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The effects of step width and arm swing on energetic cost and lateral balance during running

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ABSTRACT

In walking, humans prefer a moderate step width that minimizes energetic cost and vary step width from step-to-step to maintain lateral balance. Arm swing also reduces energetic cost and improves lateral balance. In running, humans prefer a narrow step width that may present a challenge for maintaining lateral balance. However, arm swing in running may improve lateral balance and help reduce energetic cost. To understand the roles of step width and arm swing, we hypothesized that net metabolic power would be greater at step widths greater or less than preferred and when running without arm swing. We further hypothesized that step width variability (indicator of lateral balance) would be greater at step widths greater or less than preferred and when running without arm swing. Ten subjects ran (3 m/s) at four target step widths (0%, 15%, 20%, and 25% leg length (LL)) with arm swing, at their preferred step width with arm swing, and at their preferred step width without arm swing. We measured metabolic power, step width, and step width variability. When subjects ran at target step widths less (0% LL) or greater (15%, 20%, and 25% LL) than preferred, both net metabolic power demand (by 3%, 9%, 12%, and 15%) and step width variability (by 7%, 33%, 46%, and 69%) increased. When running without arm swing, both net metabolic power demand (by 8%) and step width variability (by 9%) increased compared to running with arm swing. It appears that humans prefer to run with a narrow step width and swing their arms so as to minimize energetic cost and improve lateral balance.

1. Introduction

Minimizing energetic cost and maintaining lateral balance are important goals in human locomotion. Humans prefer to walk with a moderate step width (~12 cm) that minimizes energetic cost (Donelan et al., 2001). In contrast, humans run with a step width near zero (Cavanagh, 1987), which would seem to challenge lateral balance and incur a greater energetic cost. Humans also prefer to swing their arms while walking and walking without arm swing increases energetic cost (Collins et al., 2009; Ortega et al., 2008). In running, arm swing may assist with lateral balance and possibly reduce energetic cost. In this study, we investigated if humans not only minimize energetic cost but also optimize for lateral balance while running.

There are many examples of energetic optimization in human locomotion. The energetic cost of walking per unit distance (cost of transport) plotted as a function of speed exhibits a U-shaped curve with a minimum close to the preferred walking speed (Martin et al., 1992; Ralston, 1958; van der Walt and Wyndham, 1973; Workman and Armstrong, 1963; Zarrugh et al., 1974). Similarly, if walking or running speed is fixed and stride frequency is varied, energetic cost also exhibits a U-shaped relationship with a minimum near the preferred stride frequency (Cavanagh and Williams, 1982; Hogberg, 1952; Holt et al., 1991; Umberger and Martin, 2007). The walk–run transition occurs near the speed at which running becomes more economical than walking (Mercier et al., 1994). Thus, the idea that humans prefer to walk or run in a manner that minimizes energetic cost is generally accepted.

Minimizing energetic cost, however, is not the only goal during human locomotion. Maintaining lateral balance is a critical prerequisite that involves active control via sensory feedback (Bauby and Kuo, 2000; Donelan et al., 2004). One way humans demonstrate active control of lateral balance in walking is by varying step width from step-to-step (Bauby and Kuo, 2000) but humans prefer an average step width that minimizes energetic cost. Walking with step widths narrower or wider than preferred is energetically more expensive (Donelan et al., 2001). In contrast, humans run with much narrower step widths (Cavanagh, 1987). Placing the foot along the midline of the body aligns the vertical ground reaction force close to the whole body center of mass (Fig. 1; Cavanagh, 1987; McClay and Cavanagh, 1994). Thus, the

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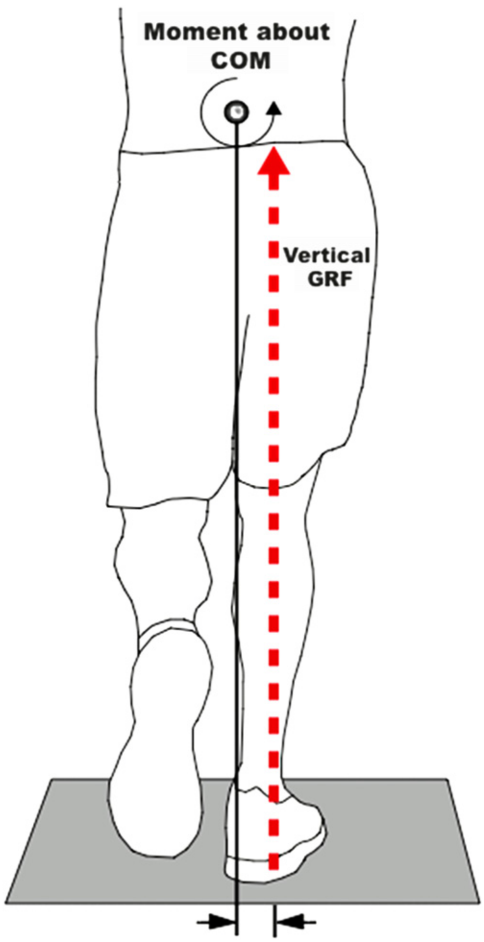

Fig. 1. Rear-view of foot placement relative to the midline of the body during human running. The vertical GRF can reach values of 2–3 times body weight and is the largest component of the resultant GRF during human running. Placing the foot along the midline of body aligns the vertical GRF close to the whole body center of mass (COM), effectively reducing the moment generated about the COM along the *A–P* axis. Modeled after McClay and Cavanagh (1994).

majority of the center of mass motion is directed in the forward and vertical directions and the side-to-side motion is relatively small (Cavanagh, 1987). Reducing the side-to-side motion of the center of mass may be an effective mechanism for balance control during running. As in walking, the preferred step width in running may minimize energetic cost and facilitate balance control.

Mann and colleagues inferred that the primary purpose of arm swing in running is to improve balance with no apparent role in reducing energetic cost (Mann and Herman, 1985; Mann, 1981). Experimental studies of running mechanics reveal that arm swing improves balance by (1) counteracting the angular momentum produced by the swinging legs about the vertical axis and (2) reducing the side-to-side motion of the center of mass (Hamner et al., 2010; Hinrichs, 1987; Hinrichs et al., 1987). Hinrichs et al. (1987) suggested that these mechanical effects might reduce energetic cost and was later supported by Egbuonu et al. (1990) who reported a 4% increase in the energetic cost of running without arm swing. However, a recent report by Pontzer et al. (2009) concluded that running without arm swing did not affect energetic cost or lateral balance. Because these studies produced conflicting results and did not all quantify balance rigorously, we investigated the independent effects of step width and arm swing on the energetic cost and lateral balance of running. Thus, we designed part of our study to test if there is a link between arm swing and lateral balance. Following the lead of previous studies (Bauby and Kuo, 2000; Donelan et al., 2001; Ortega et al., 2008), we measured step width and its variability as indicators of lateral balance.

We addressed two questions: (1) Why do humans run with a step width near zero? and (2) Why do humans prefer to swing their arms during running? We reasoned that a narrow step width and arm swing reflect important control strategies that help minimize energetic cost and improve lateral balance. We hypothesized that the energetic cost of running would be greater (1) at step widths greater or less than preferred and (2) without arm swing. We further hypothesized that step width variability would be greater (3) at step widths greater or less than preferred and (4) without arm swing.

2. Material and methods

Ten subjects volunteered for this study as per the University of Colorado IRB (5 males and 5 females, age $=24.4\pm4.2$ years, mass $=65.4\pm11.7$ kg, and leg length (LL) $=93.1\pm5.6$ cm; mean $\pm$ sd). Subjects wore their own shoes, were experienced with treadmill running, and were healthy and injury-free.

Subjects initially stood on a force measuring treadmill (Kram et al., 1998) while we measured rates of O_2 consumption ($\dot{V}_{O_2}$) and CO_2 production ($\dot{V}_{CO_2}$) for 7 min using expired gas analysis (ParvoMedics TrueMax2400, Salt Lake City, Utah). We placed reflective markers on the left and right heel, dorsum of the 2nd toe, and lateral mid-foot of each shoe. We provided real-time visual feedback (Motion Analysis Corporation, Santa Rosa, CA) of foot placement during running (Fig. 2). We created two virtual lines by positioning reflective markers in the front and back of the treadmill.

Subjects ran at 3 m/s on the force-treadmill for randomized conditions of target step widths (0%, 15%, 20%, and 25% LL) with arm swing, at preferred step width with arm swing (Arms), and at preferred step width without arm swing (No Arms). For the target step width conditions, we instructed subjects to position their heel markers on the respective virtual lines at initial contact. The 0% LL condition was accomplished by projecting a single virtual line corresponding to the middle of the treadmill belt. During the No Arms condition, subjects crossed their arms in front of their chest. Subjects ran for 7 min while we measured $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$. During the last 4 min, we recorded the three-dimensional motions of the feet (100 Hz) and the ground reaction forces (1000 Hz).

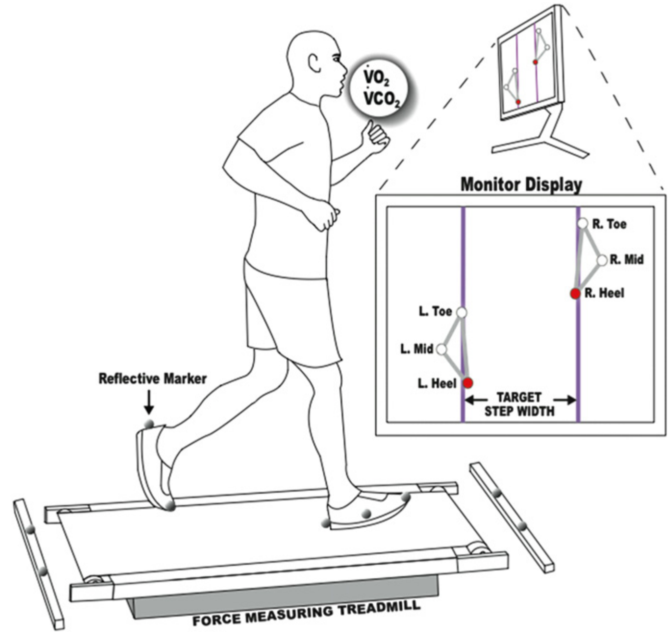

Fig. 2. Real-time visual feedback of foot placement (monitor providing a top–down view) during the target step width conditions. We placed reflective markers on the left and right feet. Adjustable markers defined the left and right virtual lines. The distance between the virtual lines was set as a percentage of leg length (% LL). For a target step width of 0% LL, we projected a single virtual line along the middle of the treadmill. Visual feedback was displayed on a computer monitor (30×47 cm^2) positioned in front of each subject ($\sim$0.5 m).

2.1. Data analysis

For each condition, we calculated the average $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ during the last 3 min and computed the net metabolic power (Brockway, 1987) by subtracting the average value during standing from the average value during running. We filtered the position data of the left and right heel markers using a 9th order, zero-lag low-pass Butterworth filter with a cutoff frequency of 6 Hz. To determine the instant of initial contact for each step, we utilized the vertical ground reaction force (GRF) data, which were filtered using a 4th order, zero-lag low-pass Butterworth filter with a cutoff frequency of 50 Hz. Initial contact was identified with a vertical GRF threshold of 10% body weight. To synchronize the kinematic and kinetic data, we down-sampled the filtered vertical GRF data to 100 Hz. As recommended (Owings and Grabiner, 2003), we calculated the average step width and step frequency during the last 401 consecutive steps for each trial. Step width was defined as the medio-lateral (M-L) distance between the right and left heel markers during successive instants of initial contact. We defined step width variability, an indicator of lateral balance, as the standard deviation about the average step width (Bauby and Kuo, 2000; Donelan et al., 2001; Ortega et al., 2008). We normalized step width and step width variability by dividing each variable by leg length and multiplying by 100.

2.2. Statistical analysis

We used a repeated measures ANOVA with *a priori* comparisons between the control (Arms) and target step width conditions using Dunnett's multiple comparison method and published data table for a one-sided comparison against a control (Dunnett, 1955, 1964). If Mauchly's test of sphericity was violated at the 0.05 level, we adjusted the degrees of freedom (e.g. Huynh–Feldt) to calculate the critical *t*-statistic. To compare between Arms and No Arms, we used paired *t*-tests with $\alpha = 0.05$ (SPSS Inc., Chicago, IL).

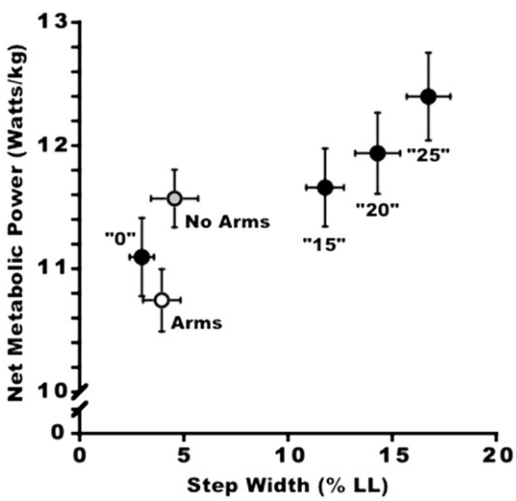

Fig. 3. Net metabolic power ($n=10$; mean ± SEM) versus step width (% LL). Arms denotes running at the preferred step width with arm swing. No Arms denotes running at the preferred step width without arm swing. Quotation marks indicate that subjects were unable to match the target step widths ("% LL"). The data demonstrate that running with step widths other than the preferred step width increases net metabolic power demand. Similarly, running without arm swing increases net metabolic power demand indicating that arm swing is important for reducing energetic cost.

3. Results

3.1. Step width

Subjects consumed energy at a faster rate when running at step widths greater than the preferred step width (Arms) condition. On average, subjects ran with a preferred step width of 3.95% LL (~3.6 cm). Compared to the Arms condition, the net metabolic power demand was 9%, 12%, and 15% greater at target step widths of 15%, 20%, and 25% LL, respectively (all p values < 0.01; Fig. 3). At 0% LL, the net metabolic power demand was 3.3% greater ($0.05 > p > 0.01$) when compared to the preferred step width (Arms) condition. Subjects were unable to match the target step widths provided by the real-time visual feedback system (Table 1). The average step width at the 15%, 20%, and 25% LL conditions was consistently narrower than the target step width.

Step width variability was greater at target step widths greater than preferred (Fig. 4). Compared to the control condition (Arms),

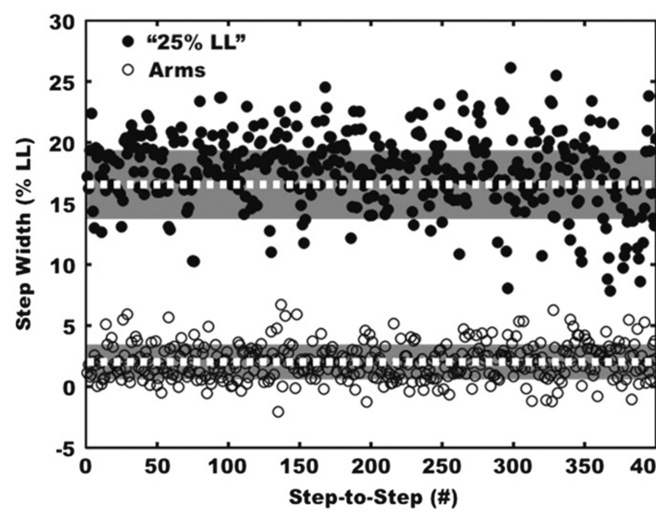

Fig. 4. Step width (% LL) from step-to-step (#) during the preferred (Arms, open circles) and 25% LL condition (filled circles) for a single subject. The broken lines (white) represent the average step width and the shaded regions (gray) represent the (±) standard deviation about the average step width. Note the larger standard deviation in the 25% LL condition as compared to the preferred condition. For clarity, the other target step width conditions are not shown.

Table 1
Data for subjects running (3 m/s) at various conditions of target step widths, Arms, and No Arms (mean ± SEM).

	Target step width (% LL)				Arm swing	
	0	15	20	25	Arms	No Arms
Net metabolic power (W/kg)	11.09 ± 0.32*	11.66 ± 0.32**	11.94 ± 0.33**	12.40 ± 0.36**	10.74 ± 0.25	11.57 ± 0.23*
Step width (% LL)	2.97 ± 0.58	11.78 ± 0.91•	14.31 ± 1.08•	16.74 ± 1.05•	3.95 ± 0.90	4.56 ± 1.13
Step width variability (% LL)	2.32 ± 0.16	2.90 ± 0.25••	3.17 ± 0.23••	3.66 ± 0.32••	2.17 ± 0.16	2.37 ± 0.17†
Step frequency (Hz)	2.80 ± 0.05	2.85 ± 0.07	2.86 ± 0.08	2.83 ± 0.09	2.85 ± 0.06	2.92 ± 0.06*

Target step width effect
Net metabolic power: *significant difference ($p < 0.05$) between 0% LL and Arms.
**significant difference ($p < 0.01$) between 15%, 20%, and 25% LL and Arms.
Step width: • significant difference (with conservative Huynh–Feldt adjustment, $p < 0.01$) between target step width and Arms conditions.
Step width variability: •• significant difference (with conservative Huynh–Feldt adjustment, $p < 0.01$) between target step width and Arms conditions.
Step frequency: no main effect detected (with conservative Huynh–Feldt adjustment, $p = 0.55$) across the various target step width conditions.
Arm swing effect
Arms vs. No Arms: † significant difference ($p < 0.05$) between the Arms and No Arms condition.

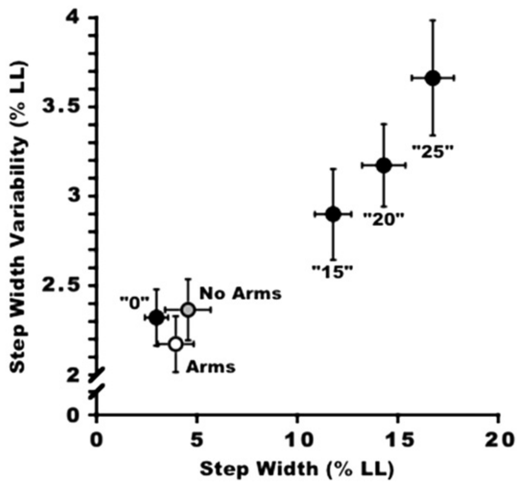

Fig. 5. Step width variability ($n=10$; mean ± SEM) versus step width (% LL). The data demonstrate that running with step width other than the preferred step width increases step width variability. Similarly, running without arm swing increases step width variability indicating that arm swing improves lateral balance.

step width variability was greater by 33%, 46%, and 69% at target step widths of 15%, 20%, and 25% LL, respectively (all p values < 0.01; Fig. 5). Step width variability at the 0% LL condition was 7% greater than the Arms condition but the difference was not statistically significant. Subjects used similar step frequencies across the target step width conditions (Table 1).

3.2. Arm swing

When running without arm swing, the net metabolic power demand increased by 8% compared to running with arm swing ($p < 0.0001$; Fig. 3). Running without arm swing did not change the average step width ($p=0.084$) but increased step width variability by 9% ($p=0.023$; Fig. 5). Finally, step frequency was 2.5% greater when running without arm swing ($p=0.01$).

4. Discussion

In support of our first and second hypotheses, net metabolic power and step width variability increased when running with step widths other than preferred. In support of our third and fourth hypotheses, net metabolic power and step width variability increased when running without arm swing. These results support our general idea that a narrow step width and arm swing minimize energetic cost and improve lateral balance during running.

Our data demonstrate that running with step widths greater or less than preferred is energetically more expensive. Subjects preferred a step width of only 3.95% LL (3.61 ± 2.56 cm; mean ± sd) while running with arm swing. Our findings demonstrate a fundamental difference between walking and running, i.e. humans prefer to walk with a moderate step width (8–13% LL; Donelan et al., 2001; Ortega et al., 2008) but prefer to run with a step width near zero.

Why do humans prefer to run with a step width near zero? McClay and Cavanagh (1994) speculated that a narrow step width has two important biomechanical functions in human running. First, narrow step widths minimize the M-L ground reaction forces generated from step-to-step since foot placement is along the midline of the body. The target step widths (15%, 20%, and 25% LL) in this study reflect a "wide-based" gait and would involve greater kinetic energy fluctuations in the M-L direction. Running with relatively wide steps is mechanically and energetically wasteful since the goal of running is to move the body in the forward direction. Second, narrow step widths minimize the moment generated about the *A–P* axis, thus reducing the muscular effort required to counteract this moment (Cavanagh, 1987).

Human walking experiments demonstrate that M-L foot placement is an important mechanism for maintaining lateral balance. A small portion (~3–6%) of the net energetic cost of walking is dedicated toward active control of lateral balance (Donelan et al., 2001; Ortega et al., 2008). Further, when an external device reduces the need for the active control of lateral balance, humans walk with much narrower step widths and reduced step width variability (Donelan et al., 2004). Thus, humans maintain lateral balance by walking with a moderate step width but this step width incurs a slight but significant energetic cost. In contrast, humans prefer to run with a step width near zero with minimal step width variability, which suggests there is little need for active control of lateral balance. If this is the case, then an important question remains: is there an energetic cost to maintaining lateral balance in human running? We hypothesize that there is not a significant energetic cost to maintaining lateral balance.

However, M-L foot placement is not the only mechanism by which humans maintain lateral balance. Running without arm swing decreases lateral balance as indicated by a 9% increase in step width variability when compared to running with arm swing. Furthermore, running without arm swing increases the net energetic cost by 8%. Overall, we conclude that arm swing plays an integral part in human running by reducing energetic cost and improving lateral balance. Our findings are in disagreement with those of Pontzer et al. (2009), who concluded that running without arm swing does not significantly affect energetic cost or lateral balance. Some limitations of their study may explain the different outcomes. First, their metabolic measurements were obtained for a relatively small sample size (six subjects) resulting in low statistical power. In our study, 10 out of 10 subjects exhibited a greater net energetic cost when running without arm swing. Second, Pontzer et al. (2009) computed step width and step width variability measures from only 8 consecutive steps, which falls short of the number of steps (~400) needed for an accurate measure of step width and step width variability (Owings and Grabiner, 2003).

More generally, Pontzer et al. (2009) proposed a passive arm swing hypothesis, suggesting that the forward and backward motion of the upper arms is derived from the mechanical energy generated by the swinging legs. If the upper body is modeled as a "passive mass-damped system", the primary role of the upper arms is to act as a supplementary mass that effectively damps torso and head rotation. The authors presented three lines of evidence in support of this hypothesis. While running with normal arm swing, (1) there was co-activation of the anterior and posterior portions of the deltoid muscle and (2) torso and shoulder rotations appeared to induce arm swing motion. While running without arm swing, (3) there were no significant changes in energetic cost or step width variability. While our data refute the third point, arm swing during running may be partly passive and deserves further investigation.

A limitation of our study was that we were unable to perform a trial with visual feedback at the preferred step width. It is possible that the act of matching foot placement to a given target at the preferred step width may itself incur an energetic cost. However, with a separation distance of less than 13% LL, the two virtual lines were indistinguishable from a single virtual line. Thus, we chose our minimum target step width to be 15% LL. As such, it may be considered inappropriate to compare the preferred step width condition (without visual feedback) to the target step width conditions (with visual feedback). However, the preferred step width (3.6 ± 2.6 cm; mean ± sd) in our study is close to zero. The overall interpretation of our results does not change if we compare the 0% LL condition to the other target step width conditions (15%, 20%, and 25% LL). An experimental condition with a negative step width, i.e. a cross-over gait, might reveal a more definitive U-shape relationship between net metabolic power and step width. A second limitation could be that we did not control for step frequency across running conditions. However, the increase in the energetic cost of running above or below the preferred step width cannot be explained by changes in step frequency since step frequency was similar across conditions (Table 1). Compared to running with arm swing, subjects increased step frequency by 2.5% when running without arm swing. Previous evidence (Cavanagh and Williams, 1982) indicates that a 2.5% increase in step frequency increases $\dot{V}_{O_2}$ by less than 0.5%.

In summary, our data reveal that humans utilize two fundamental mechanisms that minimize energetic cost and improve lateral balance during running: M-L foot placement (i.e. running with narrow step widths) and arm swing. This study is the first to demonstrate that arm swing not only reduces energetic cost but also improves lateral balance by reducing step width variability. An underlying principle that emerges from our results is that there exist U-shaped relationships not only between energetic cost and step width but also between lateral balance and step width. In conclusion, humans appear to choose their step width and swing their arms so as to minimize energetic cost and optimize for lateral balance.

Conflict of interest statement

The authors do not have any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work.

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