Metabolic cost of transport and stance time asymmetry in individuals with unilateral transtibial amputation using a passive prostheses while walking

Ryan D. Wedge, Frank C. Sup IV, Brian R. Umberger

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ABSTRACT

Background: People with unilateral amputation typically walk with greater metabolic cost than able-bodied individuals, while preferring asymmetric walking characteristics. It is unclear if asymmetric walking is energetically optimal and how metabolic cost accounts for asymmetric patterns in people with amputation. The purpose of this study was to determine the effects of stance-time asymmetry on the metabolic cost of transport.

Methods: Fourteen participants (seven with amputation) completed two laboratory sessions where they walked on a treadmill while receiving real-time visual feedback about stance-time asymmetry. Expired gases were collected to determine the metabolic cost for a range of asymmetries (15% to +15% in 5% increments, positive percentages represent more time on intact [dominant] limb).

Findings: Participants with amputation walked with greater (P = 0.008) stance-time asymmetry (4.34 ± 1.09%) compared with able-bodied participants (0.94 ± 2.44%). Stance-time asymmetry had a significant effect on metabolic cost (P < 0.001). The asymmetries coinciding with the predicted minimum metabolic cost for people with amputation (3.23 ± 2.90%) and without (1.81 ± 2.18%) amputation were not different from preferred asymmetries (P = 0.365; p = 0.513), respectively. The cost of symmetric walking was 13.6% greater than near preferred walking for people with amputation (5% more time on intact limb).

Interpretation: Metabolic cost is not the only objective of walking, but like able-bodied individuals, it may influence how people with amputation walk. Rehabilitation typically tries to restore inter-limb symmetry after an injury, yet if the limbs are asymmetric, symmetric gait may not be optimal with current assistive devices.

1. Introduction

Metabolic energy expenditure is generally accepted as one of the key objectives in the multi-objective selection of locomotor patterns, along with other likely criteria such as stability, smoothness, and joint loading. It is unclear how energy expenditure is prioritized relative to other factors during walking in people with lower limb amputation. People with lower limb amputation who use a passive prosthesis generally have greater metabolic energy expenditure during walking compared with able-bodied individuals (Waters et al., 1976; Waters and Mulroy, 1999), with the exception of those who are highly fit, such as active-duty military personnel (Russell Esposito et al., 2014). Greater metabolic energy expenditure while walking can negatively impact function and quality of life (Pell et al., 1993). For most people with lower limb amputation, metabolic energy expenditure is important but is likely elevated because of prosthesis limitations compared to a biological limb. Therefore, even though people with lower limb amputation generally demonstrate greater metabolic energy expenditure than able-bodied individuals, they may still be selecting preferred gait patterns with the least metabolic energy expenditure.

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While there are some exceptions in the literature (Gundersen et al., 1989), able-bodied people typically demonstrate nearly symmetrical inter-limb stride mechanics for preferred walking conditions (Eng and Winter, 1995; Forczek and Staszkiewicz, 2012; Hamill et al., 1983; Hannah et al., 1984; Seeley et al., 2008). When able-bodied individuals are constrained to walk with stride asymmetry (i.e., non-preferred pattern), metabolic rate increases directly with the amount of asymmetry (Ellis et al., 2013; Stenum and Choi, 2020). Hence, symmetric stride characteristics may be preferred because they lead to the lowest metabolic cost. In contrast, the connections between gait asymmetry and metabolic cost in people with unilateral lower limb amputation are unclear because of potential adaptations to compensate for limitations of the prosthesis.

People with lower limb amputation have an altered morphology (i.e., limb structure) and must rely on a prosthesis to replace the missing anatomy. The prosthesis may have energy assistance features using either passive components that can only manipulate energy flow (i.e., spring-like foot-ankles and damper knees) or active components that can contribute energy (i.e., motors). Even with a well-fitting prosthesis that replaces some of the lost biological power, people with lower limb amputation may have residual limb pain (Ehde et al., 2000), gait instability (Hak et al., 2014), and muscle weakness (Hewson et al., 2020). Due to these deficits, asymmetric anatomy, and prosthetic device constraints, a consistent finding is that people with unilateral amputations spend more time on the intact limb compared with the prosthetic limb during the stance phase (Isakov et al., 2000; Sadeghi et al., 2001; Sanderson and Martin, 1997). In a limited number of studies, people with unilateral limb amputation have been trained to walk with symmetric stride characteristics in a research setting (Dingwell et al., 1996; Davis et al., 2004; Mahon et al., 2019). In one small, heterogeneous sample (i.e., different causes of amputation and amputation levels), metabolic cost of walking was reduced when using real-time visual feedback to promote symmetrical push-off force (Davis et al., 2004). In contrast, in a two-participant case series, symmetric walking was not metabolically optimal, and each participant selected some form of asymmetry after adapting to split belts moving at different speeds (Mahon et al., 2019). While such studies have been insightful, it is problematic to draw firm conclusions based on the limited existing data. Therefore, more research is needed within the different subpopulations of people with lower limb amputation. Since energy expenditure is an important criterion for self-selected gait patterns, people with unilateral lower limb amputation may adopt asymmetric gait patterns to reduce the metabolic cost of walking. Conversely, if symmetry is energetically optimal, as in able-bodied walkers, promoting symmetric gait could reduce metabolic cost for people with lower limb amputation.

The purpose of this study was to determine the effects of stance time asymmetry on the metabolic cost of transport (CoT). Based on previous literature regarding stride symmetry in people with and without amputation, we hypothesized that for preferred gait patterns, participants with unilateral transtibial amputation would exhibit greater stance time on the intact side compared with the prosthetic side, while able-bodied participants would exhibit symmetrical stance times. Further, we hypothesized that the CoT versus inter-limb asymmetry would demonstrate a U-shaped curve for both groups, and the CoT would be least at preferred stride characteristics for both groups. A direct consequence of these hypotheses is that participants with unilateral transtibial amputation are predicted to have an elevated CoT when required to walk symmetrically, compared with the CoT for their preferred, asymmetrical gait pattern. Thus, we predict that people with unilateral lower limb amputation walk asymmetrically, at least in part, to reduce the metabolic cost of walking.

2. Methods

Seven participants with unilateral transtibial amputation and seven able-bodied participants took part in this study (Table 1). Participants with unilateral transtibial amputation were between 16 and 48 years old, rated a Medicare activity classification of K3 or K4 (Centers for Medicare and Medicaid Services, 2020), had the amputation more than one year ago due to non-vascular causes (e.g., trauma, cancer, congenital), and used a passive prosthesis (Table 2). People with a K3 or K4 rating are prescribed an energy storage with elastic return prosthetic foot and ankle because they are active and can walk with variable cadences. Participants were excluded from the study if they had any condition, other than amputation, that affected their ability to walk (e.g., chronic pain, neurological or cardiovascular disorders), or if they had lower limb surgery in the last year. We only recruited participants with unilateral transtibial amputation from non-vascular causes to avoid confounding effects of vascular disease such as neuropathy and decreased fitness that affect metabolic cost and walking. We recruited the same number of female and male able-bodied participants as in the group with lower limb amputation. Age, height, and mass were not directly controlled for; however, the primary dependent variables were scaled by body mass (metabolic cost) and expressed as a percentage (asymmetry), accounting for the effects of body size. This study was approved by the University of Massachusetts and Quinnipiac University Institutional Review Boards. All participants read and signed an informed consent document prior to participation.

Each participant attended two laboratory sessions, 12 of the 14 participants (5 with amputation and 7 able-bodied) at the Biomechanics Laboratory at the University of Massachusetts Amherst (Amherst, MA, USA), and 2 with amputation at the Motion Analysis Laboratory at Quinnipiac University (North Haven, CT, USA). During each session, participants walked on a treadmill (Treadmetrix, Park City, UT, USA at UMass, and Woodway, Waukesha, WI, USA at Quinnipiac) at their preferred overground walking speed while receiving real-time visual feedback about inter-limb stance time asymmetry. During the first session, preferred overground walking speed was determined, followed by training and familiarization with the real-time visual feedback conditions without metabolic measurement. Preferred walking speed was determined with an over ground 400-m walk that consisted of twenty consecutive 20-m lengths. A six-meter segment of each length was timed with photogates (Johnson et al., 2020). Overground speed was used

<table>
<thead>
<tr>
<th>Participant</th>
<th>Amputation cause</th>
<th>Years since amputation</th>
<th>Prosthesis ankle type</th>
<th>Suspension type</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>Congenital</td>
<td>28</td>
<td>Osur Vari-Flex</td>
<td>End-bearing</td>
</tr>
<tr>
<td>S02</td>
<td>Congenital</td>
<td>24</td>
<td>OsurVari-Flex</td>
<td>End-bearing</td>
</tr>
<tr>
<td>S03</td>
<td>Trauma</td>
<td>4.4</td>
<td>Osur Pro-Flex</td>
<td>Pin</td>
</tr>
<tr>
<td>S04</td>
<td>Trauma</td>
<td>3</td>
<td>Ottobock</td>
<td>Suction</td>
</tr>
<tr>
<td>S05</td>
<td>Trauma</td>
<td>25</td>
<td>Osur Cheetah Xplore</td>
<td>Suction</td>
</tr>
<tr>
<td>S06</td>
<td>Trauma</td>
<td>2</td>
<td>Innovations Kinterra</td>
<td>Pin</td>
</tr>
<tr>
<td>S07</td>
<td>Cancer</td>
<td>29</td>
<td>Osur Vari-Flex</td>
<td>Suction</td>
</tr>
</tbody>
</table>
Because it matches habitual speed more closely (Malatesta et al., 2017). During the second session, the real-time visual feedback conditions were repeated on the treadmill while metabolic data were collected. Each walking trial lasted five minutes.

Stance times were determined from insole foot switches (B&L Engineering, Santa Ana, CA, USA; collected at 500 Hz) and a custom MATLAB (Math Works, Natick, MA, USA) program. The amount of asymmetry between limb stance times was calculated using an asymmetry index (Dingwell et al., 1996):

\[ \text{Asymmetry}_{\text{a}} = \frac{\text{Intact stance time} - \text{Prosthetic stance time}}{\text{Intact stance time} + \text{Prosthetic stance time}} \times 100\% \]  

\[ \text{Asymmetry}_{\text{c}} = \frac{\text{Dominant stance time} - \text{Nondominant stance time}}{\text{Dominate stance time} + \text{Nondominant stance time}} \times 100\% \]  

Asymmetry \(_{\text{a}}\) is the asymmetry index for the participants with an amputation, and Asymmetry \(_{\text{c}}\) is the asymmetry index for the able-bodied participants. Real-time visual feedback on stance time asymmetry consisted of a two-stride moving average line graph of the stance time symmetry index with a dashed black target line and ±2.5% bounds with solid red lines (Fig. 1). The participants were oriented to the feedback during the first session before completing the experimental trials by instructing them to walk with more time on one limb over multiple strides, observe the changes to the displayed data, and then walk with more time on the other limb. This guided-exploration time helped participants understand what they needed to do to complete each condition. During pilot testing, we found that a two-stride moving average permitted participants to make consistent adaptations to meet the asymmetry goal without having differences from stride-to-stride displayed that were too large (i.e., no averaging) or too small (i.e., three to four stride average).

The asymmetry feedback conditions were -15% to +15% in 5% increments, with 0% representing symmetric stance times between limbs, and performed in randomized order. Positive values indicated greater stance time on the intact limb for participants with lower limb amputation, and the dominant limb for able-bodied participants. The dominant limb was defined as the limb the participants self-reported to be the limb they preferred to use to kick a ball (van Melick et al., 2017). Negative values indicated greater stance time on the prosthetic limb and non-dominant limb, respectively. Participants with an amputation did not perform the -15% condition because this extreme condition was not consistently attainable during pilot testing. To avoid the effects of fatigue, participants were given five minutes of seated rest after each walking trial. Participants reported their perceived exertion on a scale from 1 to 10 (i.e., 1 was resting and 10 was extremely difficult) during each condition (Borg, 1982). Rating of perceived exertion (RPE) was collected to determine how participants subjectively assessed each condition. A condition may be perceived as difficult due to other factors beyond metabolic cost, such as abnormal joint loading or feeling less stable.

Expired gases were collected via open-circuit spirometry (Parvo Medics, Sandy, UT, USA). Prior to the gait trials, pulmonary gases were collected for five minutes during quiet standing to determine the metabolic cost of standing. The metabolic cost from the last minute of each five-minute walking trial was averaged, representing a time by which all participants had attained metabolic steady state. The gross rate of metabolic energy expenditure was estimated from the approach developed by Brockway (Brockway, 1987) and is based on the amount of oxygen consumed and carbon dioxide produced. Net metabolic energy expenditure during walking was derived by subtracting the energy expenditure during quiet standing from the gross energy expenditure during the walking trials. A normalized net CoT was calculated by dividing the rate of metabolic energy expenditure by both walking speed (m s\(^{-1}\)) and body mass (kg) (Ralston, 1959).

The results were evaluated statistically using a combination of binomial hypothesis tests, effect sizes, and 95% confidence intervals (CI) (Cohen, 1988). Preferred stance time asymmetry was compared between groups with an unpaired t-test (\(\alpha \leq 0.05\)), effect size, and CI. The effects of group and stance time asymmetry on CoT were analyzed with a two-way (group x asymmetry) analysis of variance. In the event of a significant F value, orthogonal polynomial contrasts were used to determine the mathematical trends describing net CoT versus the amount of asymmetry within each group (Keppel, 1991). The highest-order statistically significant trend (e.g., linear, quadratic, cubic) was then used to estimate the degree of asymmetry corresponding to minimum metabolic cost. A goodness of fit between the experimental values and trend line was determined with an r-squared value. The preferred asymmetry and predicted minimum cost asymmetry within each group were compared with a paired t-test, effect size, and 95% CI. The effect sizes were characterized using expanded ranges as defined by Sawilowsky (Sawilowsky, 2009). The effects of group and stance time asymmetry on RPE were analyzed with a two-way (group x asymmetry) analysis of variance, followed by polynomial contrasts. Statistical analyses were performed using R-Studio version 3.2.2 (R-Studio Inc., Boston, MA, USA).

3. Results

Participants with amputation walked with significantly greater stance time asymmetry (4.34 ± 1.09%, 95% CI: 3.54% - 5.15%) compared with able-bodied participants (0.94 ± 2.44%, 95% CI: -0.86% - 2.75%) during the preferred walking condition, with a very large effect size (\(P = 0.008, d = 1.93\)) (Fig. 2, Table 3). This expected finding indicates that among our participants, people with unilateral transtibial amputation spent more time on the intact limb than the prosthetic limb, and the inter-limb asymmetry is greater in our participants with amputation.

CoT was significantly greater in participants with amputation than able-bodied participants (\(F = 6.224, P = 0.015\)), and there was a significant effect of asymmetry on CoT (\(F = 4.643, P < 0.001\)). There was not a significant group by asymmetry interaction (\(F = 0.357, P = 0.876\)). A quadratic trend best described the relationship between CoT and stance time asymmetry (\(F = 25.560, P < 0.001; R^2_{\text{amputee}} = 0.84, R^2_{\text{control}} = 0.96\)) (Fig. 2). The asymmetry that coincided with the predicted minimum metabolic cost (3.23 ± 2.90%, 95% CI: 1.24% - 5.22%) and the preferred asymmetry (4.34 ± 1.09%) for participants with amputation were not significantly different and had a medium effect size (\(P = 0.365, d = 0.557\)). The asymmetry that coincided with the predicted minimum cost (1.81 ± 2.18%, 95% CI: 0.32% - 3.31%) and the preferred asymmetry (0.94 ± 2.44%) for able-bodied participants was also not significantly different and had a small effect size (\(p = 0.513, P = 0.84\)).

Fig. 1. Representation of Real-time Visual Feedback: Participants had real-time visual feedback of stance time asymmetry with a two-stride moving average line graph, with a dashed target line (0% in this figure) and solid red lines that were +/- 2.5% of the target. The x-axis would shift to keep most recent feedback right of center. The graph was displayed on a monitor at eye-level at the front of the treadmill.
Fig. 2. Group and Individual Net Cost of Transport (CoT): Net CoT for people with (black upward triangles, left and middle figures) and without (red downward triangles, right and middle figures) unilateral lower limb amputation across asymmetry conditions (vertical error bars and shading representing 1 SD), and when walking with preferred patterns (including horizontal error bars representing 1 SD percent asymmetry). Quadratic trend lines of the group averages for people with (black) and without (red) amputation across (a)symmetry conditions. Individual participant trend lines are presented for people with (center pane) and without (right pane) amputation. Asymmetries corresponding to the predicted minimum net CoT are denoted with the downward facing arrows. Preferred and predicted stance time asymmetry was greater (significantly greater for preferred) for people with amputation. Our participants preferred more time on the intact limb, and a similar asymmetry was predicted from the asymmetry that coincided with the minimum CoT.

Table 3

<table>
<thead>
<tr>
<th>Group</th>
<th>Preferred Speed (m/s)</th>
<th>Preferred Asymmetry (%)</th>
<th>Predicted Asymmetry (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amputee</td>
<td>1.13 ± 0.22</td>
<td>4.34 ± 1.09</td>
<td>3.23 ± 2.90</td>
</tr>
<tr>
<td>Able-bodied</td>
<td>1.42 ± 0.12</td>
<td>0.94 ± 2.44</td>
<td>1.81 ± 2.18</td>
</tr>
<tr>
<td>p-value</td>
<td>0.021</td>
<td>0.008</td>
<td>0.323</td>
</tr>
<tr>
<td>d</td>
<td>1.71</td>
<td>1.13</td>
<td>0.556</td>
</tr>
<tr>
<td>95% CI AMP</td>
<td>0.97–1.29</td>
<td>3.54%–5.15%</td>
<td>1.24%–5.22%</td>
</tr>
<tr>
<td>95% CI</td>
<td>1.33–1.51</td>
<td>−0.86%–2.75%</td>
<td>0.32%–3.31%</td>
</tr>
</tbody>
</table>

Preferred walking speed, preferred asymmetry and predicted asymmetry of the people with amputation and able-bodied participants. Values are mean ± 1 SD.

The asymmetries corresponding to predicted minimum cost for participants with amputation (3.23 ± 2.90%) and without amputation (1.81 ± 2.18%) were not significantly different and had a medium effect size (P = 0.323, d = 0.556) (Fig. 2). When connecting the asymmetries predicted by metabolic cost minima to preferred walking asymmetries, predicted and preferred were not significantly different and the range of asymmetries from the 95% confidence intervals overlap within each group (Table 1). The preferred asymmetries were significantly different, and the 95% CI ranges do not overlap between groups; yet, the predicted asymmetries between groups were not significantly different and the 95% CI did overlap (Table 1). The effect of stance time asymmetry on RPE was not significantly different between groups (F = 2.679, P = 0.106), but was significantly different across asymmetry conditions (F = 2.240, P = 0.048) (Fig. 3). As with CoT, a quadratic trend best described the relationship between RPE and stance time asymmetry (F = 7.914, P = 0.006, R²_AMP = 0.97, R²_CONTROL = 0.89) (Fig. 3).

4. Discussion

The purpose of this study was to determine the effects of stance time asymmetry on the metabolic CoT in people with and without unilateral lower limb amputation. We hypothesized that for preferred gait patterns, participants with unilateral transtibial amputation would exhibit greater stance time on the intact side compared with the prosthetic side, while able-bodied participants would exhibit symmetric stance times. We also hypothesized that the metabolic cost versus inter-limb asymmetry would demonstrate a U-shaped curve for both groups, and the CoT would be least at the preferred stride characteristics for both groups. Our hypotheses were generally supported in that: 1) participants with amputation had greater stance time asymmetry (i.e., more time on intact compared with prosthetic limb) compared with able-bodied participants, 2) a quadratic, U-shaped trend best explained the relationship between CoT and stance time asymmetry for both groups, and 3) the asymmetry that coincided with the predicted minimum metabolic CoT was similar to the preferred asymmetry (Fig. 2, Table 3). However, this latter result should be viewed cautiously, as this study may not have been adequately powered to detect such differences due to the small sample size.

Fig. 3. Rating of Perceived Exertion. people with (upward triangles; left and middle figures) and without (downward triangles; right and middle figures) unilateral lower limb amputation across asymmetry conditions (vertical error bars and shading representing 1 SD), and when walking with preferred patterns (including horizontal error bars representing 1 SD percent asymmetry). Quadratic trend lines for people with (black) and without (red) amputation across (a)symmetry conditions. Our participants reported greater difficulty when walking with more asymmetry in either direction (i.e., more time on the intact or prosthetic limb), and more time on the prosthetic limb was consistently rated as more difficult.
As has been previously shown, our participants with unilateral amputation preferred to walk with more time on the intact limb compared with the prosthetic limb (Isakov et al., 2000; Sadeghi et al., 2000; Sanderson and Martin, 1997), and able-bodied participants preferred more time on the dominant limb versus the non-dominant limb (Vanden-Abeele, 1980). However, the degree of asymmetry was less than 1% for the able-bodied participants and may not be related to limb laterality (Sadeghi et al., 2000). The asymmetries that coincided with the predicted minimum metabolic CoT were greater for participants with amputation than without amputation. This difference had a moderate effect size but was not statistically significant, likely due to the modest sample size, and thus should be interpreted cautiously. Stance time asymmetry may be a compensation for structural asymmetry (i.e., residual limb and prosthesis) and influenced by metabolic cost as evident by the asymmetry predicted from minimum metabolic CoT being similar to the preferred asymmetry (Fig. 2).

Minimum CoT has been shown to be associated with symmetric stride timing in able-bodied individuals, with CoT increasing directly with greater stride asymmetry (Ellis et al., 2013). CoT was lowest in our able-bodied participants near symmetric stance timing, similar to previous findings (Ellis et al., 2013), and was lowest for our participants with amputation when walking with asymmetric stance timing (Fig. 2). The predicted CoT minima were not statistically different between groups (Fig. 2), but the predicted minima trended toward each group’s preferred asymmetry and was greater for people with amputation than able-bodied. Two studies (Davis et al., 2004; Mahon et al., 2019) have had people with amputation walk symmetrically while measuring metabolic cost but no studies have had people walk with a large range of inter-limb asymmetry like our study, therefore direct comparisons to the literature cannot be made. Our asymmetry results are similar to the relationship between CoT and walking speed in that people with amputation and able-bodied individuals have greater net CoT when walking slower and faster than preferred speed (Genin et al., 2008; Ralston, 1958), and people with amputation have a greater net CoT than able-bodied (Genin et al., 2008).

We predicted the asymmetries corresponding to minimum CoT using polynomial fits across conditions separated by 5% intervals, which is subject to some uncertainty but demonstrated good fits as indicated by the R² values (≥ 0.84) (Fig. 2). More closely spaced intervals (e.g., 2.5%) would permit more precision in predicting minima, but would require more trials which could cause fatigue, and would be unlikely to lead to a fundamentally different result. Focusing on the measured data, the experimental feedback condition with the lowest CoT for participants with amputation was at the ±5% condition, which is closest to their preferred asymmetry and the asymmetry predicted to yield the minimum CoT. Similarly, the experimental feedback condition with the lowest CoT for able-bodied participants was at the symmetrical (i.e., 0%) condition, which is closest to their preferred asymmetry and the asymmetry predicted to yield the minimum CoT. Based on the experimental data points (Fig. 2), able-bodied participants had the lowest cost at 0% and a deviation to ±5% asymmetry would result in a trivial 0.87% increase in cost. In contrast, participants with amputation had the lowest cost at ±5% asymmetry and a deviation to symmetric walking (0%) would result in a 13.6% increase in cost (Tables S2 and S4). A 13.6% cost associated with restoring symmetric gait may be clinically meaningful, and this finding warrants replication in a broader range of participants.

Perception of greater difficulty and lack of gait stability with more time on the prosthetic limb may explain why more time is spent on the intact limb, and metabolic energy expenditure may not be the primary reason. A previous study (Russell Esposito et al., 2014) found that people with a unilateral transfibial amputation who were still in the military did not have a statistically different metabolic cost compared with able-bodied participants when walking with preferred characteristics. Our participants were not in the military but were a group of active people who had an amputation from non-vascular causes and had a similar CoT at their preferred asymmetry (Fig. 2 left panel). Even in active and relatively fit people with amputation, like the military and our participants, they walk asymmetrically, potentially for reasons aside from metabolic cost. People with amputation are constrained by the limitations of the prostheses and the connection between the residual limb and socket. The residual limb–socket interface can be uncomfortable and people with amputation may spend more time on the intact limb to reduce loading on the residual limb. Results of a previous simulation study (Handford and Srinivasan, 2016) suggest that more time on the prosthetic may be best for lowering metabolic energy expenditure, but due to current prosthesis limitations, this is not preferred by people with amputation. Therefore, other factors (e.g., gait stability and joint loading) that also influence preferred patterns warrant further investigation.

The number of participants in this study was a limitation that we tried to address by collecting data at two different sites. Our sample size was influenced by time and the sparsity of the target population (Lakens, 2021). In our region, it was difficult to find willing participants who met the inclusion criteria. This is not surprising considering most amputations are due to vascular pathology (Ziegler-Graham et al., 2008), and our age range was limited to people between 16 and 50 years old. However, due to the novelty of having people with amputation walk with a wide range of non-preferred gait patterns, the results of this study provide important, initial insights into how people with amputation prioritize metabolic energy expenditure. Moreover, while the P-values reported here should be interpreted cautiously, the effect sizes and confidence intervals provide critical information for planning future studies on gait asymmetry and CoT in people with amputation.

There was an age disparity between groups (Table 1), but the age disparity should not have influenced our conclusions because significant changes with gait usually do not occur until later in life (Judge et al., 1996). While the sample size was limited, the group was homogeneous, representing relatively active participants rated at a K3 or K4 activity level, making it possible to directly compare the effect of amputation on the CoT-asymmetry relationship without confounding factors such as advanced age, comorbidities, or substantial differences in mobility.
Even with the small sample size (Cumming, 2014), minimum metabolic cost asymmetry predictions and preferred asymmetries within groups were not different for participants with and without amputation, respectively. Participants walked at their preferred speeds, which were significantly slower for participants with amputation. Preferred walking speed is the most relevant condition for the comparisons presented here; however, it is currently unknown how asymmetry may interact with walking speed and how that might influence the results. Further research is needed in people with transfemoral amputation and amputation from vascular disease to better understand how CoT relates to gait asymmetry in people with amputation.

A common objective of rehabilitation is to restore inter-limb symmetry after an injury (e.g., joint arthroplasty, amputation); yet, after anatomical structures have been altered, symmetric function may not result in optimal performance. Participants with amputation in our study preferred more time on the intact limb compared with the prosthetic limb, while able-bodied participants preferred walking almost symmetrically. In both cases, preferred asymmetry coincided closely with the lowest CoT, therefore we expect that having our participants with amputation walk symmetrically would increase metabolic cost. However, minimizing metabolic cost is likely not the only factor driving the selection of gait patterns (Jeng et al., 1996). Further investigation is needed regarding how asymmetry affects factors such as joint and residual limb loading, smoothness, and stability to better understand how preferred gait patterns emerge after an injury, and if these factors evolve with more time after amputation, aging, and physical fitness. If asymmetrical patterns naturally emerge in people after the initial learning and adaptation phase of prosthesis use, perhaps some degree of gait asymmetry should be expected, and symmetric walking should not be a goal for rehabilitation and prosthesis in people with lower limb amputation. Given the modest sample size and focus on only one performance criterion, metabolic cost, our results should be interpreted cautiously. Nevertheless, our results raise the possibility that asymmetrical gait patterns may represent a beneficial adaptation when using specific types of prostheses and does not represent a problem that should be corrected.

Declaration of Competing Interest

We did not have any conflicts of interest with this study or submission.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clincbiomech.2022.105632.

References


