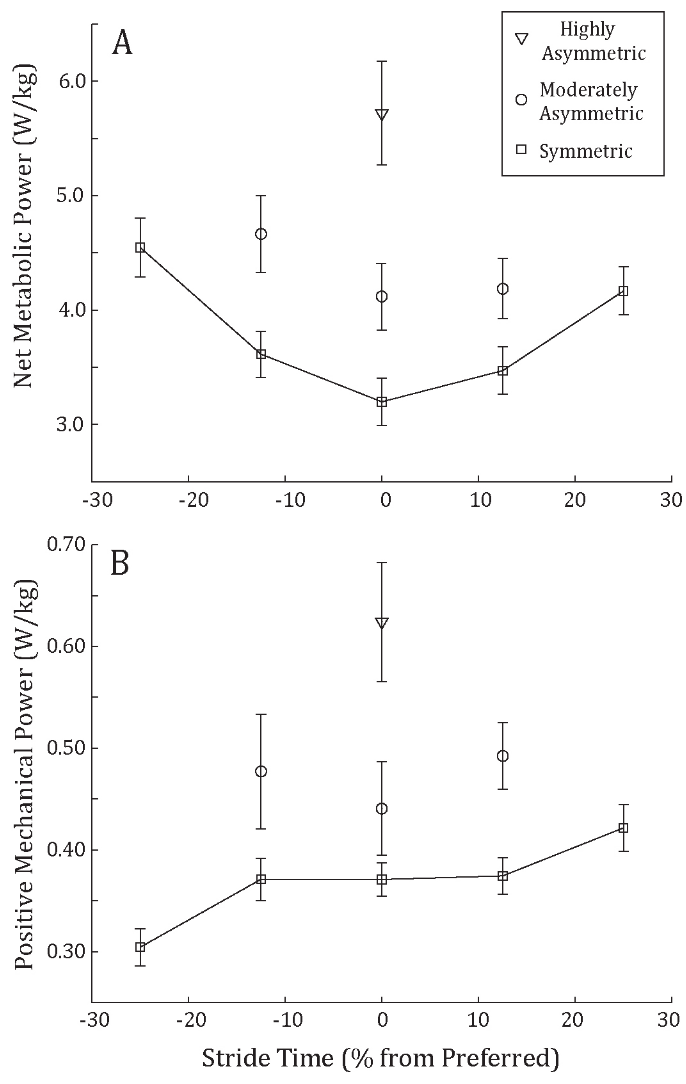

Fig. 6. Net metabolic power (A) and mechanical power (B) against stride time. Deviation from preferred in either dimension (symmetry or stride time) resulted in increasing metabolic and mechanical demands.

perturbation resulted in markedly asymmetric velocity profiles, suggesting a need for asymmetric step-to-step collisions, potentially impairing this coordination. I also find that subjects compensate by performing substantially more positive work during left leg single support, emphasizing the importance of single support work during walking (Neptune et al., 2004).

Although my asymmetric conditions were both metabolically and mechanical more expensive than corresponding symmetric conditions, I find that these costs would be relatively small across the range of asymmetry typically observed in a healthy population. My regression results suggest that a SI index of 0.01 (1% asymmetry) would result in only a ~0.75% increase in net metabolic power, consistent with recent findings of only minimal costs to small amounts of gait asymmetry (Srinivasan, 2011).

One key limitation of this study is the use of a single force platform to measure and correlate both left and right GRF's. I believe my approach is sound for the large asymmetries imposed in this study, but do not believe it is sensitive to the smaller asymmetries typically observed in healthy populations. I therefore did not attempt to quantify these gait parameters during the symmetric conditions, instead choosing to assume symmetry as is common in biomechanical analyses.

I also examined only external mechanical power. The perturbation resulted in noticeable swing phase adaptations and altered the need for internal power production. Subjects tended to delay their right leg swing to achieve a slower step time while swinging their left leg more quickly than normal. Part of the increase in metabolic cost may therefore be attributed to changing leg-swing dynamics, which have been shown to constitute a substantial metabolic cost during human walking (Doke et al., 2005; Gottschall and Kram, 2005).

Additionally, although the degree of asymmetry I imposed is within the range observed in human patient populations, the asymmetries used here are toward the upper end of those typically reported (Kim and Eng, 2003; Seliktar and Mizrahi, 1986). I chose this approach partly because preliminary testing showed that subjects were unable to consistently walk at conditions closer to symmetry. Subjects could not identify small auditory asymmetries and struggled to meaningfully differentiate their gait from a symmetric one. Further, I believed that larger imposed asymmetries might result in more dramatic results.

Although I find that symmetry is broadly optimal in healthy adults, these findings do not support symmetry as an end goal in rehabilitation for individuals with pathological gait asymmetry. Here, I asked physically symmetric individuals to walk asymmetrically, however many individuals with pathological gait asymmetries are physically asymmetric. I found that that the costs of small asymmetries are small, suggesting that in a slightly asymmetric individual, asymmetry may be optimal. Similarly, metabolic efficiency is not they only possible optimality criteria in human gait; for example, individuals may instead favor balance (Hof et al., 2007) or minimizing joint pain (Powers et al., 1999). Indeed, I suspect that asymmetry may be optimal in physically asymmetric individuals.

Walking with asymmetric step times required marked metabolic costs above those imposed by non-preferred step time. I explain the increased metabolic cost through an increased need for positive mechanical power production. Subjects walked by performing less positive push-off work and more negative collision work, while compensating by performing more positive work during single support. I identify an inherent metabolic and mechanical cost to gait asymmetry and find that symmetry is optimal in healthy, symmetric adults.

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