

1 **Title:**

2 Energy expenditure does not explain step length-width choices during walking

3

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21 Abstract

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

40

41 Keywords

42 Energy expenditure, Two-alternative forced-choice, Utility theory, Motor control, Gait,
43 Locomotion

44 Background

45 Most healthy individuals do not lunge, shuffle, or waddle when they walk. There are some gait
46 patterns that we prefer more than others. A person's most preferred gait speed, step length, and
47 step width are close to energetically optimal¹⁻⁴. Just as each gait pattern has an associated
48 energetic cost, each gait pattern also has a perceived preference. Similar to how studying how
49 people control their gait, understanding how people perceive their gait may help identify what
50 factors drive movement decisions.

51
52 Utility theory provides a framework to examine people's preferences and decision making^{5,6}. A
53 utility function can measure preferences over a set of movement parameters. Such functions are
54 often represented as cost functions or loss functions (negative of utility functions) for
55 optimization problems^{7,8}. Classic examples of cost functions for upper extremity reaching tasks
56 include minimizing torque⁹, jerk¹⁰, or variation in endpoint error⁷. Utility functions can also be
57 applied to conscious decision via a two-alternative forced-choice paradigm. That is, a person
58 experiences two movement choices and then selects the movement they preferred. For example,
59 you could be given a choice to run or walk 400 meters. If you cared most about minimizing cost
60 of transport, you should choose to walk¹¹. Whereas if you cared minimizing the amount of time it
61 takes, you should choose to run. Applying utility theory to walking can help us describe the
62 choices one makes, and further understand what factors influence a person's movement
63 decisions.

64
65 We can examine a person's step length-width choices and test whether their choices are energy
66 optimal because people can voluntarily walk with different, non-preferred step lengths and

67 widths. Based on previous studies, a person's most preferred step length and width coincides
68 with an energetic minimum^{2,4,12}. However, this evidence only considers a single point in their
69 utility function: the point of maximum utility (Figure 1A). Because energy expenditure can often
70 explain walking behaviors, we chose to investigate whether energy expenditure was equal for
71 equally preferable stepping patterns. Walking with shorter, wider, or longer than normal steps
72 can affect both energy expenditure^{4,12} and a person's preference. At non-preferred step lengths
73 and widths, other factors (e.g. stability^{13,14}, joint torques, muscle length¹⁵) influencing a person's
74 decisions may also become amplified and shift their preferences away from the energetic
75 optimum.

76
77 Here we used a two-alternative forced choice paradigm to find sets of step length-width patterns
78 that were perceived as equally preferable, and then measured energy expenditure for each
79 pattern. If energy expenditure dominates a person's decisions, then energy expenditure should be
80 equal across equally preferred step length-width patterns. If energy expenditure is not equal
81 across equally preferred step length-width patterns, there must be other factors dominating a
82 person's choice of step length and width (Figure 1A). We hypothesized that energy expenditure
83 would be different across equally preferable step length-width patterns.

85 Methods

86 Participants

87 We recruited fifteen healthy young adults between the ages of 18-30; participants were excluded
88 if they had any injuries or impairments that affected their gait or decision making. This study

89 was approved by the Northwestern Institutional Review Board (STU00203331) and all
90 participants provided written, informed consent.

91

92 Experimental design

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

106

107 Finding equally preferred step length-width patterns

108 Participants began by walking on the treadmill for at least 5 minutes to acclimate to our
109 experimental setup, and then for two additional minutes as we measured their baseline (most
110 preferred) step length and width. Next, participants practiced walking on rectangular targets for
111 five minutes to become comfortable walking with different step lengths and widths. We used a

112 two-alternative forced choice paradigm to find a set of equally preferred shorter, wider, and
113 longer than normal steps (Figure 1B). Equally preferred patterns, also known as indifference
114 patterns, are step length-width patterns in which there is a 50% chance of choosing one pattern
115 over the other. Each trial, participants walked with two stepping patterns for 10 seconds each.
116 Then participants chose the pattern they preferred most and walked with that pattern again for 10
117 seconds. We fixed one of the two choices to be 75% of the participant's baseline step length
118 (short steps) and 100% of their baseline step width. The other choice in each trial was either a
119 wide or long step option that adapted based on the participants' previous decisions. For the wide
120 step option, we fixed step length to the participant's baseline step length while we varied the step
121 width. For the long step option, we fixed step width to the participant's baseline step width while
122 we varied the step length. We chose short steps to be the fixed pattern because, in our pilot
123 studies, all participants were capable of taking much shorter steps as opposed to much longer
124 steps. Participants completed 30 trials for each preference pair (short-wide and short-long) for a
125 total of 60 trials. For each preference pair, we bootstrapped the participants' decisions
126 (N=10,000), fit logistic curves, and found the point of subjective equivalence ($p = 0.5$, Figure
127 1C).

128
129 We provided participants with the following instructions: "After you have experienced both
130 choices, please tell us which one you preferred the most (choice one or choice two) and you will
131 walk with it again. If you cannot physically perform one of the choices, you can walk normally
132 during that choice and should choose the other option. We are studying walking, so one foot
133 should always be in contact with the ground. Please do not jump."

134

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

142

143 Measuring energy expenditure

144 After finding equally preferred shorter, wider, and longer than baseline steps, we measured $\dot{V}O_2$
145 (mL/s), normalized by body weight (kg), and calculated metabolic power (W/kg) for six
146 conditions. We first collected trials for standing, baseline walking with no stepping targets, and
147 then baseline walking with stepping targets. Participants then walked with the equally preferred
148 shorter, wider, and longer steps in a random order. All trials were six minutes: the first three
149 minutes were for the participant to reach steady state and the last three minutes were used to
150 calculate the average $\dot{V}O_2$. We then calculated metabolic power using the Brockway Equation ¹⁶.
151 We subtracted the metabolic power of the standing trial from all walking trials to obtain the net
152 metabolic power (W). Respiratory exchange ratios ($\dot{V}O_2/\dot{V}CO_2$) indicated predominately aerobic
153 metabolism for all subjects and conditions.

154

155 Subjective Reports

156 We were also interested in participants' subjective decision-making process, whether there was a
157 change in stepping preferences across time scales (10 seconds vs. 6 minutes), and how well

158 participants could perceive their energy expenditure. After the finding equally preferred shorter,
159 wider, and longer steps, participants commented on their decision-making process. After walking
160 with each pattern for six minutes during metabolic data collection, we asked participants to rank
161 order the shorter, wider, and longer steps from most preferred to least preferred, and from most
162 energetically costly to least energetically costly.

163

164 Statistical Analysis

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

169

170 We also performed a descriptive analysis for participants' subjective preference rankings,
171 subjective energy rankings, and actual energy expenditure. First, for each participant, we
172 calculated whether the percent difference in energy expenditure for equally shorter, wider, and
173 longer steps. We used a percent difference tolerance of 10% to determine whether energy
174 expenditures were "approximately equal". This tolerance is greater than the reported effects of
175 arm swing during running¹⁷ Then, we examined whether participants' subjective preference and
176 subjective energy rankings matched. Finally, we looked at whether the subjective preference and
177 subjective energy rankings aligned with actual energy expenditure. Rankings were considered
178 "not aligned" only if there was a meaningful difference for that participant. That is, if a
179 participant had similar energy expenditures (<10% difference), their rankings would always be
180 considered "aligned" with actual energy expenditure.

181 Results

182 Fifteen participants (7 Female /8 Male, age 25.3 ± 2.5 years) walked on an oversized treadmill
183 while stepping onto projected visual targets to guide their step length and width. Each trial,
184 participants walked with two step length-width patterns, chose the pattern they preferred, and
185 walked with that pattern again. We found a set of equally preferable shorter, wider, and longer
186 than normal steps and then measured energy expenditure for each step length-width pattern. If a
187 person's decisions were based solely on energy expenditure, then energy expenditure should be
188 equal for equally preferred stepping patterns.

189

190 Step length-width preferences

191 Participants could perform the stepping task with an average error less than 3cm, and we could
192 find a set of equally preferred shorter, wider, and longer than normal steps for all participants.
193 We found that stepping preferences varied across participants (Figure 2).

194

195 Energy expenditure for equally preferred step length-width patterns

196 To determine whether energy expenditure was the only factor influencing step length-width
197 preferences, we tested if equally preferred shorter, wider, and longer than normal steps had equal
198 energy expenditures. We found that metabolic power was not equal for equally preferred step
199 length-width patterns (Figures 3 and 4, $p < 0.001$, $F_{2,42} = 16.2$). Longer steps had greater
200 metabolic power than the shorter ($p < 0.001$, $F_{1,42} = 30.8$) and wider steps ($p < 0.001$, $F_{1,42} =$
201 15.1); there was no significant difference between shorter and wider steps ($p = 0.10$, $F_{1,42} = 2.8$).

202 Only one participant had energy expenditures that were similar across all patterns (<10%
203 difference). Energy expenditure could not fully explain participants' step length-width decisions.

204

205 Subjective rankings

206 After collecting metabolic data, we asked participants to rank the shorter, wider, and longer than
207 normal steps from most preferred to least preferred, and from most energetically costly to least
208 energetically costly. Of the 15 participants, only 7 had subjective energy and preference rankings
209 that matched, 8 had preference rankings that aligned with actual energy expenditure, and 8 had
210 energy rankings that aligned with actual energy expenditure (Table 1). All but one participant
211 preferred shorter steps the most when walking for six minutes. Two thirds of participants
212 preferred longer steps over wider steps, often reporting that the wider steps were less
213 comfortable or required increased hip effort. Even on a longer time scale, subjective rankings
214 and objective measurements of energy expenditure did not align with preferences for many
215 participants.

216

217 Discussion

218 In this study we investigated if a person's step length-width preferences could be explained by
219 energy expenditure. First, we found a set of equally preferred shorter, wider, and longer than
220 normal steps for healthy young adults. Then, we tested whether energy expenditure was equal for
221 equally preferred stepping patterns. We found that step length-width preferences did not align
222 with energy expenditure, suggesting that additional factors influence a person's stepping
223 preferences. We also found that preferences changed between short (10 seconds) and long (6

224 minutes) time scales. For all but one participant, shorter steps became more preferable for longer
225 bouts of walking. Although preferences changed for longer bouts of walking, many participants'
226 preferences still did not align with their actual or perceived energy expenditure.

227
228 We demonstrated how to find equally preferred step length-width patterns using a two-
229 alternative forced choice paradigm. Our approach can be extended to other movement
230 parameters that people can voluntarily control (e.g. gait speed) to investigate people's choices as
231 a function of movement. Few studies have explicitly measured movement preferences¹⁸⁻²¹,
232 particularly for walking¹¹. Ultimately, the goal of many rehabilitation interventions is to change
233 a person's movement behavior. If we can understand which factors most influence a person's
234 movement preferences, then targeting those factors may, hopefully, lead to greater changes in
235 behavior. Based on the variability in preferences and personal anecdotes from our participants,
236 we believe that these factors are likely person specific.

237
238 We found that energy expenditure alone cannot explain a person's step length-width preferences.
239 While several studies have found that people naturally select the most energetically efficient
240 gait^{1,3,22-24}, there is also growing body of evidence demonstrating that people do not always adopt
241 the most energetically efficient gait^{11,13,25-27}. For example, when walking downhill, people
242 naturally select a gait pattern that increases stability but also increases metabolic cost.¹³ Our
243 study differs from the studies above because we examined participants' movement perception
244 rather than movement control. In our study, participants made conscious choices based on their
245 perceived movement preference, rather than being asked to perform a task and naturally adopting
246 gait pattern. This distinction is critical because perception (i.e. preference) and control (action)

247 utilize different neural mechanisms, and by measuring movement perceptions we cannot make
248 conclusions about movement control. Studying movement perception, control, and how they
249 interact is critical to further our understanding of walking behavior.

250
251 There were several limitations to our study. While we have shown that energy alone cannot
252 explain preferences, we cannot make conclusions about what other factors influence decisions, or
253 the extent their influence. We limited our decision trials to 10 seconds because it provided
254 participants enough time to make consistent decisions but was short enough to make our
255 experiment feasible. Although participants' decisions remained consistent during preference
256 measurements, preferences are likely dynamic and can change over different time scales.

257 Furthermore, we had participants walk with novel gaits. People may need more experience or
258 longer exposure times to be able to make metabolically efficient decisions for unfamiliar gait
259 patterns. However, we found that many participants could not correctly rank energy expenditure
260 after six minutes of exposure, and their stepping preferences after six minutes often differed from
261 the actual and perceived energy expenditures.

262
263 Previous work suggests that time¹¹, comfort²⁵, and stability¹³ may also contribute to a person's
264 gait choices. We held time constant across all choices in our study, so while time and energy
265 may both influence a person's choice of gait, even these factors combined cannot fully explain
266 step length-width preferences. Several of our participants reported that wide steps were their
267 least preferred pattern – even though they were more energetically efficient – because it was
268 uncomfortable for their hip abductors. This suggests that the perception of local factors may
269 contribute more to movement utility than global energy expenditure. This was unsurprising,

270 given that many of our participants could not correctly rank energy expenditure for the set of
271 equally preferred short, wide, and long steps.

272

273 Conclusion

274 We demonstrated how to measure equally preferred stepping patterns and then found that equally
275 preferable gaits do not translate into energy minimization.

276

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279 study.

280

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285

286

287

Table 1 – Preference and energy rankings after six minutes with each pattern

Participant	Were energy expenditures approximately equal?	Did preference/energy rankings match?	Did preference rankings align with energy expenditure?	Did energy rankings align with energy expenditure?
1	N	N	N	Y
2	N	Y	N	N
3	N	N	N	N
4	N	Y	N	N
5	N	Y	N	N
6	N	Y	Y	Y
7	N	N	Y	Y
8	Y	N	Y	Y
9	N	Y	Y	Y
10	N	N	Y	N
11	N	Y	N	N
12	N	N	Y	Y
13	N	N	Y	N
14	N	N	N	Y
15	N	Y	Y	Y
Total Y	1/15	7/15	8/15	8/15

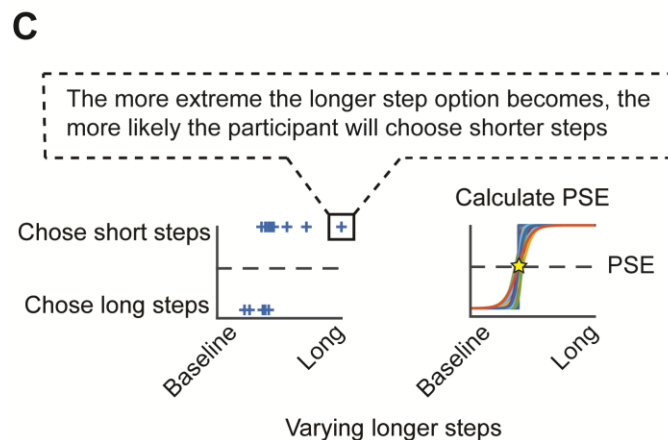
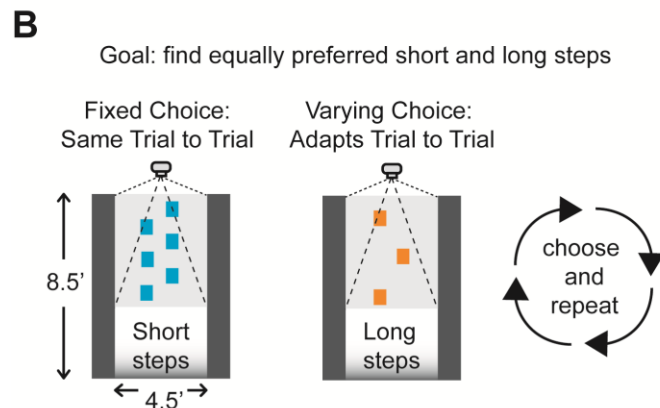
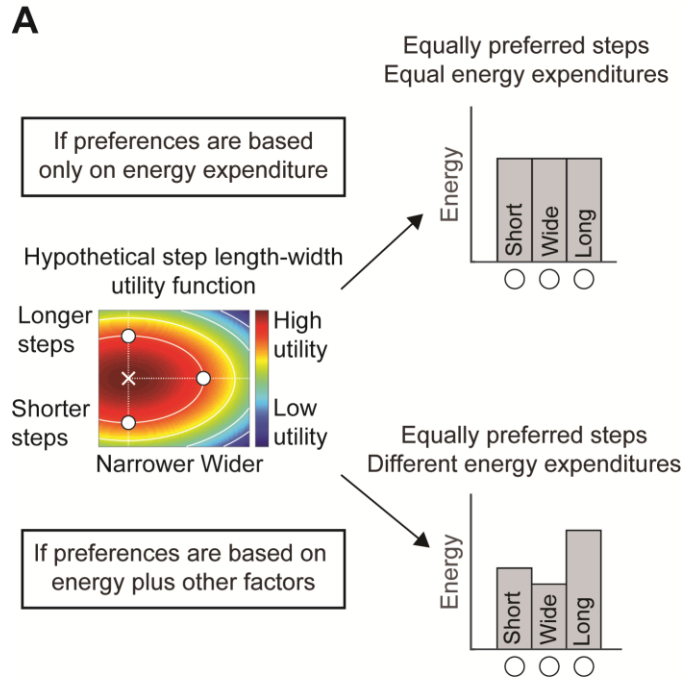


Figure 1- Experimental methods. A) Hypothetical step length-width utility function. The “X” is a person’s most preferred step length-width pattern, and has the highest perceived utility. The

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) Example to find a pair of equally preferred shorter and longer steps. Participants walked with two stepping patterns: shorter than normal steps (fixed every trial), and longer than normal steps (varied each trial). The participant chose the stepping pattern they preferred most, and walked with that pattern again. The longer step option adapts on future trials to make the decision more difficult on subsequent trials. C) Example of choice data: a blue cross represents 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, fit logistic curves, and calculated the point of subjective equivalence (PSE), where $p=0.5$.

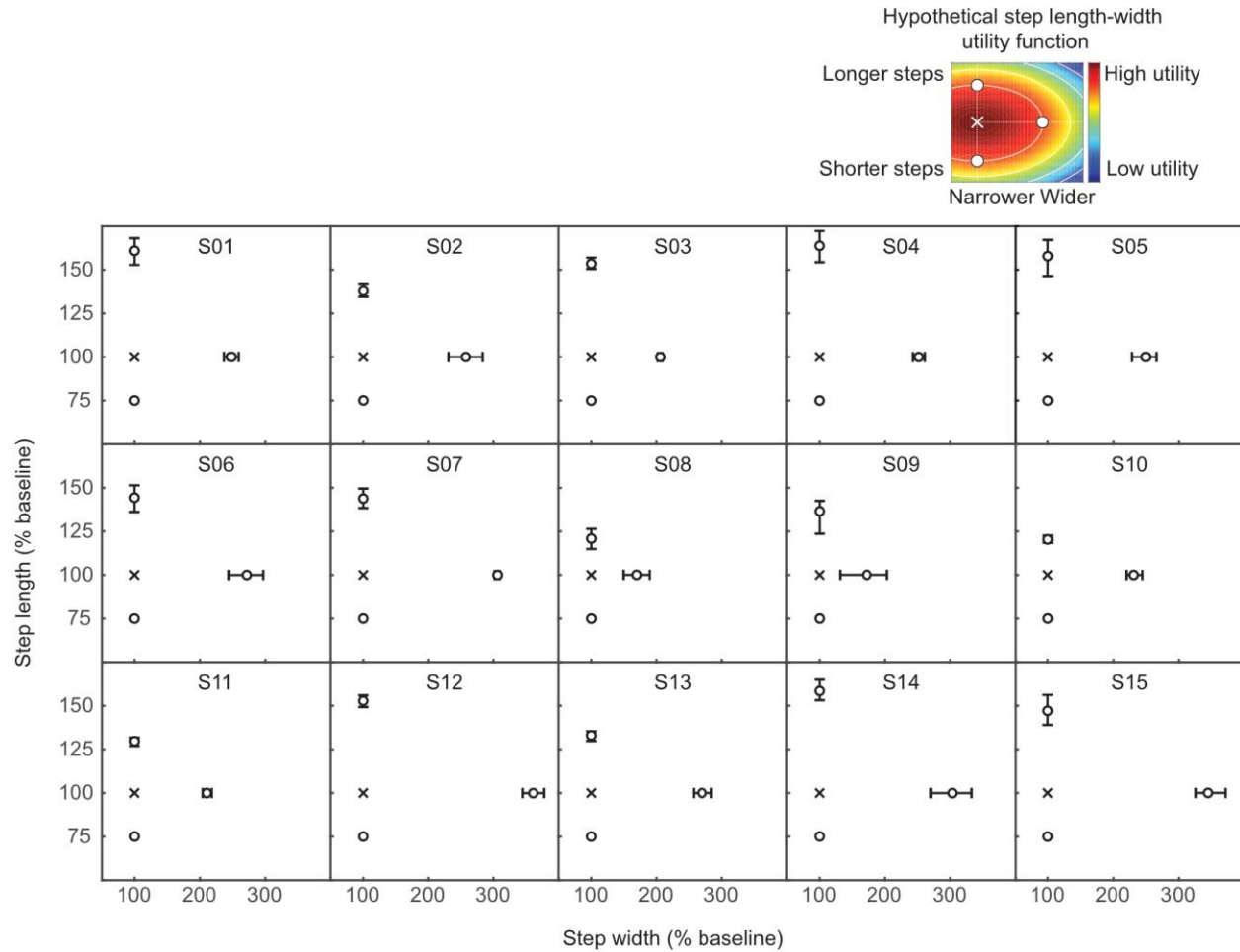


Figure 2 – Equally preferred step length-width patterns. The X denotes a participant's baseline step length and step width; circles denote a set of equally preferred shorter, wider, and longer than baseline stepping patterns. Error bars denote 95% confidence intervals.

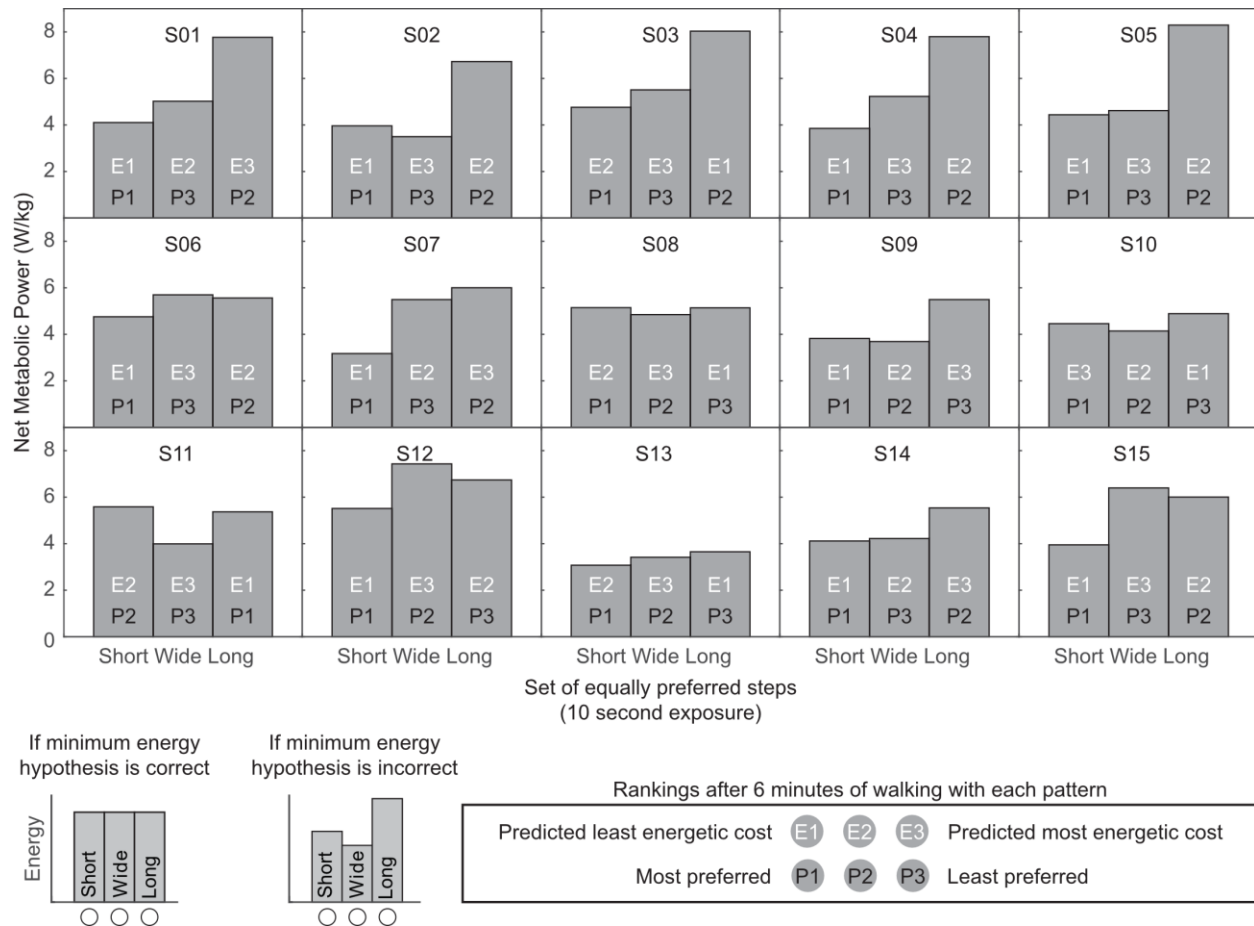


Figure 3 – Net metabolic power for equally preferred step length-width patterns for 10 second trials. Only one participant (S08) had net metabolic powers that had less than a 10% difference across their equally preferred short, wide and long steps. Participants also ranked the set of equally preferred stepping patterns after a longer exposure time (six minutes) from 1) most preferred to least preferred and 2) least energetic cost to most energetic cost. Subjective preference and energy rankings after six minutes 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.

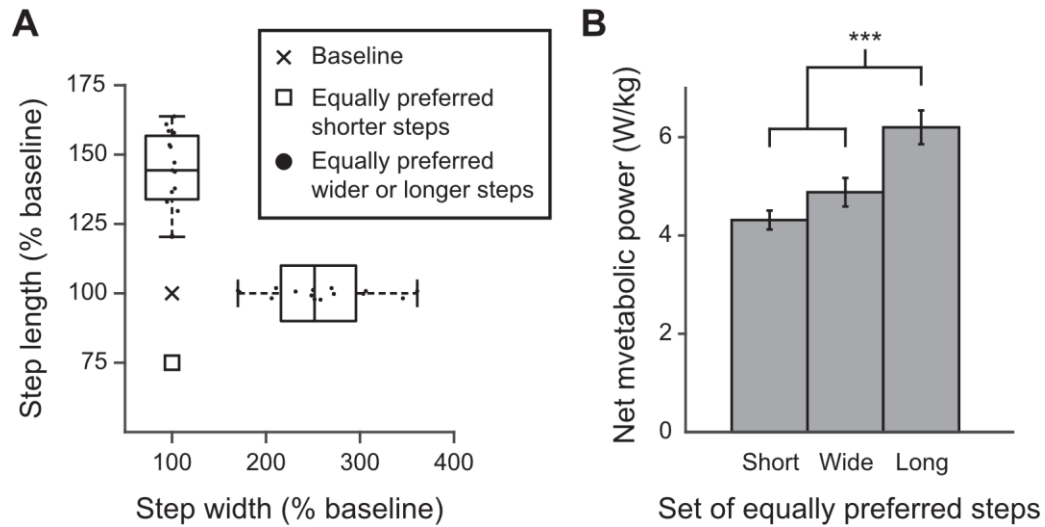


Figure 4 – Grouped results. A) Box and whisker plots for equally preferred shorter, wider, and longer than normal steps across all participants. There was a large range of preferences across participants. B) Average net metabolic power for equally preferred shorter, wider, and longer than normal steps 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 ($p < 0.001$).

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