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RESEARCH ARTICLE

Energy expenditure does not solely explain step length–width choices during walking

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ABSTRACT

Healthy young adults have a most preferred walking speed, step length and step width that are close to energetically optimal. However, people can choose to walk with a multitude of different step lengths and widths, which can vary in both energy expenditure and preference. Here, we further investigated step length–width preferences and their relationship to energy expenditure. In line with a growing body of research, we hypothesized that people's preferred stepping patterns would not be fully explained by metabolic energy expenditure. To test this hypothesis, we used a two-alternative forced-choice paradigm. Fifteen participants walked on an oversized treadmill. Each trial, participants performed two prescribed stepping patterns and then chose the pattern they preferred. Over time, we adapted the choices such that there was 50% chance of choosing one pattern over another (equally preferred). If people's preferences are based solely on metabolic energy expenditure, then these equally preferred stepping patterns should have equal energy expenditure. In contrast, we found that energy expenditure differed across equally preferred step length–width patterns ($P<0.001$). On average, longer steps with higher energy expenditure were preferred over shorter and wider steps with lower energy expenditure ($P<0.001$). We also asked participants to rank a set of shorter, wider and longer steps from most preferred to least preferred, and from most energy expended to least energy expended. Only 7/15 participants had the same rankings for their preferences and perceived energy expenditure. Our results suggest that energy expenditure is not the only factor influencing a person's conscious gait choices.

KEY WORDS: Metabolic cost, Gait, Locomotion, Motor control, Two-alternative forced-choice, Utility theory

INTRODUCTION

Most healthy individuals do not lunge, shuffle or waddle when they walk. There are some gait patterns that we prefer more than others. A person's most preferred gait speed, step length and step width are close to energetically optimal (Donelan et al., 2001; Ralston, 1958; Zarrugh and Radcliffe, 1978; Zarrugh et al., 1974). Just as each gait pattern has an associated energetic cost, each gait pattern also has a perceived preference. In addition to studying how people control their gait, understanding how people perceive their gait may help identify what factors drive movement decisions.

Utility theory provides a framework to examine people's preferences and decision making (Fishburn, 1970; Von Neumann and Morgenstern, 1944). A utility function represents relative utility, or desirability, over a set of choices. In motor control, such functions are often represented as cost functions or loss functions (negative of utility functions) for optimization problems (Kording and Wolpert, 2004; Todorov and Jordan, 2002). Classic examples of cost functions for upper extremity reaching tasks include minimizing torque (Uno et al., 1989), jerk (Flash and Hogan, 1985) or variation in endpoint error (Todorov and Jordan, 2002). Preferences can be used to probe utility functions via a two-alternative forced-choice paradigm. That is, a person experiences two movement choices and then selects the movement they preferred. For example, you could be given a choice to run or walk 400 m. If you cared most about minimizing cost of transport, you should choose to walk (Summerside et al., 2018). Whereas, if you cared most about minimizing the amount of time it takes, you should choose to run. Applying utility theory to walking can help us describe the choices one makes, and further understand what factors influence a person's movement decisions.

We can examine a person's step length–width choices and test whether their choices are energy optimal because people can voluntarily walk with different, non-preferred step lengths and widths. Based on previous studies, a person's most preferred step length and width coincides with an energetic minimum (Donelan et al., 2001; Kuo et al., 2005; Zarrugh et al., 1974). However, this evidence only considers a single point in their utility function: the point of maximum utility (Fig. 1A). Because energy expenditure can often explain walking behaviors, we chose to investigate whether energy expenditure was equal for equally preferable stepping patterns. Walking with shorter, wider or longer than self-selected steps can affect both energy expenditure (Donelan et al., 2001; Kuo et al., 2005) and a person's preference. At non-preferred step lengths and widths, other factors [e.g. stability (Cajigas et al., 2017; Hunter et al., 2010), joint torques, muscle length (Panizzolo et al. 2018), fear, pain] influencing a person's decisions may also become amplified and shift their preferences away from the energetic optimum.

Here, we used a two-alternative forced-choice paradigm to find sets of step length–width patterns that were perceived as equally preferable, and then measured energy expenditure for each pattern. If energy expenditure dominates a person's decisions, then energy expenditure should be equal across equally preferred step length–width patterns. If energy expenditure is not equal across equally preferred step length–width patterns, there must be other factors affecting a person's choice of step length and width (Fig. 1A). As stated earlier, factors such as stability and comfort are often amplified the further a person deviates from their most preferred step length–width pattern. Therefore, we hypothesized that energy expenditure would be different across equally preferable step length–width patterns.

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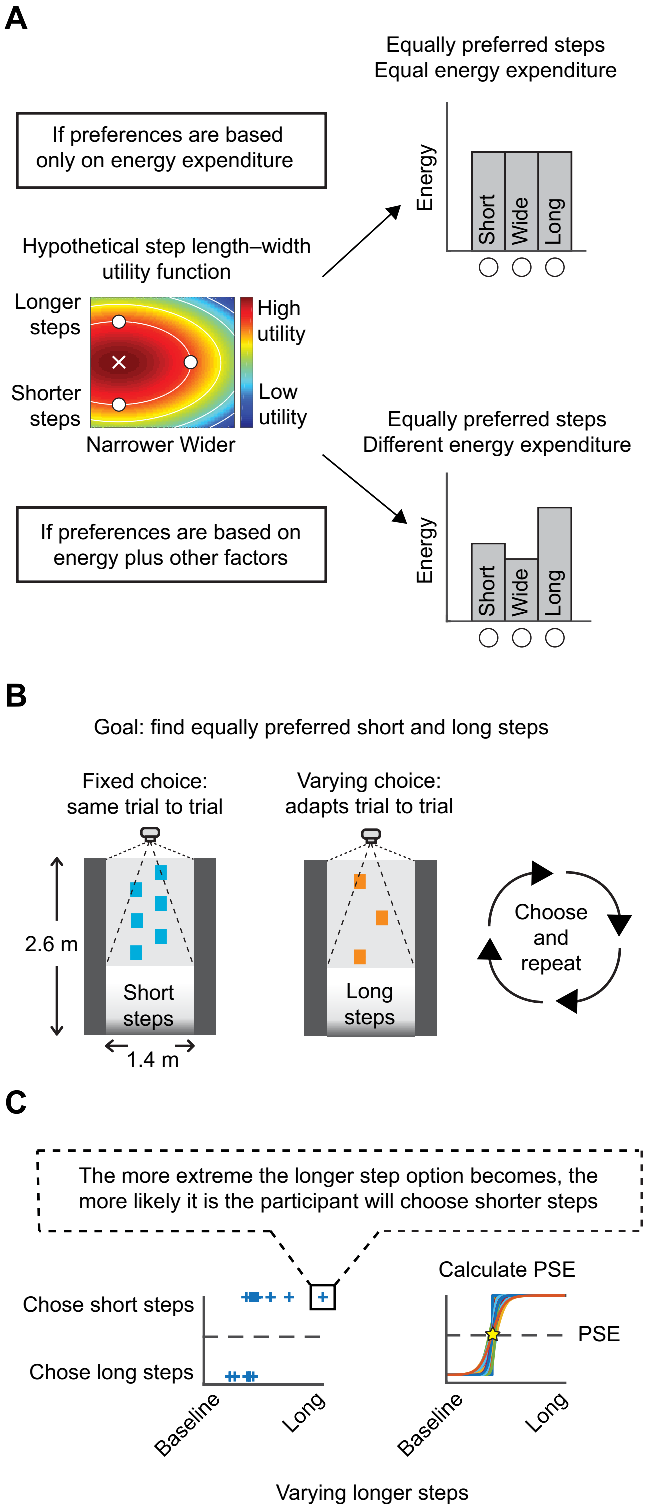

Fig. 1. Experimental methods. (A) Hypothetical step length–width utility function. The utility function was generated based on our hypothesized energy expenditure landscape: J=(step length − most preferred step length)^4 + (step width − most preferred step width)^2 (Donelan et al., 2001; Kuo et al., 2005). The white cross represents a person's most preferred step length–width pattern and has the highest perceived utility. The white contours are indifference curves – curves of equal utility. The white circles are indifference points and lie on one indifference curve. If a person's preferences are based solely on energy expenditure, then energy should be equal along indifference curves. (B) Process to find a pair of equally preferred shorter and longer steps. Participants walked with two stepping patterns: shorter than self-selected steps (fixed every trial) and longer than self-selected steps (varied each trial). The participant chose the stepping pattern they preferred most, and walked with that pattern again. The longer step option is adapted on future trials to make the decision more difficult. (C) Example of choice data: blue crosses represent a participant's decision. For example, when longer steps became more extreme, the participant preferred shorter steps, and vice versa. We bootstrapped the decision data, fitted logistic curves, and calculated the point of subjective equivalence (PSE), where P=0.5.

MATERIALS AND METHODS

Participants

We recruited 15 healthy young adults (7 females, 8 males) between the ages of 18 and 30 years (mean±s.d. 25.3±2.5 years); participants were excluded if they had any injuries or impairments that affected their gait or decision making. This study was approved by the Northwestern University Institutional Review Board (STU00203331) and all participants provided written, informed consent.

Experimental design

Our experiment consisted of two parts: (1) finding a set of equally preferred step length–width patterns and (2) measuring energy expenditure for the equally preferred set. Participants walked on an oversized treadmill (Tuff Tread, Willis, TX, USA) at a constant speed ($1.2\ \mathrm{m\ s^{-1}}$), while a projector (Hitachi, 60 Hz) displayed rectangles as stepping targets to control step length and step width. A black poster board was placed in front of the treadmill so participants could plan at least two steps ahead. We collected kinematic data using 11 active markers and a 12-camera motion capture system (Qualisys). We placed markers on the calcaneus, second metatarsal, fifth metatarsal, lateral malleolus, greater trochanter and T10 spinous process. Markers were labeled in real time and streamed at a rate of 60 Hz to a custom-written Matlab program (version 2013B; MathWorks, Natick, MA, USA) to provide feedback to the experimenter about participants' step length and width. Step length and width were calculated as the maximum distance between fifth metatarsal markers for each step. In the second part of the experiment, we measured the $\dot{V}_{O_2}$ using indirect calorimetry (K4b2, Cosmed, Chicago, IL, USA) to calculate metabolic power.

Finding equally preferred step length–width patterns

Participants began by walking on the treadmill for at least 5 min to acclimate to our experimental setup, and then for an additional 2 min as we measured their baseline (most preferred) step length and width. Next, participants practiced walking on rectangular targets for 5 min to become comfortable walking with different step lengths and widths. We used a two-alternative forced-choice paradigm to find a set of equally preferred shorter, wider and longer than self-selected steps (Fig. 1B). Equally preferred patterns, also known as indifference patterns, are step length–width patterns in which there is a 50% chance of choosing one pattern over the other. Each trial, participants walked with two stepping patterns for 10 s each. Then, participants chose the pattern they preferred most and walked with that pattern again for 10 s. We fixed one of the two choices to be 75% of the participant's baseline step length (short steps) and 100% of their baseline step width. The other choice in each trial was either a wide or long step option that was adapted based on the participant's previous decisions. For the wide step option, we fixed step length to the participant's baseline step length while we varied the step width. For the long step option, we fixed step width to the participant's baseline step width while we varied the step length. We chose short steps to be the fixed pattern because, in our pilot studies, all participants were capable of taking much shorter steps as opposed to much longer steps. Participants completed 30 trials for each preference pair (short–wide and short–long) for a total of 60 trials. For each preference pair, we bootstrapped the participants' decisions (*N*=10,000), fitted logistic curves, and found the point of subjective equivalence (*P*=0.5; Fig. 1C).

The process of finding a short–long preference pair is as follows for a fictional participant. For every trial of the preference pair, one of the participant's options would be shorter steps (75% of their baseline step length). The other, longer step option, could be any step length greater than or equal to 100% of the participant's baseline step length. For example, on their first trial, the participant chooses between 75% and 100% of their baseline step length; they choose 100% of their baseline step length and walk with that step length again. Because the participant preferred the longer steps, the next trial adjusts the longer step option to have an even greater step length. On the second trial, the participant chooses between 75% and 200% of their baseline step length; they choose 75% of their baseline step length because the 200% step length is less preferable. Because the participant preferred the shorter steps, the next trial will adjust the longer step option to have a shorter step length. On the third trial, the participant chooses between 75% and 120% of their baseline step length… As this process continues for 30 trials, the adaptive algorithm adjusts the longer step option to make the participant's decision more difficult. The goal is to find the longer step length at which the participant chooses the shorter step option 50% of the time, and the longer step option 50% of the time. After all trials have been completed, we can estimate the point of subjective equivalence. We fitted a logistic curve to the participant's decisions as a function of the long step lengths to find the step length corresponding to a probability of 50% (Fig. 1C). To find confidence intervals for our estimate, we resampled the 30 trials with replacement over 10,000 iterations (i.e. bootstrapping). For each iteration, we fitted a logistic curve and estimated the point of subjective equivalence. With 10,000 points of subjective equivalence, we took the estimates at the 2.5% and 97.5% percentiles to form our 95% confidence intervals. The same process can be used to find short–wide preference pairs.

We provided participants with the following instructions: 'After you have experienced both choices, please tell us which one you preferred the most (choice one or choice two) and you will walk with it again. If you cannot physically perform one of the choices, you can walk normally during that choice and should choose the other option. We are studying walking, so one foot should always be in contact with the ground. Please do not jump.'.

We pre-randomized the order of the wide and long step options over all trials, as well as the choice order (one or two) within each trial. We wanted participants to step accurately, but also wanted the tasks to feel natural. After each trial, we calculated the step-to-step error by subtracting the actual step length and width from the desired step length and width. If a participant's average step length or width error over all steps for that trial was greater than 3 cm, we provided the participant with a verbal cue to make their steps wider, narrower, shorter or longer depending on the direction of the error, and the participant repeated the trial.

Measuring energy expenditure

After finding equally preferred shorter, wider and longer than baseline steps, we measured $\dot{V}_{O_2}$ (ml s^{-1}), $\dot{V}_{CO_2}$ (ml s^{-1}), normalized by body mass (kg), and calculated metabolic power (W kg^{-1}) for six conditions. We first collected trials for standing, baseline walking with no stepping targets, and then baseline walking with stepping targets. Participants then walked with the equally preferred shorter, wider and longer steps in a random order. All trials were 6 min: the first 3 min were for the participant to reach steady state and the last 3 min were used to calculate the average $\dot{V}_{O_2}$. We then calculated metabolic power using the Brockway equation (Brockway, 1987). We subtracted the metabolic power of the standing trial from the metabolic power for each walking trial to obtain the net metabolic power (W). Respiratory exchange ratios ($\dot{V}_{O_2}/\dot{V}_{CO_2}$) indicated predominately aerobic metabolism for all participants and conditions.

Subjective reports

We were also interested in participants' subjective decision-making process, whether there was a change in stepping preference across time scales (10 s versus 6 min), and how well participants could perceive their energy expenditure. After finding equally preferred shorter, wider and longer steps, participants commented on their decision-making process. After walking with each pattern for 6 min during metabolic data collection, we asked participants to rank the shorter, wider and longer steps from most preferred to least preferred, and from most energetically costly to least energetically costly.

Statistical analysis

We used a linear mixed effects model to test whether metabolic power was different for equally preferred step length–width patterns. Our dependent variable was metabolic power. We treated the type of stepping pattern (shorter, wider and longer) as a fixed effect; participants were treated as random effects (intercept only).

We also performed a descriptive analysis for participants' subjective preference rankings, subjective energy rankings and actual energy expenditure. First, for each participant, we calculated the percentage difference in energy expenditure for equally shorter, wider and longer steps. We used a percentage difference tolerance of 10% to determine whether energy expenditures were 'approximately equal'. The purpose of setting this threshold was to ensure that differences in energy expenditure had a meaningful effect size (Arellano and Kram, 2011; Selinger et al., 2015; Wong et al., 2019). By choosing a conservative (higher) threshold for a meaningful effect size, our results also hold for lower thresholds defined by other studies that found people will adapt their gait patterns for energetic savings as low as 5% (Selinger et al., 2015). Then, we examined whether participants' subjective preference and subjective energy rankings matched. Finally, we analyzed whether the subjective preference and subjective energy rankings aligned with actual energy expenditure. Rankings were considered 'not aligned' only if there was a meaningful difference in energy expenditure across the equally preferred short–wide–long triplet for that participant. That is, if a participant had similar energy expenditures (<10% difference), their rankings would always be considered 'aligned' with actual energy expenditure.

RESULTS

The 15 participants walked on an oversized treadmill while stepping onto projected visual targets to guide their step length and width. For each trial, participants walked with two step length–width patterns, chose the pattern they preferred, and walked with that pattern again. We found a set of equally preferable shorter, wider and longer than self-selected steps and then measured energy expenditure for each step length–width pattern. If a person's decisions were based solely on energy expenditure, then energy expenditure should be equal for equally preferred stepping patterns.

Step length–width preference

Participants were able to perform the stepping task with an average error less than 3 cm, and we could find a set of equally preferred shorter, wider and longer than self-selected steps for all participants. After excluding trials for which the participant could not physically perform the target stepping pattern, we found that stepping error did not have a significant effect on preference (P=0.78, t_{831}=0.28). During the later trials, all participants reported that it was difficult to choose between the two options presented. We found that stepping preference varied across participants (Fig. 2).

Energy expenditure for equally preferred step length–width patterns

To determine whether energy expenditure was the only factor influencing step length–width preference, we tested whether equally preferred shorter, wider and longer than self-selected steps had equal energy expenditure. We found that metabolic power was not equal for equally preferred step length–width patterns (Figs 3 and 4; P<0.001, $F_{2,42}$=16.2). Longer steps had greater metabolic power than the shorter (P<0.001, $F_{1,42}$=30.8) and wider steps (P<0.001, $F_{1,42}$=15.1); there was no significant difference between shorter and wider steps (P=0.10, $F_{1,42}$=2.8). Only one participant (S08) showed similar energy expenditure across all patterns (<10% difference). Energy expenditure could not fully explain participants' step length–width decisions.

Subjective rankings

After collecting metabolic data, we asked participants to rank the shorter, wider and longer than self-selected steps from most preferred to least preferred, and from most energetically costly to least energetically costly. Of the 15 participants, only 7 had subjective energy and preference rankings that matched, 8 had preference rankings that aligned with actual energy expenditure, and 8 had energy rankings that aligned with actual energy expenditure (Table 1). Although participants reported difficulty choosing between stepping patterns towards the end of the 10 s trials (i.e. near equally preferred options), all participants reported that at least one stepping pattern was clearly preferred to the others during the 6 min trials. All but one participant preferred shorter steps the most when walking for 6 min. Two-thirds of participants preferred longer steps over wider steps, often reporting that the wider steps were less comfortable or required increased hip effort. Even on a longer time scale, subjective rankings and objective measurements of energy expenditure did not align with preferences for many participants.

DISCUSSION

In this study, we investigated whether a person's step length–width preferences could be explained exclusively by energy expenditure. First, we found a set of equally preferred shorter, wider and longer than self-selected steps for healthy young adults. Then, we tested

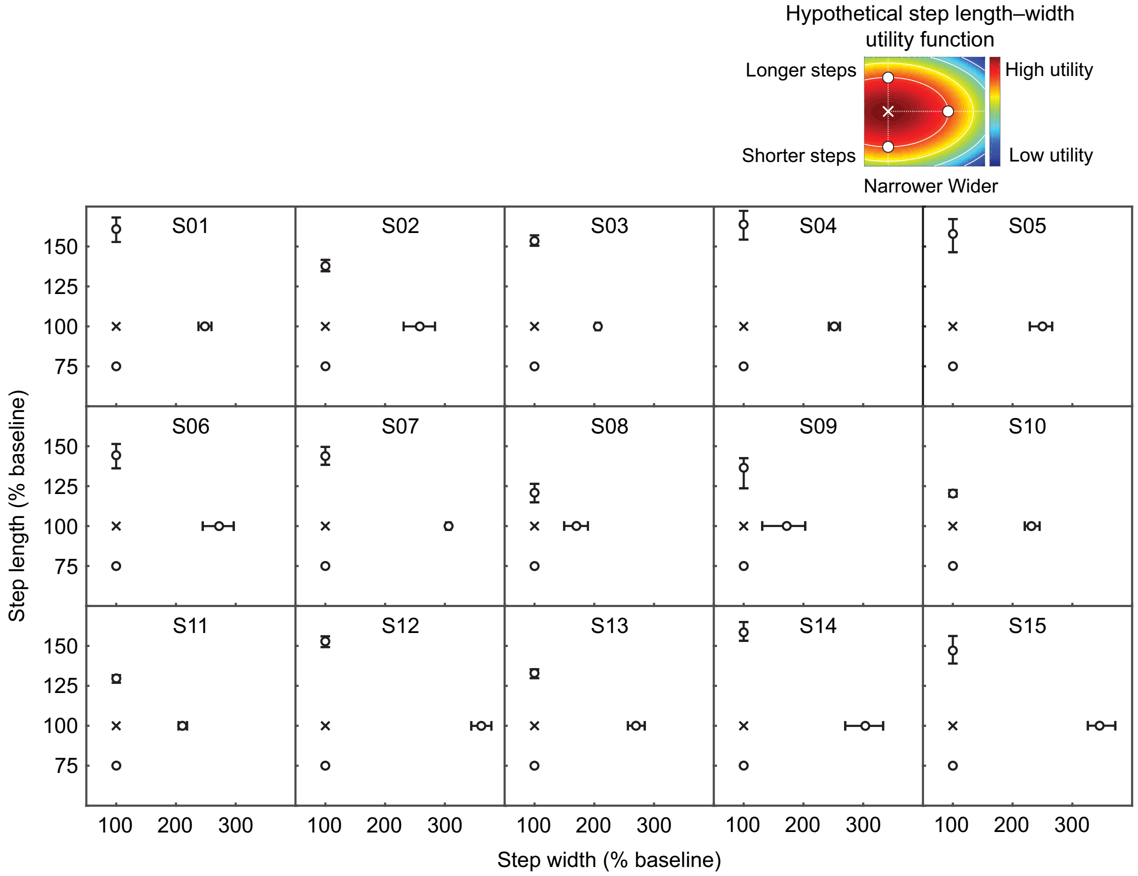

Fig. 2. Equally preferred step length–width patterns. Data are for all 15 participants (S01–15). The black cross denotes a participant's baseline step length and step width; circles denote a set of equally preferred shorter, wider and longer than baseline stepping patterns. Error bars denote 95% confidence intervals.

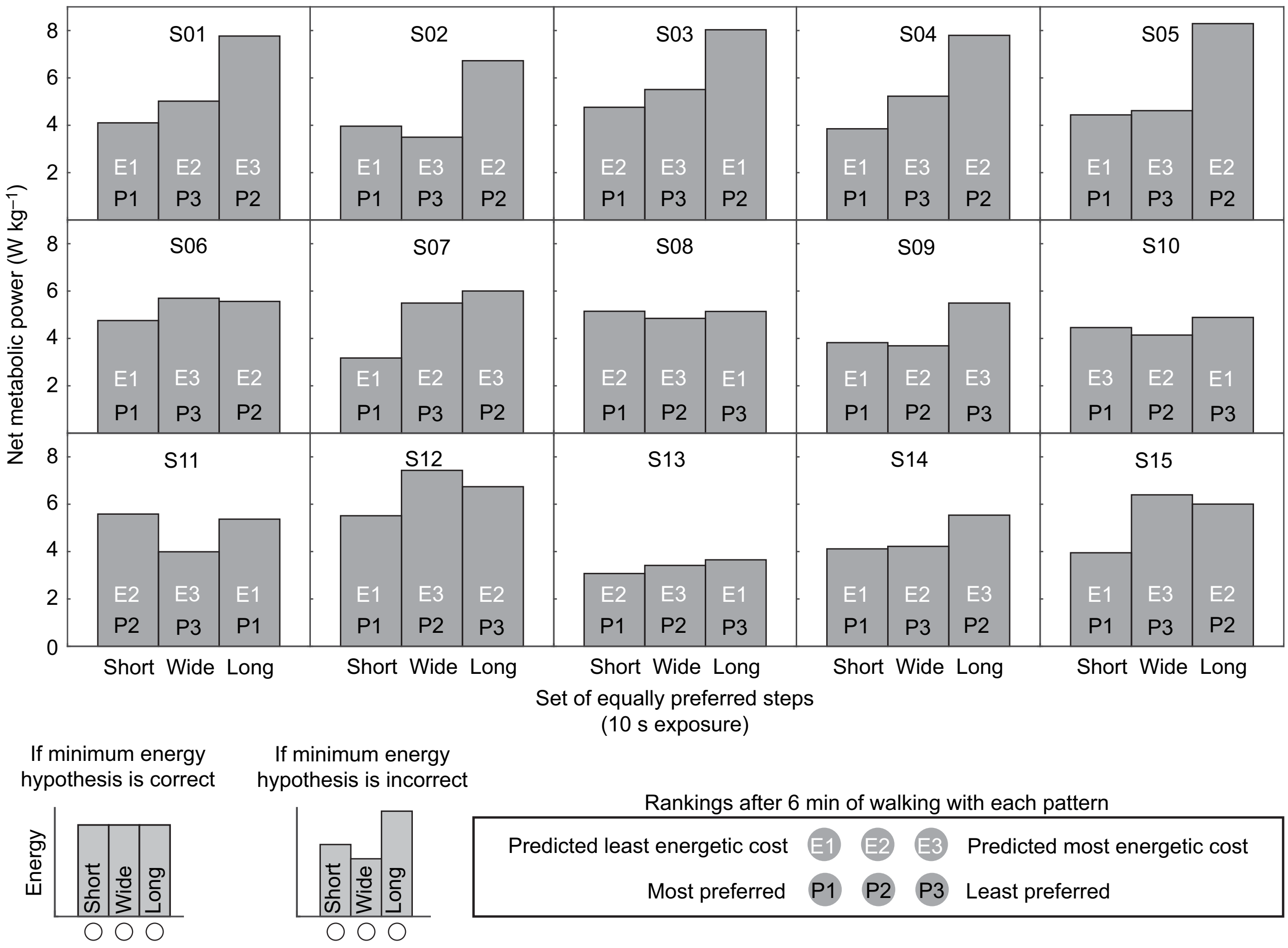

Fig. 3. Net metabolic power for equally preferred step length–width patterns for 10 s trials. Only one participant (S08) had net metabolic power values that had less than a 10% difference across their equally preferred short, wide and long steps. Participants also ranked the set of equally preferred stepping patterns after a longer exposure time (6 min) from (1) most preferred to least preferred and (2) least energetic cost to most energetic cost. Subjective preference and energy rankings after 6 min of walking did not match for 8/15 participants. Furthermore, of the participants with matching preference and energy rankings (7/15), only three had rankings that aligned with their actual metabolic power (S06, S09, S15).

whether energy expenditure was equal for equally preferred stepping patterns. We found that step length–width preferences did not align with energy expenditure, suggesting that additional factors influence a person's stepping preferences. Participants reported that their preferences changed between short (10 s) and long (6 min) time scales. For all but one participant, shorter steps became more preferable for longer bouts of walking. Although preferences changed for longer bouts of walking, many participants' preferences still did not align with their actual or perceived energy expenditure.

We demonstrated how to find equally preferred step length–width patterns using a two-alternative forced-choice paradigm.

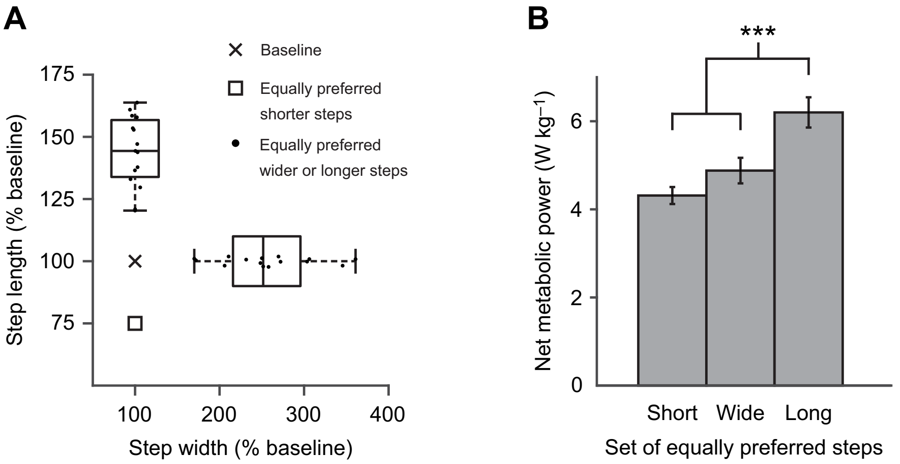

Fig. 4. Grouped results. (A) Box and whisker plots (median, upper and lower quartiles, 1.5× interquartile range) for equally preferred shorter, wider and longer than self-selected steps across all participants (*n*=15). There was a large range of preferences across participants. (B) Average net metabolic power for equally preferred shorter, wider and longer than self-selected steps over all participants. Error bars denote 95% confidence intervals. On average, participants preferred longer steps at an increased energy expenditure over shorter and wider steps (***P<0.001).

Table 1. Preference and energy rankings after 6 min with each pattern

Subject	Was energy expenditure approximately equal?	Did preference/energy rankings match?	Did preference rankings align with energy expenditure?	Did energy rankings align with energy expenditure?
S01	N	N	N	Y
S02	N	Y	N	N
S03	N	N	N	N
S04	N	Y	N	N
S05	N	Y	N	N
S06	N	Y	Y	Y
S07	N	N	Y	Y
S08	Y	N	Y	Y
S09	N	Y	Y	Y
S10	N	N	Y	N
S11	N	Y	N	N
S12	N	N	Y	Y
S13	N	N	Y	N
S14	N	N	N	Y
S15	N	Y	Y	Y
Total Y	1/15	7/15	8/15	8/15

Y, yes; N, no.

Our approach can be extended to other movement parameters that people can voluntarily control (e.g. gait speed) to investigate people's choices as a function of movement. Few studies have explicitly measured movement preferences (Kording et al., 2004; Morel et al., 2017; O'Brien and Ahmed, 2015; Shadmehr et al., 2016), particularly for walking (Summerside et al., 2018). Ultimately, the goal of many rehabilitation interventions is to change a person's movement behavior. If we can understand which factors most influence a person's movement preferences, then targeting those factors may, hopefully, lead to greater changes in behavior. Based on the variability in preferences and personal anecdotes from our participants, we believe that these factors are likely person specific.

We found that energy expenditure alone cannot explain a person's step length–width preferences. While several studies have found that people naturally select the most energetically efficient gait (Holt et al., 1991; Minetti et al., 1995; Ralston, 1958; Umberger and Martin, 2007; Zarrugh and Radcliffe, 1978), there is also a growing body of evidence demonstrating that people do not always adopt the most energetically efficient gait (Gast et al., 2019; Hunter et al., 2010; Simha et al., 2019; Summerside et al., 2018; Wong et al., 2019; Yandell and Zelik, 2016). For example, when walking downhill, people naturally select a gait pattern that increases stability but also increases metabolic cost (Hunter et al., 2010). Our study differs from the studies above because we examined participants' movement perception rather than movement control. In our study, participants made conscious choices based on their perceived movement preference, rather than being asked to perform a task and naturally adopting a gait pattern. This distinction is critical because perception (i.e. preference) and control (action) utilize different neural mechanisms, and by measuring movement perceptions we cannot make conclusions about movement control. Studying movement perception, control and how they interact is critical to further our understanding of walking behavior.

There are several limitations to our study. While we have shown that energy alone cannot explain preferences, we cannot make conclusions about what other factors influence decisions, or the extent of their influence. We limited our decision trials to 10 s because this provided participants with enough time to make consistent decisions but was short enough to make our experiment feasible. Although participants' decisions remained consistent during preference measurements, preferences are likely dynamic and can change over different time scales. Furthermore, we had participants walk with novel gaits. People may need more experience or longer exposure times to be able to make metabolically efficient decisions for unfamiliar gait patterns. However, we found that many participants could not correctly rank energy expenditure after 6 min of exposure, and their stepping preference after 6 min often differed from the actual and perceived energy expenditure. Further experiments are needed to better understand what additional factors contribute to a person's stepping preferences, and how these contributions can change over time.

Previous research suggests that time (Summerside et al., 2018), stability (Hunter et al., 2010) and comfort (Yandell and Zelik, 2016) may also contribute to a person's gait choices. We held time constant across all choices in our study, so while time and energy may both influence a person's choice of gait, even these factors combined cannot fully explain step length–width preferences. Four participants reported that feeling unbalanced during longer steps influenced their decisions. Another four participants reported that wide steps were their least preferred pattern – even though they were more energetically efficient – because it was uncomfortable for their hips. This suggests that the perception of local factors may contribute more to movement utility than does global energy expenditure (Bartlett and Kram, 2008). This was unsurprising, given that many of our participants could not correctly rank energy expenditure for the set of equally preferred short, wide and long steps.

Conclusion

We have demonstrated a novel method to measure equally preferred stepping patterns and found that equally preferable gaits do not translate into energy minimization.

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Competing interests
The authors declare no competing or financial interests.

Author contributions
Conceptualization: S.A.A., K.P.K., K.E.G.; Methodology: S.A.A., K.P.K., K.E.G.; Software: S.A.A.; Validation: S.A.A., K.P.K., K.E.G.; Formal analysis: S.A.A., K.E.G.; Investigation: S.A.A., K.P.K., K.E.G.; Resources: S.A.A., K.P.K., K.E.G.; Data curation: S.A.A.; Writing - original draft: S.A.A., K.P.K., K.E.G.; Writing - review &

editing: S.A.A., K.P.K., K.E.G.; Visualization: S.A.A.; Supervision: K.P.K., K.E.G.; Project administration: S.A.A., K.P.K., K.E.G.; Funding acquisition: S.A.A., K.P.K., K.E.G.

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Data availability

The dataset is available from the Dryad digital repository (Antos et al., 2021): doi:10.5061/dryad.b2rbnzsgk

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