

1 **ENERGY OPTIMIZATION DURING WALKING CAN BE A PRIMARILY IMPLICIT**  
2 **PROCESS**

3 Running Title: Implicit Energy Optimization During Walking

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11 **Key words:** gait adaptation; motor learning; dual-task paradigm; implicit and explicit cognition;  
12 energy optimization; exoskeletons

13

## 14 **Summary statement**

15 People can adapt to energy optimal walking patterns without being consciously aware they are  
16 doing so. This allows people to discover energetically efficient gaits while preserving attentional  
17 resources for other tasks.

## 18 **Abstract**

19 Gait adaptations, in response to novel environments, devices or changes to the body, can be  
20 driven by the continuous optimization of energy expenditure. However, whether energy  
21 optimization is primarily an implicit process—occurring automatically and with minimal  
22 cognitive attention—or an explicit process—occurring as a result of a conscious, attention-  
23 demanding, strategy—remains unclear. Here, we use a dual-task paradigm to test whether energy  
24 optimization during walking is primarily an implicit or explicit process. To create our primary  
25 energy optimization task, we used lower-limb exoskeletons to shift people’s energetically  
26 optimal step frequency to frequencies lower than normally preferred. Our secondary task,  
27 designed to draw explicit attention from the optimization task, was an auditory tone  
28 discrimination task. We found that adding this secondary task did not disrupt energy  
29 optimization during walking; participants in our dual-task experiment adapted their step  
30 frequency toward the optima by an amount similar to participants in our previous single-task  
31 experiment. We also found that performance on the tone discrimination task did not worsen  
32 when participants were optimizing for energetic cost; accuracy scores and reaction times  
33 remained unchanged when the exoskeleton altered the energy optimal gaits. Survey responses  
34 suggest that dual-task participants were largely unaware of the changes they made to their gait to  
35 optimize energy, whereas single-task participants were more aware of their gait changes yet did  
36 not leverage this explicit awareness to improve gait optimization. Collectively, our results  
37 suggest that energy optimization is primarily an implicit process, allowing attentional resources  
38 to be directed toward other cognitive and motor objectives during walking.

## 39 **Introduction**

40 Humans have a remarkable ability to adapt their gait to changing terrains, tasks, and even  
41 constraints on their body. When we encounter a steep hill, navigate a crowded space, or carry a  
42 heavy load, we change how we walk. Although we often do so with relative ease, the underlying

43 control mechanism is necessarily complex. To coordinate the movements of our limbs, we adjust  
44 the time-varying activation of tens of thousands of motor units across hundreds of muscles. In  
45 turn, by altering these coordination patterns we choose between different gaits, such as walking  
46 or running, and adapt countless gait parameters, such as speed, step frequency, and limb  
47 symmetry. Our research group, and others, have recently demonstrated that gait adaptations can  
48 be driven by continuous optimization of energy expenditure—when searching the expanse of  
49 possible gaits, we often prefer and converge on those that minimize the calories we burn in a  
50 given context (Abram et al. 2019; Finley et al. 2013; Roemmich et al. 2019; Selinger et al. 2015,  
51 2019). However, whether energy optimization is primarily an *implicit process*—occurring  
52 automatically and with minimal cognitive attention—or rather an *explicit process*—occurring as  
53 a result of a conscious, attention-demanding, strategy—remains unclear (Frensch 1998;  
54 Kahneman and Egan 2011; Mazzoni and Krakauer 2006). For example, when we encounter a  
55 hill, we might implicitly slow our speed and reduce our step rate, without even realizing it  
56 (Kawamura et al. 1991; Sun et al. 1996). Or, we might see the steep terrain, judge it looks tiring,  
57 and explicitly decide on a strategy to slow down and alter our angle of approach to reduce  
58 steepness. Both implicit and explicit processes may be used to reduce energy expenditure, either  
59 in isolation or in unison.

60 Dual-task paradigms have been used to assess to what extent a task is implicit or explicit in  
61 nature. Typically, a *primary task* of interest is simultaneously performed with a *secondary task*  
62 known to require explicit processing, such as counting backwards or stating the color of text  
63 incongruent with the word it spells (Beauchet et al. 2005; Bench et al. 1993; Kahneman 1973;  
64 Stroop 1935). The theory underlying this design is that our cognitive attention is a *limited*  
65 *capacity resource*—we can only think and explicitly strategize about so many things at a time  
66 (Magill 2011; Schmidt and Lee 2011; Woollacott and Shumway-Cook 2002). Therefore, if the  
67 secondary task is sufficiently challenging and the primary task is explicit in nature, performance  
68 on one or both tasks will be hindered. Alternatively, if the primary task is implicit in nature,  
69 performance decrements should not occur. For example, dual-task paradigms have been used to  
70 interrogate the role of explicit control in walking. In able-bodied adults, during unperturbed  
71 walking in a predictable environment, walking is primarily an implicit process (Lajoie et al.  
72 1993; Malone and Bastian 2010; Paul et al. 2005; Regnaud et al. 2005). Regardless of the nature  
73 of the secondary explicit task, be it counting backward, verbally repeating sentences, or

74 buttoning a shirt, walking performance characteristics, such as speed, step length, and the  
75 variability of each, are largely unchanged (Beauchet et al. 2003; Ebersbach et al. 1995; Lajoie et  
76 al. 1999; Paul et al. 2005). This is not however the case in all contexts and for all populations.  
77 Dual-task paradigms have been used to demonstrate the enhanced role of explicit control when  
78 navigating obstacles during walking or when stepping to defined visual targets like one might  
79 encounter on a stone path (Mazaheri et al. 2014; Peper et al. 2012; Sparrow et al. 2002;  
80 Weerdesteyn et al. 2003). They have also been used to demonstrate that in children, older adults,  
81 and individuals with cognitive impairments, even unperturbed straight-line walking can involve  
82 significant explicit control, evidenced by slowing gait speeds and increased variability under the  
83 demands of a secondary task (Beauchet et al. 2003; Haggmann-von Arx et al. 2016; Lajoie et al.  
84 1999; Li et al. 2000; Montero-Odasso et al. 2012; Theill et al. 2011). Dual-task paradigms are a  
85 tool to probe the nature of explicit control during movement and have been used extensively in  
86 walking contexts.

87 While dual-task paradigms have been used for decades to probe the nature of various well-  
88 learned motor tasks like walking, they have only recently been applied to the *adaptation* of  
89 motor tasks (Conradsson et al. 2019; Malone and Bastian 2010; Taylor et al. 2014; Taylor and  
90 Thoroughman 2007). Motor adaptation, where a well-learned movement is modified in response  
91 to a new context through trial and error, has long been assumed to be an implicit process (Benson  
92 et al. 2011; Masters et al. 2008; Mazzoni and Krakauer 2006; Willingham 1998). For example, in  
93 canonical force-field paradigms, where forces from a robotic manipulandum alter limb dynamics  
94 during reaching, a common understanding is that adaptation is driven by sensory-prediction  
95 errors that update an internal model (or stored prediction) of the task dynamics. (Shadmehr et al.  
96 2010; Shadmehr and Mussa-Ivaldi 1994). This recalibration was thought to be primarily  
97 automatic, occurring below the level of conscious control. However, recent work has revealed  
98 that explicit processes can play a significant role in adaptation (Conradsson et al. 2019; Malone  
99 and Bastian 2010; Taylor et al. 2014; Taylor and Thoroughman 2007). In one experiment, Taylor  
100 and Thoroughman (2007) had participants perform a tone discrimination task (secondary explicit  
101 task) while adapting to perturbations from a novel force-field during reaching (primary task).  
102 They found participants' ability to correct arm position during a given movement was not  
103 affected, but adaptation from one reach to the next was (Taylor and Thoroughman 2007). This  
104 implies that within-movement feedback control may be primarily implicit, but that movement-to-

105 movement error corrections and the updating of predictive control involves explicit strategy  
106 (Taylor and Thoroughman 2007). In later visuomotor adaptation experiments, Taylor et al.  
107 (2014) confirmed these findings and were able to decouple the contribution and time course of  
108 implicit and explicit processes during adaptation by asking participants to verbalize their aiming  
109 direction (state their explicit strategy) at the onset of each reach. Evidence from walking  
110 paradigms have provided further evidence that motor adaptation can in fact involve explicit  
111 strategy. In split-belt treadmill walking paradigms, where participants adapt to belts travelling at  
112 different speeds under each foot, explicit secondary tasks can disrupt adaptation, particularly in  
113 older adults (Conradsson et al. 2019; Malone and Bastian 2010). Current understanding is that  
114 motor adaptation, whether in discrete upper-arm reaching tasks or continuous lower-limb  
115 walking tasks, can involve both implicit and explicit processes.

116 Here, we use a dual-task paradigm to test whether *energy optimization* during walking is  
117 primarily an implicit or explicit process. We define energy optimization, our primary task of  
118 interest, as the process of adapting one's gait to minimize metabolic energy expenditure. To  
119 study the energy optimization process, we leverage our previous experimental paradigm where  
120 robotic exoskeletons are used to shift people's energetically optimal step frequency to  
121 frequencies lower than normally preferred (Selinger et al. 2015, 2019). We evaluate performance  
122 in this task by adaptation toward the optima, measured by decreases in step frequency. We have  
123 previously shown that people adapt to energy optimal step frequencies when performing only  
124 this task (in a single-task context). Here, we add a secondary tone discrimination task to this  
125 primary energy optimization task. This explicit secondary task requires that participants indicate  
126 whether a current audio tone is of higher or lower frequency than the previous tone. Performance  
127 in this task is evaluated in terms of accuracy (correct responses) and reaction time (time to  
128 respond). One hypothesis is that energy optimization during walking is primarily an implicit  
129 process and performance in both tasks will be maintained. This would be consistent with the  
130 more traditional perspective that the control of well-learned movements, and the motor  
131 adaptation of these movements, are largely automatic and occur below the level of conscious  
132 control (Lajoie et al. 1993; Malone and Bastian 2010; Paul et al. 2005; Regnaud et al. 2005;  
133 Shadmehr et al. 2010). An alternative hypothesis is that energy optimization is primarily an  
134 explicit process and performance on one or both tasks will deteriorate. This would be consistent  
135 with the more recent findings that motor adaptation, in both reaching and walking paradigms,

136 can result from conscious execution of an explicit strategy (Conradsson et al. 2019; Malone and  
137 Bastian 2010; Taylor and Thoroughman 2007).

## 138 **Methods**

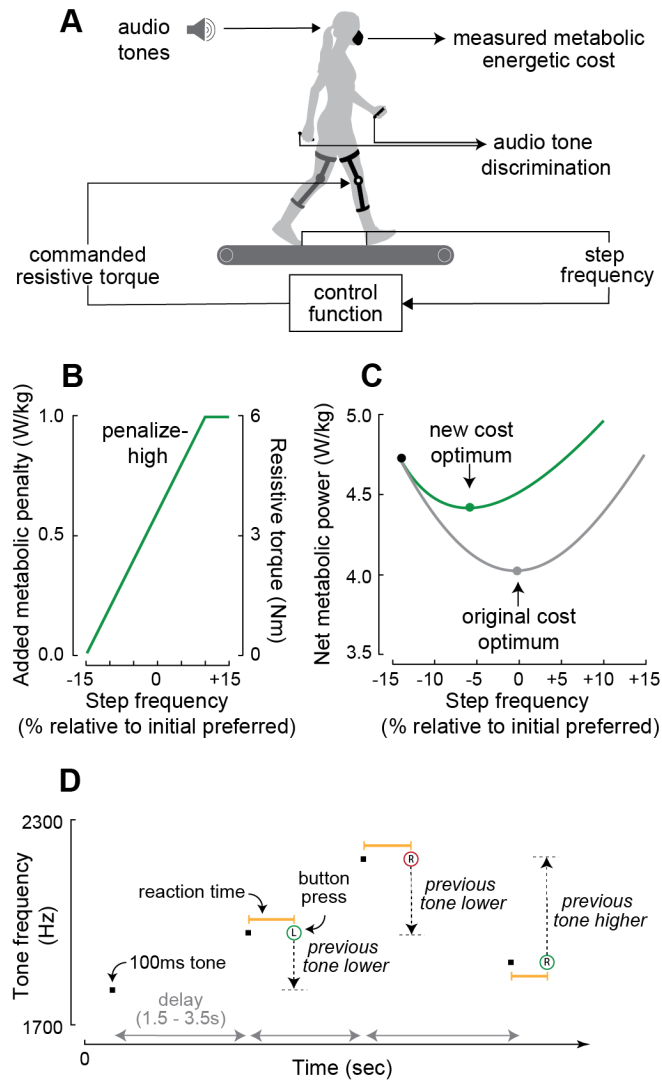
### 139 *Participants*

140 We performed testing on a total of 11 healthy adults (7 female, 4 male) with no known gait,  
141 cardiopulmonary, or cognitive impairments. Simon Fraser University's Office of Research Ethics  
142 approved the protocol, and participants gave their written, informed consent before testing.

### 143 *Primary energy optimization task*

144 To create a task where participants had to adapt their gait in order to minimize energy  
145 expenditure, we leveraged our previous paradigm where robotic exoskeletons are used to shift  
146 people's energetically optimal step frequency. We have previously shown, in a single-task  
147 context, that people adapt toward energy optimal step frequencies (Selinger et al. 2015, 2019).  
148 We used custom software to measure and control the magnitude of the resistive torque applied to  
149 the knees in real-time at 200 Hz (Simulink Real-Time Workshop, MathWorks). In our current  
150 experiment, all participants experienced a 'penalize-high' control function where the resistive  
151 torque, and therefore added energetic penalty, was minimal at low step frequencies and increased  
152 as step frequency increased (Fig. 1B) (Selinger et al. 2015). This function reshapes the *energy*  
153 *landscape*—in this case the relationship between step frequency and energetic cost—creating a  
154 positively sloped energetic gradient at the participants' naturally preferred step frequency, and an  
155 energetic minimum at a lower step frequency (Fig. 1C). To implement this control function, we  
156 made the commanded resistive torque to the exoskeleton proportional to the participants' step  
157 frequency measured from the previous step (Fig. 1A). To measure step frequency at each step,  
158 we calculated the inverse of the time between foot contact events, identified from the fore-aft  
159 translation in ground reaction force centre of pressure from the instrumented treadmill (FIT,  
160 Bertec Inc.). We sampled ground reaction forces at 200 Hz (NI DAQ PC1-6071E, National  
161 Instruments Corporation). When commanding step frequency to the participants, we used a  
162 custom auditory metronome (Simulink Real-Time Workshop, MathWorks). Full details about the  
163 exoskeleton hardware, controller and paradigm can be found in our previous papers (Selinger et

164 al. 2015, 2019). To measure participants' resulting energy expenditure throughout the protocol,  
165 we used indirect calorimetry (VMax Encore Metabolic Cart, VIASYS®).



166

167 **Figure 1:** Dual-task experimental design. **A:** To create the primary energy optimization task, a  
168 control function commands resistive torques to the knee exoskeletons that are proportional to  
169 step frequency, making higher step frequencies energetically costly and lower step frequencies  
170 less costly. To create the secondary tone discrimination task, audio tones are presented, and the  
171 participant must indicate if the frequency of the current tone is higher or lower than the  
172 preceding tone by pressing a button held in the right or left hand, respectively. **B:** Design of the  
173 penalize-high control function. **C:** Schematic energetic cost landscape of the penalize-high  
174 control function (green) and the original cost landscape (grey). **D:** In the secondary task, we used  
175 custom software to output a steady stream of 100 ms audio tones (black squares) with a  
176 frequency between 1700 and 2300 Hz. The time between tones randomly varied from 1.50-3.50s  
177 (horizontal grey arrows). Left-hand and right-hand button presses are represented by circles

178 encompassing a **L** or **R**, respectively. A button press circle colored green indicates a correct  
179 response, while red indicates an incorrect response. The dashed vertical arrows indicate the  
180 difference in frequency between the current tone and the preceding tone. Reaction times, from  
181 onset of tone to button press, are indicated by the horizontal yellow lines.

### 182 *Secondary tone discrimination task*

183 To create a secondary explicit task, we used a *one-back* audio tone discrimination task (Fig 1D).  
184 In this task, participants listened to a stream of auditory tones and continually distinguished if the  
185 present tone was of higher or lower frequency than the tone immediately preceding it (*one-back*)  
186 (Kane et al. 2007). In pilot testing ( $n=2$ ), under natural walking conditions (no exoskeleton), we  
187 also explored a simpler *paired-tone* task, where participants distinguished the frequency between  
188 two tones presented sequentially and can then discard them from memory (Taylor and  
189 Thoroughman 2007), as well as a more complex *two-back* task, where the participants must  
190 continually distinguish if the present tone is of higher or lower frequency than the second from  
191 last tone preceding it (*two-back*) (Kane et al. 2007). Consistent with findings from Taylor and  
192 Thoroughman (2007), we found that the paired-tone task may not be challenging enough to  
193 sufficiently tax the explicit cognitive process. Average scores were consistently above 90%.  
194 Conversely, we found the two-back task was likely too challenging (correct response rates only  
195 slightly higher than 50% chance rate), risking participant disengagement. We settled on the *one-*  
196 *back* task, for which average responses were just above 80% in piloting.

197 To implement the *one-back* tone discrimination task, we output the stream of audio tones to a  
198 speaker using custom software (Matlab 2013b, MathWorks) (Fig. 1D). We made the duration of  
199 each tone 100ms, while the time between tones ranged from 1.50-3.50s, chosen randomly from a  
200 uniform distribution (Taylor and Thoroughman 2007). To output tones of continuously varying  
201 frequencies, we created a three-tone loop. The frequency of the first tone in the three-tone loop  
202 was randomly selected from a uniform distribution ( $2000 \text{ Hz} \pm 150 \text{ Hz}$ ). The second and third  
203 tones in the three-tone loop occurred at a frequency  $\pm 150 \text{ Hz}$  of the first tone, chosen randomly  
204 from a uniform distribution. The participants held a thumb activated push-button in each hand  
205 and we gave them the following instructions:

206 *You will be conducting a one-back audio discrimination task over the duration of each*  
207 *trial. That means you will listen to a stream of tones and compare the tone you just heard*  
208 *to that immediately before it. You are comparing tones in terms of higher or lower sound.*



209           *Once you have determined that the tone you just heard was higher or lower than that*  
210           *immediately preceding, indicate your response via a button press. A left button press*  
211           *means lower and a right button press means higher. Just remember, left equals lower.*

212 We collected button press analog signals, as well as tone frequency, timing and duration through  
213 a data acquisition board (BNC-2110, National Instruments) using a custom software script  
214 (Matlab 2013b, MathWorks). To ensure that participants understood the instructions and could  
215 adequately execute the secondary task, they practiced during a one-minute sample of the tone  
216 discrimination task, prior to our experimental protocol, while standing.

### 217 *Experimental protocol*

218 We replicated the protocol of our previous experiment (Selinger et al. 2019), but with the  
219 addition of the secondary tone discrimination task. This was done to allow us to directly compare  
220 dual-task and single-task results. The protocol consisted of four testing periods: Baseline Period,  
221 Habituation Period, First Experience Period, and Second Experience Period (Fig. 2). Participants  
222 performed the secondary tone discrimination task throughout the entirety of all four periods  
223 while walking on the treadmill at 1.25 m/s. We provided 5-10-minute rest periods between each  
224 period. During the Baseline Period, participants walked for 12 minutes with the exoskeleton  
225 controller turned off (Fig. 2A). We used this period to determine participants' *initial preferred*  
226 *step frequency* under natural conditions, calculated as the average step frequency during the last  
227 150 seconds of the period. During the Habituation Period, to familiarize participants with  
228 walking at a range of step frequencies while completing the tone discrimination task, we  
229 instructed participants to match their steps to both high and low frequency metronome tempos  
230 (+10% and -15% of their initial preferred step frequency, respectively) over the course of 18  
231 minutes (Fig. 2B). The controller remained off during this period. During the First Experience  
232 Period, after six minutes the exoskeleton controller was turned on for the first time and  
233 participants walked for an additional 12 minutes while experiencing the new cost landscape (Fig.  
234 2C). We used this period to determine if participants were *spontaneous initiators* (individuals  
235 that adapt toward the optima prior to any perturbation toward higher or lower cost gaits. See  
236 *Identifying Spontaneous Initiators* below). We calculated the *first experience preferred step*  
237 *frequency* as the average step frequency during the final 150 seconds of this period. During the

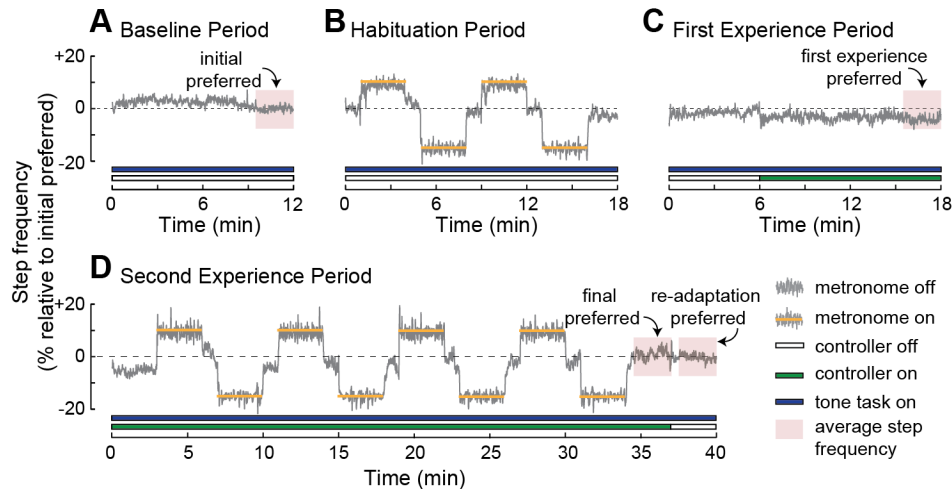
238 Second Experience Period, participants continued to be exposed to the new cost landscape while  
239 being held at higher and lower cost gaits (higher and lower step frequencies) by a metronome  
240 (Fig. 2D). The metronome tempos were again set to -15% and +10% of initial preferred step  
241 frequency to allow participants to experience the extremes of the new cost landscape, while  
242 avoiding step frequencies directly to the optima or initial preferred step frequency  
243 (approximately -5% and 0% of initial preferred step frequency, respectively). We played each  
244 high and low metronome tempo for three minutes, four times each in alternating order, with the  
245 first tempo direction randomized. Following each metronome tempo, the metronome turned off  
246 for one-minute probes of participants' self-selected step frequency. We informed participants  
247 that at times the metronome would be turned on, during which they should match their steps to  
248 the steady-state tempo, and that when the metronome turned off, they no longer had to remain at  
249 that tempo. We did not give participants any further directives about how to walk. During the  
250 final three minutes of this period, the exoskeleton controller turned off, returning participants to  
251 their natural energetic landscape. We calculated the *final preferred step frequency* as the average  
252 step frequency during the 150 seconds of the period just prior to the exoskeleton controller  
253 turning off. To assess participants' re-adaptation when returned to the natural cost landscape, we  
254 calculated the *re-adaptation preferred step frequency* as the average of the final 150s of the  
255 Second Experience Period, after the exoskeleton controller turned off. To determine if  
256 participants could articulate an explicit strategy for this energy optimization process, we  
257 administered a survey following the final collection period. We asked participants to answer five  
258 free form questions (Table 1) in an online platform (Google Forms). We designed these  
259 questions to probe their level of awareness and perception of control during optimization.

260

261 **Table 1:** Survey questionnaire. Participants in the single-task and dual-task experiments  
 262 answered these five questions in an online form following the final collection period.

Question #	Keywords*	Question
1	Changed your gait?	When you were walking naturally (no metronome), did you change how you walked? If so, in what way and why?
2	Made conscious decisions?	When you were walking naturally (no metronome), were you making conscious decisions to change how you walked? If so, how did you make these decisions? And, when did you start making these decisions?
3	Had control over exo?	Did you feel that you had any control over what the exoskeleton was doing? If so, in what way?
4	How exo worked?	How was the exoskeleton making walking easier or harder?
5	Exo walking characteristic?	Did you think any walking characteristic was related to what the exoskeleton was doing? If so, state what characteristic and explain how you thought it related to what the exoskeleton was doing.

263 \* Keywords were not provided to participants or response raters but are included here and used in Figure  
 264 5 to allow for easier interpretation.  
 265



266 **Figure 2:** Experimental protocol. Each participant completed four periods: Baseline Period (A),  
 267 Habituation Period (B), First Experience Period (C), and Second Experience Period (D). We  
 268 provided participants with rest periods of 5–10 minutes between each testing period. Data shown  
 269 are from one representative participant.  
 270

271 Our dual-task protocol described above does deviate from the previous single-task protocol in a  
 272 few ways. First, the original single-task experiment used four different metronome tempos (-  
 273 15%, -10%, +5% and +10%), while here we used only the two extremes (-15% and +10%). We  
 274 did so because in our prior experiment we found different effects of probe direction (i.e. +10%

275 vs. -10%), but not magnitudes (i.e. -10% vs. -15%). Here and in other studies subsequent to the  
276 single-task experiment (Abram et al. 2019; Selinger et al. 2019; Simha et al. 2019, 2020) we  
277 have chosen to simplify our protocol to a single high and low tempo, which are used during both  
278 the Habituation Period and the Second Experience Period. Second, in the original single-task  
279 experiment, the Second Experience Period was 30 minutes in length, while here it is 40 minutes  
280 due to the addition of two extra metronome bouts. This change to a longer Second Experience  
281 Period was made to allow us to further investigate the time course of adaptation. However, we  
282 have subsequently found that adaptation following metronome holds is largely complete after 20  
283 minutes and so do not expect the protocol change to have a significant effect (Abram et al.  
284 2019). Third, in the original single-task experiment, the exoskeleton controller remained on for  
285 six minutes following the last metronome hold, while here in our dual-task experiment it  
286 remained on for only three minutes. We made this protocol change to help reduce the total length  
287 of the period for participants and because in the original single-task experiment we found  
288 adaptation during the final probe to be rapid and complete within tens of seconds (time  
289 constant:  $10.5 \pm 1.8$  seconds). When calculating final preferred step frequency in this dual-task  
290 experiment, we therefore used a 150-second window of time starting 30 seconds after the final  
291 metronome hold, whereas in the original single-task experiment we used a 180-second window  
292 of time starting 180 seconds after the final metronome hold. To ensure our primary outcome  
293 measure was not affected by this difference, we recalculated the final preferred step frequency  
294 from the original single-task experiment data set using the earlier and shorter time window that  
295 we use here.

### 296 *Experimental outcome measures*

297 To assess performance on our primary energy optimization task, we tested if participants adapted  
298 toward the energy optima. To do so, we tested if the average final preferred step  
299 frequency decreased from initial preferred step frequency using a one-sample one-tailed *t*-test  
300 and a significance level of 0.05. To test if energy optimization was affected by the secondary  
301 tone discrimination task, we compared the average final preferred step frequency from our dual-  
302 task experiment to that from the previous single-task experiment, calculated over the same time-  
303 window. We did so using a two-sample two-tailed *t*-test with a significance level of 0.05. To  
304 determine our minimum required participant number we performed an *a priori* power analysis

305 for our primary outcome measure—step frequency adaptation. Based on our two previous  
306 studies (Selinger et al. 2015, 2019) we expected complete energy optimization to result in  
307 participants decreasing their step frequency by approximately 5% and with an across participant  
308 standard deviation of approximately 3.5%, when exposed to the penalize-high controller. To  
309 detect an across-participant average difference in step frequency of at least 5%, given an across-  
310 participant average standard deviation in step frequency of 3.5% and a single-task participant  
311 number of 14, we calculated that we required a minimum of only four dual-task participants to  
312 achieve a power of 0.8. Unfortunately, to detect smaller differences in step frequency a  
313 prohibitive number of participants would be required. For example, detecting 2.5% or 1%  
314 differences would require nearly one-hundred and over ten-thousand participants, respectively.  
315 Therefore, in our experiment we chose to test 11 participants, increasing our expected power to  
316 over 0.9 when detecting complete versus fully abolished step frequency adaptation. However, it  
317 is important to note that we are only able to test if the addition of a secondary explicit task fully  
318 disrupts energy optimization.

319 We also tested if the rate of adaptation was affected by the secondary tone discrimination task.  
320 Because most of our participants were non-spontaneous initiators, who required a metronome  
321 hold at a low-cost gait before initiating adaptation, we compared the rate of adaptation following  
322 the first low holds. Rate of adaptation was calculated by fitting each participant's step frequency  
323 data from one minute prior to the metronome release to the end of the one-minute release period  
324 (minutes 5 – 7 of the Second Experience Period) with a single-term exponential curve. To test  
325 for differences in adaptation rates between the dual-task and single-task participants, we  
326 compared the time constants from the dual-task participants (fit individually and over the same  
327 time window) to the reported average time constant from the single-task participants using a one-  
328 sample two-tailed *t*-test with a significance level of 0.05.

329 To assess participants' re-adaptation when returned to the natural cost landscape, we tested if  
330 participants returned to their initial preferred step frequency and the rate at which they converged  
331 back to their initial preferred step frequency when the exoskeleton was turned off. To determine  
332 whether re-adaptation preferred step frequency values were different from initial preferred step  
333 frequency values (0%), we used a one-sample *t*-test with a significance level of 0.05. To assess  
334 the rate of re-adaptation, we fit each participant's step frequency data from the moment the

335 exoskeleton turned off until the end of the Secondary Experience Period (minutes 37 – 40) with a  
336 single-term exponential curve. To test for differences between the dual-task and single-task  
337 experiments, we compared the time constants from the participants in our dual-task experiment  
338 (fit individually and over the same time window) to the reported average time constant from the  
339 single-task participants using a one-sample two-tailed  $t$ -test with a significance level of 0.05.

340 To assess performance on the secondary tone discrimination task, we calculated response  
341 accuracies and reaction times. We calculated these metrics for the same 150-second time  
342 windows over which we calculated the initial preferred step frequency during the Baseline  
343 Period and the final preferred step frequency during the Second Experience Period. We  
344 calculated response accuracy as the percentage of correct button presses during a given time  
345 window. We calculated reaction time as the time between presentation of a tone and the onset of  
346 a button press, determined by a threshold. To confirm that the secondary tone discrimination task  
347 was challenging and required an explicit strategy, we compared participants' reaction times  
348 during the Baseline Period to an average reaction time from a previous experiment where  
349 participants completed a simple button press task (Stuss et al. 1989). To do so, we used a one-  
350 sample one-tailed  $t$ -test with a significance level of 0.05. To determine if performance on the  
351 secondary tone discrimination task was affected by the primary energy optimization task, we  
352 compared reaction times and accuracies during the Baseline Period (when the exoskeleton was  
353 off and the energy optima was unchanged) to those during the Second Experience Period (when  
354 the exoskeleton was on and the energy optima had shifted to a lower step frequency). We did so  
355 using paired-sample  $t$ -tests with a significance level of 0.05.

356 To assess participants' ability to articulate a strategy for the energy optimization process, we  
357 compared survey responses from participants in our dual-task experiment to those from the  
358 single-task experiment using three independent and blinded raters. All participant responses for a  
359 given question, from both the single-task and dual-task experiments, were randomized. Each of  
360 the three raters then independently rated all responses for one question (starting with question 1)  
361 before moving on to the next. We did not tell raters if the response was from a participant in the  
362 single-task experiment or our dual-task experiment. We asked raters to score each response in  
363 terms of participant *awareness* and *control* using a 0 to 6 scale. We gave raters the following  
364 definitions: '*Awareness* refers to the participant's awareness of the relationship between stride

365 length/step frequency and resistance from the exoskeleton. A rating of 0 means the participant is  
366 unaware of the relationship and a rating of 6 means the participant is fully aware. *Control* refers  
367 to the participant's reporting that they changed their stride length/step frequency to control the  
368 exoskeleton. A rating of 0 means the participant did not consciously change their gait and a  
369 rating of 6 means they did consciously change their gait.' Raters fully understood our energy  
370 optimization paradigm, the exoskeleton control function, and the experimental hypotheses. To  
371 compare awareness and control scores between single-task and dual-task participants, we  
372 averaged scores across raters to obtain a single score for each participant on each question. We  
373 then used a two-sample, one-tailed *t*-test with a significance level of 0.05 to test for differences  
374 for each of the five survey questions.

### 375 *Identifying spontaneous initiators*

376 Some participants spontaneously initiated optimization, during the First Experience Period, prior  
377 to any perturbation to lower or higher cost gaits. To keep our analysis consistent with that from  
378 our previous single-task experiment, we tested for the presence of these spontaneous initiators  
379 during the First Experience Period and excluded them from all further analyses (Selinger et al.  
380 2019). To identify spontaneous initiators, we used the same two criteria as previously reported.  
381 First, the average step frequency at the end of the First Experience Period, first experience  
382 preferred step frequency, must be below three standard deviations in steady-state variability,  
383 determined from the time window used to calculate initial preferred step frequency. Second, the  
384 change in step frequency cannot be an immediate and sustained response to the exoskeleton  
385 turning on. To ensure that this was true, first experience preferred step frequency had to be  
386 significantly lower than the average step frequency measured from seconds 10 – 40 after the  
387 exoskeleton turned on. We tested this using a one-tailed two-sample *t*-test with a significance  
388 level of 0.05. We also tested whether there was a difference in the proportion of participants  
389 identified as spontaneous initiators between our dual-task experiment and the previous single-  
390 task experiment. To do so we used a binomial distribution model with a cumulative distribution  
391 function to calculate the probability of identifying at least as many spontaneous initiators as we  
392 did in our dual-task experiment, given the prior proportion of spontaneous initiators in the single-  
393 task experiment.

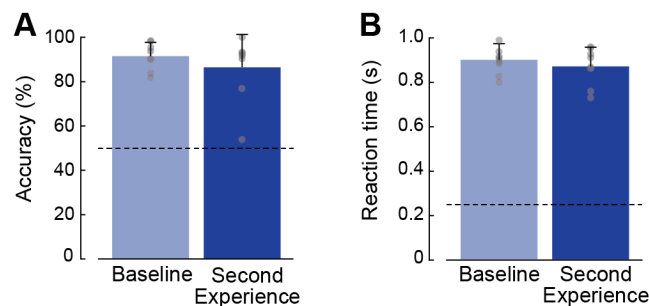
394 **Results**

395 *Identifying spontaneous initiators*

396 We identified three of the eleven participants to be spontaneous initiators. Although this  
397 proportion (27%) is higher than that reported in our previous single-task experiment (6/36, 17%),  
398 it is not significant (we estimate a 28% chance of finding at least this many spontaneous  
399 initiators). On average during the First Experience Period our spontaneous initiators converged  
400 to a step frequency lower than their initial preferred step frequency ( $-3.77\% \pm 1.31\%$ ,  $p=0.038$ ).  
401 In contrast, non-spontaneous initiators remained at a step frequency that was not different from  
402 their initial preferred step frequency during this First Experience Period ( $-1.39\% \pm 2.25\%$ ,  
403  $p=0.122$ ).

404 *Tone discrimination task requires explicit attention*

405 Our secondary tone discrimination task was cognitively challenging, demanding attention and  
406 explicit processing. We found that even during the Baseline Period, when the exoskeleton  
407 controller was off and the energy optima unchanged, participants made response errors. On  
408 average response accuracy was  $91.4\% \pm 6.2\%$ , which is better than chance (50%) but not perfect  
409 (100%) (Fig. 3A). Moreover, we found that participants' reaction times were more than three  
410 times that typically reported for a simple button press in the absence of a tone discrimination task  
411 ( $0.901s \pm 0.073s$  vs.  $0.247 \pm 0.014s$ ,  $p=1.9 \times 10^{-8}$  (Stuss et al. 1989) (Fig. 3B), indicating that the  
412 task demanded significant explicit processing.



413

414 **Figure 3:** Secondary tone discrimination task performance. **A:** Average accuracy score (%)  
415 during the Baseline Period (light blue) and Second Experience Period (dark blue). The dashed  
416 horizontal line represents chance (50% accuracy). **B:** Average reaction time (seconds) during the  
417 Baseline Period (light blue) and Second Experience Period (dark blue). The dashed horizontal  
418 line represents average reaction time (0.247 s) for a simple button press task in the absence of a



419 tone discrimination task (Stuss et al. 1989). Error bars represent one standard deviation. Circles  
420 represent individual data from each participant (n=8).

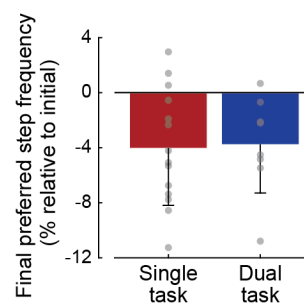
421 *Tone discrimination task performance was unaffected by the energy optimization process*

422 Participants' performance on the secondary tone discrimination task did not worsen when the  
423 primary energy optimization task was presented. We found no differences in accuracy scores  
424 calculated during the Baseline Period, when the exoskeleton was turned off, and the Second  
425 Experience Period, when the exoskeleton was turned on and the energy optima changed ( $91.4\% \pm 6.2\%$  vs.  $86.4\% \pm 14.7\%$ , respectively;  $p=0.221$ ; Fig. 3A). The same was true for reaction time  
426 scores ( $0.901s \pm 0.073s$  vs.  $0.872s \pm 0.086s$ , respectively;  $p=0.397$ ; Fig. 3B).

428 *Tone discrimination task does not disrupt the energy optimization process*

429 Participants optimized their gait to reduce energy expenditure, despite the demands of the  
430 secondary tone discrimination task. We found that participants adapted toward the optima,  
431 displaying a final preferred step frequency that was lower than their initial preferred step  
432 frequency ( $-3.8\% \pm 3.5\%$  vs  $0\%$ ,  $p=0.010$ ; Fig. 4). Moreover, the magnitude of this adaptation  
433 was similar to that for the single-task experiment ( $-4.02 \pm 4.2\%$ ;  $p=0.880$ ). We also found no  
434 differences in rate of adaptation between dual- and single-task participants ( $p=0.149$ ).  
435 Furthermore, participants re-adapted to a step frequency similar to their initial preferred step  
436 frequency ( $0\%$ ) when the exoskeleton was turned off and they were returned to a natural cost  
437 landscape ( $-1.01\% \pm 2.3\%$  vs.  $0\%$ ,  $p=0.262$ ). The rate of re-adaptation was variable between  
438 participants in our dual-task experiment (average time constant:  $21.6s \pm 25.7s$ ), but we found no  
439 differences in rate of re-adaptation between dual- and single-task participants ( $p=0.262$ ).

440

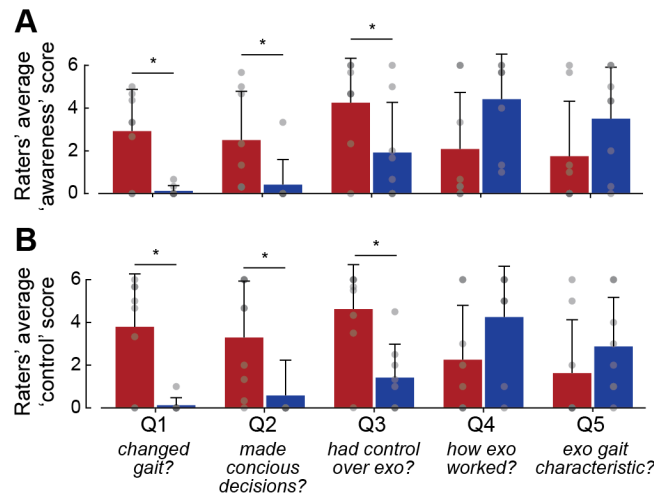


441 **Figure 4:** Average final preferred step frequency for participants in the single-task and dual-task  
442 experiments (red and blue bars, respectively). Error bars represent one standard deviation.

443 Circles represent individual data from each participant in the single-task and dual-task  
444 experiments (n=14 and n=8, respectively).

445 *Tone discrimination task disrupts explicit awareness of the energy optimization process*

446 The presence of a secondary explicit task disrupted participants' awareness of their gait  
447 adaptation and perception of control over the exoskeleton during the primary energy  
448 optimization task. We found that raters' average scores of participant awareness in our dual-task  
449 experiment were lower than those in the single-task experiment for questions 1 – 3 ( $0.1 \pm 0.2$  vs.  
450  $2.9 \pm 2.0$ ;  $p=6.6 \times 10^{-4}$ ,  $0.4 \pm 1.2$  vs.  $2.5 \pm 2.3$ ;  $p=0.019$ ,  $1.9 \pm 2.4$  vs.  $4.3 \pm 2.1$ ;  $p=0.027$ ; Fig.  
451 5A). For these questions, average scores for our dual-task experiment indicated no to low levels  
452 of awareness (scores between 0 and 2), while those for the single-task experiment indicated  
453 moderate levels of awareness (scores between 2.5 and 4.5). We found similar differences for  
454 raters' average scores of participant control for questions 1 – 3 ( $0.1 \pm 0.4$  vs.  $3.8 \pm 2.5$ ;  $p=5.0 \times$   
455  $10^{-4}$ ,  $0.6 \pm 1.6$  vs.  $3.3 \pm 2.6$ ;  $p=0.014$ ,  $1.4 \pm 1.6$  vs.  $4.6 \pm 2.1$ ;  $p=0.002$ ; Fig. 5B). Average scores  
456 for our dual-task experiment indicated no to low levels of control (scores between 0 and 1.5),  
457 while those for the single-task experiment indicated moderate to high levels of control (scores  
458 between 3 and 5). There were no differences in awareness or control scores between dual-task  
459 and single-task participants for questions 4 and 5 (Fig. 5A,B).



460

461 **Figure 5:** Survey results. **A:** Raters' average scores of participant awareness. **B:** Raters' average  
462 scores of participants' perception of control. Red bars represent single-task participants and blue  
463 bars represent dual-task participants. Error bars represent one standard deviation. Circles  
464 represent individual data from each participant in the single-task and dual-task experiments  
465 (n=14 and n=8, respectively).

## 466 **Discussion**

467 Here, we used a dual-task paradigm to test whether energy optimization during walking is  
468 primarily an implicit or explicit process. We found that adding a secondary, cognitively  
469 demanding, explicit task does not disrupt optimization. Participants in our dual-task experiment  
470 showed a level of optimization similar to participants in our previous single-task experiment,  
471 where attentional resources were not shared with another task. We also found that performance  
472 on the secondary tone discrimination task did not worsen when participants were optimizing for  
473 energetic cost; accuracy scores and reaction times remained unchanged when the exoskeleton  
474 altered the energy optimal gaits. Additionally, the survey responses suggest that dual-task  
475 participants were distracted by the secondary task; they were largely unaware of the changes they  
476 made to their gait to optimize energy or the control they had over exoskeleton. Interestingly,  
477 although single-task participants scored higher for both their awareness of gait change and  
478 perception of control, they displayed similar magnitudes and rates of optimization as those in the  
479 dual-task. This suggests that even when explicit awareness exists it may not be used during  
480 energy optimization. Collectively, our results suggest that energy optimization during walking is  
481 primarily an implicit process, requiring minimal conscious attention.

482 The primary limitation of our experiment is our inability to detect partial changes in the level of  
483 optimization between single- and dual-task participants. We found that the magnitude and rate of  
484 step frequency adaptations were similar between dual- and single-task experiments—we found  
485 no statistical differences. However, variability in individual step frequency measures are high,  
486 and although we had the power to detect a full disruption of adaptation (0% vs. 5%), we lacked  
487 the statistical power to detect smaller, partial changes. Our results indicate that in our experiment  
488 energy optimization is primarily an implicit process, but we are unable to determine if minor  
489 explicit contributions existed and were disrupted.

490 Other limitations of our experiment are inherent to dual-task paradigms. First, it is difficult to  
491 know, with certainty, if our participants were sufficiently distracted by the secondary tone  
492 discrimination task. Participants' average accuracy scores (> 85%) were higher than we expected  
493 from piloting. If our secondary task was not challenging enough, it is possible that participants  
494 had the attentional resources necessary to simultaneously carry out the primary energy  
495 optimization task using an explicit process, without displaying performance decrements on either

496 task. However, our survey results suggest this was likely not the case. Dual-task participants  
497 were less aware of their gait changes and their ability to affect the exoskeleton behaviour,  
498 indicating that they were meaningfully distracted by the secondary task. A second potential  
499 interpretation of our findings is that our two tasks draw on distinct cognitive ‘resource pools’.  
500 The *central-resource capacity theory* suggests there is a single source of attentional resources for  
501 which all simultaneous activities compete, for example walking and having a conversation with a  
502 friend (Kahneman 1973; Magill 2011; Schmidt and Lee 2011). Alternatively, *multiple-resource*  
503 *capacity theory* suggests there are several resource pools, each with limited capacity, and each  
504 specific to different tasks or processing stages (Magill 2011; Wickens 2010). It is possible that  
505 our primary energy optimization task and secondary tone discrimination task draw from two  
506 different resource pools, in which case we would not expect performance decrements in either  
507 task. Again, however, dual-task participants’ lower survey scores suggest any cognitive  
508 awareness of the primary optimization task, whether used to optimize or not, draws from the  
509 same pool of resources as our tone discrimination task. Moreover, previous findings, in walking  
510 and reaching adaptation paradigms, suggest that tone discrimination tasks can compete for the  
511 same resources as these motor tasks (Conradsson et al. 2019; Malone and Bastian 2010; Taylor  
512 and Thoroughman 2007). While not possible to conclusively rule out these alternative  
513 interpretations, or a minor contribution from an explicit process, our experimental and survey  
514 results in combination suggest that energy optimization is primarily an implicit process.

515 Our distraction task appears to have prevented participants from strategically altering their gait,  
516 but may not have fully abolished their explicit understanding of the exoskeleton controller. Our  
517 first three survey questions (Q1-3) focused on understanding if participants were strategically  
518 changing how they walked (‘Did you change how you walked? Did you make conscious  
519 decisions? Did you feel you had control?’). Dual-task participants scored very low on these  
520 questions (average scores less than two), and scored significantly lower than those in the single-  
521 task experiment (average scores greater than 2.5). Our last two survey questions (Q4-5) focused  
522 on understanding if participants understood how the exoskeleton controller worked (‘How did  
523 the exoskeleton make walking easier or harder? What gait characteristic affected what the  
524 exoskeleton was doing?’). Here, dual-task participants’ average scores were higher than for  
525 previous questions (average scores greater than three), although we found no significant  
526 difference compared to single-task participants. This suggests that in the presence of the

527 secondary tone discrimination task, participants may still have some explicit understanding of  
528 how the exoskeleton controller works, but may not be able to simultaneously develop an explicit  
529 gait strategy in response (Bronstein et al. 2009). Single-task participants, who were not distracted  
530 and therefore had additional attentional resources, did appear to be able to articulate an explicit  
531 gait strategy. That this explicit strategy did not lead to better performance on the energy  
532 optimization task—single-task and dual-task participants’ level of gait adaptation and rate of  
533 adaptation were similar—further suggests the process of energy optimization itself is primarily  
534 implicit.

535 Our findings are consistent with prior work demonstrating that locomotor adaptations that drive  
536 learning are remarkably invariant and unaffected by explicit processes. One approach to  
537 understanding the role of conscious control in gait is to disrupt participants’ explicit strategy  
538 formation, through a secondary task, and see if this distraction will diminish gait adaptation (as  
539 we have done here). An opposite approach is to give participants an explicit strategy, often  
540 through direct feedback about the errors they need to reduce, and to see if this awareness will  
541 enhance gait adaptation. Malone and Bastian (2010) used both approaches to investigate the role  
542 of conscious, or explicit, gait corrections during adaptation to a split-belt treadmill. They found  
543 that distraction slowed the rate of adaptation while conscious correction sped it up. However,  
544 aftereffects during de-adaptation lasted the longest following distraction, indicating that gait  
545 adaptation was more engrained, or better learned, despite the slower adaptation rate. Roemmich  
546 et al. (2016) extended this work and demonstrated that explicit information about errors during  
547 split-belt walking can lead to rapid and substantial improvements in motor performance without  
548 any true improvements in learning. They showed that when explicit feedback is removed,  
549 participants revert to a level of gait adaptation consistent with that expected based on rates of  
550 adaptation from implicit, in their case proprioceptive, sources. In other words, one can make  
551 conscious changes to their gait, based on explicit feedback about errors, but this is not retained  
552 and does not improve learning in novel contexts. The finding that voluntary corrections are  
553 mechanistically distinct from implicit adaptation and learning is consistent with prior models of  
554 gait response to perturbation proposing two processes—one rapid but approximate based on  
555 prediction and one slow but accurate driven by optimization (O’Connor and Donelan 2012;  
556 Snaterse et al. 2011). That we found no difference in adaptation or de-adaptation between our  
557 dual- and single-task experiments implies that in our paradigm, implicit optimization is

558 dominant. It is possible that in other gait adaptation paradigms, such as the split-belt, explicit  
559 predictions are more evident because the task is more visually or kinematically clear. The more  
560 complex and closed-loop nature of our exoskeleton controller may have prevented rapid explicit  
561 prediction. In future, providing participants with explicit feedback about energy costs could offer  
562 additional insight into the energy optimization process and serve as an added test of its implicit  
563 nature.

564 That energy optimization is an implicit process has both potential benefits and drawbacks for an  
565 adapting human. One clear advantage is that attentional resources can be directed toward other  
566 movement objectives. For example, cognitive attention during walking can be directed toward  
567 accuracy and navigation demands when encountering obstacles. These explicit demands may act  
568 as constraints, while energy optimization proceeds implicitly within these bounds. Another  
569 advantage is that when energy optimal solutions are complex and difficult to explicitly predict,  
570 the implicit system may still be able to navigate them over sufficient timescales. This may well  
571 be the case when people are adapting to injuries that change body mechanics and neural control,  
572 or when adapting to assistive devices that apply novel forces and alter limb dynamics, as we did  
573 here. While a therapist or prosthetist may be unable to coach an individual to an energy optimal  
574 coordination pattern, their nervous system may implicitly learn this over time. However, this  
575 ability may be a double-edged sword. Although gait rehabilitation strategies often focus on  
576 restoring a desired ‘normal’ or ‘healthy’ gait, our implicit optimization process may be at odds  
577 with these kinematic goals if the gaits are no longer energy optimal following injury (Roemmich  
578 et al. 2019). A focus on aligning these otherwise competing objectives may lead to more  
579 effective and enduring rehabilitation. Another possible disadvantage of implicit optimization is  
580 that many have found adaptation that relies solely on an implicit process will be incomplete—  
581 even after many trials, residual errors, or an asymptotic offset, persist (Albert et al. 2020; Bond  
582 and Taylor 2015). Albert et al. (2020) demonstrated that this offset is a signature of implicit  
583 learning and its magnitude relates to one’s sensitivity to past errors. In our experiment, our  
584 inability to precisely identify the energy optimal gait makes it difficult to determine if adaptation  
585 was incomplete. However, in some of our past work, partial adaptation toward energy optimal  
586 gait is clear, further implicating an implicit process during energy optimization (Abram et al.  
587 2019; Simha et al. 2019).

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591 **Competing interests**

592 No financial or competing interests declared.

593 **Author contributions**

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595 M.J.M.; Writing - original draft: M.J.M., J.C.S.; Writing - review & editing: M.J.M., R.L.B., J.,  
596 J.M.D., J.C.S.; Visualization: M.J.M., J.C.S.; Supervision: J.C.S., J.M.D.; Funding acquisition:  
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604

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