Arm swing during human walking:
active and passive contributions to a hybrid system

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1 Introduction

Controversy exists as to whether arm swing is actively driven by muscle forces, a passive pendulum response to the accelerations of the body, or some combination. Recently, Pontzer et al. [5] and Collins et al. [2] proposed that arm swing can arise primarily from passive dynamics with little to no muscular effort to drive the arms. Motivated by these recent passive arm swing hypotheses, we sought to determine if biological arm swing during walking could arise from passive dynamics alone. We studied people walking 1) normally with their biological arms and 2) while wearing passive mechanical arms that matched the pendulum characteristics of their biological arms (Fig. 1).

First, we measured anterior and posterior deltoid electromyographic (EMG) activity and the amplitude of biological arm swing across a range of step frequencies. If biological arm swing is the result of purely passive pendulum motion, then we would expect the arms to swing without the need for shoulder muscular activity. Alternatively, if arm swing is not purely passive, then biological arm swing should require some degree of muscular activity to drive the arms.

Second, we measured the swing amplitude of anthropomorphic passive mechanical arms while subjects walked across a range of step frequencies. If biological arm swing is the result of purely passive pendulum motion, then we would expect the motion of the pendulum-like passive mechanical arms to be similar to biological arms. Alternatively, if arm swing is not purely passive, then the passive mechanical arms should swing with amplitudes that are less than the swing amplitudes of biological arms.

2 Methods

Ten male subjects (age = 25.1 ± 4.5 years, mass = 77.0 ± 7.1 kg, height = 1.83 ± 0.1 cm; mean ± sd) provided informed consent as per the University of Colorado IRB.

2.1 Experimental design

Subjects completed two sessions in random order that included: 1) walking with their biological arms and 2) walking with pendulum-like passive mechanical arms. Subjects initially walked normally at 1.25 m/s while we measured their step frequency using a stopwatch. For each session, subjects walked on a treadmill for randomized conditions of 70, 80, 90, 100, 110, 120, and 130% of their normal step frequency with speed held fixed at 1.25 m/s. We enforced step frequency with a metronome. On average, subjects preferred a step frequency of 1.74 ± 0.08 Hz (mean ± sd).

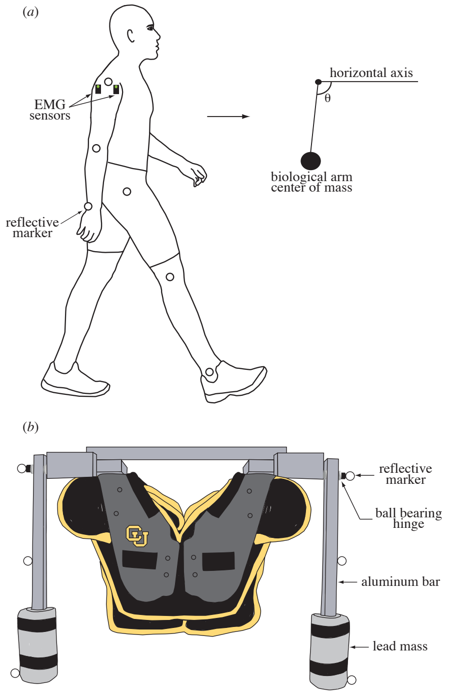

Figure 1: (a) Reflective marker and EMG sensor placement for measurements of biological arm swing, leg swing, and deltoid muscle activity. (b) During passive mechanical arm swinging, subjects wore our custom-built device, consisting of a set of football shoulder pads linked to aluminum bars that hung from a ball bearing hinge. Reflective markers were placed at the locations of the hinge, middle of the bar, and end of the lead mass. Damping of the passive mechanical arms was very small (1.05 Ns/m) and equivalent to only 3.0% of the critical damping (35.59 Ns/m).

2.2 Biological arm swing

We recorded the motions of reflective markers placed on anatomical landmarks of the left and right side of the body (Motion Analysis Corporation, Santa Rosa, CA) as well as surface EMG of the left and right shoulder muscles (anterior and posterior deltoid) with wireless sensors (Delsys Inc., Boston, MA). For each trial, we simultaneously recorded the three-dimensional motions of the reflective markers (100 Hz) and surface EMG (1000 Hz) for 20 seconds.

2.3 Passive mechanical arm swing

For the free-swinging, passive mechanical arm swing trials, we placed reflective markers at the shoulder hinge joint, middle and end of the aluminum bar (Fig. 1b). While walking with our device, subjects crossed their biological arms in front of their chest. For each trial, we recorded the three-dimensional motions of the reflective markers (100 Hz) for 20 seconds.

2.4 Kinematic and EMG analysis

For biological arm swing, we computed the sagittal plane coordinates of the arm center of mass (COM) using reflective marker position data and published anthropometric data tables. For passive arm swing, we computed sagittal plane coordinates of the mechanical arms using the position of the reflective marker placed at the hinge joint and at the end of the aluminum bar. We processed the EMG signals to obtain linear envelopes and then time normalized each individual cycle of angle and EMG data to 1001 data points, representing the arm swing cycle from 0-100%. In the case of passive mechanical arm swing, we time normalized the angle data only. We normalized the average EMG amplitude at the preferred step frequency by setting this value to 1.0 for each subject.

2.5 Statistical analysis

We used a general linear model (GLM) repeated-measures analyses with step frequency as a within subjects fixed factor to evaluate a main effect for biological and passive mechanical arm swinging amplitude. We also used a GLM repeated measures analyses with step frequency as a within subjects fixed factor to evaluate a main effect for normalized EMG amplitude. For all statistical tests, significance was set at an α level = 0.05 (SPSS Inc., Chicago, IL). If significant main effects were detected for step frequency, we followed up with planned comparisons between the control (100% of preferred step frequency) and the other step frequency conditions. All values are reported as mean ± SEM unless noted otherwise.

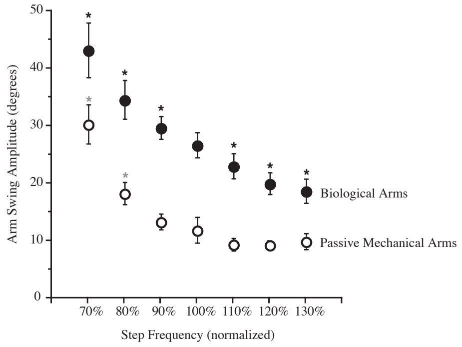

Figure 2: Average swing amplitude of biological (filled) and passive mechanical arms (open) while walking across normalized step frequencies (mean ± SEM; n = 10).

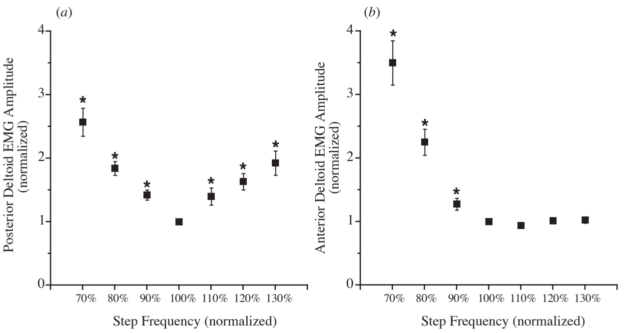

Figure 3: Across step frequencies, the average EMG amplitude for the (a) posterior and (b) anterior deltoid resembled V-shaped and L-shaped trends, respectively (n = 10). When compared to their preferred step frequency (100%), subjects significantly increased posterior deltoid activity when walking at slower and faster step frequencies (* denotes p <0.05). In contrast, subjects only increased anterior deltoid activity at slower step frequencies (when compared to 100%, * denotes p <0.05). The anterior deltoid remained nearly silent at preferred and faster step frequencies. Values are mean ± SEM.

3 Results and Discussion

At the preferred step frequency (100%), biological arm swing required muscular actuation for retraction (i.e. backwards motion), which was initiated by the posterior deltoid, the primary extensor muscle at the shoulder (data not shown). Similar to the findings of Fernandez-Ballesteros et al. [4], the posterior deltoid showed a burst of EMG activity lasting from just before until just after the biological arm reached its maximum forward position during arm swing, presumably slowing down the forward motion and initiating retraction. The subsequent swinging of the biological arm in the forward direction occurred in the absence of any significant anterior deltoid EMG activity, the primary flexor muscle at the shoulder. All 10 subjects showed this general behavior in the EMG activity and amplitude of biological arm swing. Our EMG data provide evidence that when walking normally, biological arm swing is not a purely passive process but rather resembles a hybrid system whereby the backward swing is driven by active retraction by the posterior deltoid muscle and the forward swing is driven by passive pendular motion.

At the preferred step frequency (100% = 1.74 Hz), biological arm swing swept an average angle of 27 degrees. In contrast, passive mechanical arm swing swept an average angle of just 12 degrees. The amplitude of biological arm swing increased at slower step frequencies and decreased at fast step frequencies (Fig. 2). At the slowest step frequency (70%), biological arm swing reached an amplitude of 43 degrees and at the fastest step frequency (130%), the amplitude only reached 19 degrees. The changes in the amplitude of biological arm swing were accompanied by changes in the muscular activation of the posterior and anterior deltoid (Fig. 3a, b). At the slowest step frequency, the EMG amplitude of the anterior and posterior deltoid muscle increased by 160% and 250%, respectively. At the fastest step frequency (130%), the EMG amplitude of the posterior deltoid increased by 92% while the anterior deltoid remained silent. When compared to the preferred step frequency, no significant changes in anterior deltoid EMG amplitude were detected at 110, 120, or 130%, indicating that the forward swinging of the biological arm was achieved passively.

We further explored the passive arm swing hypothesis using the established theory of forced mechanical vibrations [1, 3]. Every simple pendulum has a natural frequency of oscillation ($\omega = \sqrt{\frac{g}{l}}$) that depends on gravity (g) and the length (l) of the pendulum. A pendulum can be induced to swing back and forth when the pivot is subjected to a driving force, due to a sinusoidal, horizontal displacement [*http://www.elmer.unibas.ch/pendulum/index.html*]. This phenomenon is illustrated by the resonance diagram in Fig. 4a which demonstrates three important effects of the forcing frequency, ω_{force}. At point *i*, when ω_{force} approaches zero, the forcing frequency applied to the pivot becomes extremely slow, thus the amplitude of the swinging pendulum approaches zero. At point *iii*, at very high forcing frequencies ($\omega_{force}/\omega_{natural} \gg 1$), the forcing frequency oscillates so fast that the swinging pendulum cannot follow, thus the swinging amplitude is very small. Point *ii* represents resonance whereby the forcing frequency coincides with the natural frequency of the pendulum, causing it to swing at infinitely large amplitudes. Using this theoretical framework, we treated step frequency as the forcing frequency and compared changes in the amplitude of biological and passive arm swing to the amplitude predicted from a horizontally driven pendulum. Since the legs generate force against the ground during each step which causes forward motion of the upper body, we reasoned that walking at a fixed speed (1.25 m/s) but at different step frequencies would change the forcing frequency applied to the pivot point and therefore excite the swinging amplitude of the pendulum-like passive mechanical arms.

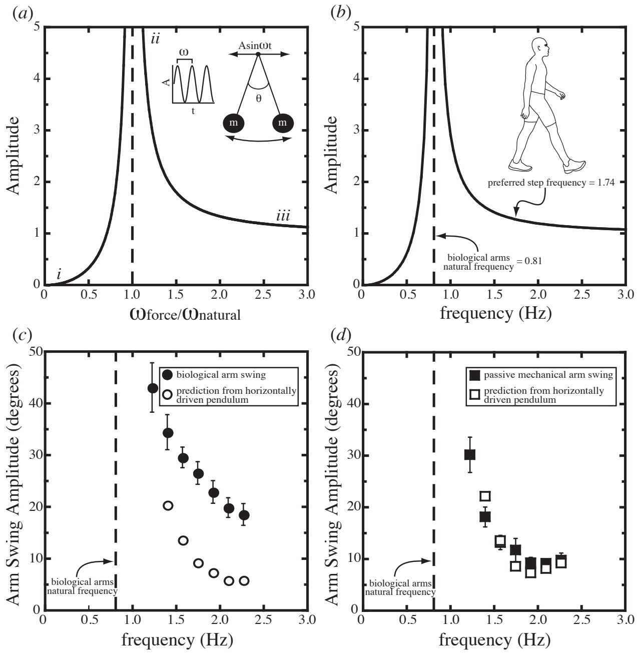

Figure 4: (a) Resonance diagram for a horizontally driven pendulum subjected to different frequencies. (b) Resonance diagram comparing the biological arms natural frequency (0.81 Hz) to the preferred step frequency adopted during walking (1.74 Hz). (c) Biological arm swing amplitude measured experimentally (closed circles) and predicted (open circles) for a horizontally driven anthropomorphic pendulum subjected to different step frequencies during walking. Note, the linearized approximation for a horizontally driven pendulum is not valid for angles much greater than 20 degrees, thus we do not include the predicted amplitude for the slowest step frequency.

In general, the amplitude of purely passive mechanical arm swing was much less than biological arm swing across the range of step frequencies (Fig. 2). At the slowest (70%) and fastest (130%) step frequency, biological arm swing amplitude exceeded that of passive arm swing by 13 and 9 degrees, respectively. Nonetheless, the amplitude of passive mechanical arm swing was excited by steady decreases in step frequency, similar to what occurs when an external force excites a pendulum at different frequencies. In contrast, walking at faster step frequencies did not change the amplitude of passive mechanical arm swing, indicating that step frequencies greater than preferred did not further excite the passive arms. Our data demonstrate that normal amplitudes of biological arm swing cannot be accomplished by purely passive dynamics; shoulder muscular actuation is also necessary to drive arm swing during walking.

As demonstrated in Fig. 4b, we find that the preferred step frequency during walking (1.74 Hz) was much greater than the natural pendulum frequency of the subject's biological arms (0.81 Hz). In short, the resonance diagram suggests that the preferred step frequency is too fast ($\omega_{force}/\omega_{biological\ arm's\ natural frequency} \gg 1$) to generate large amplitudes of passive arm swing. The preferred step frequency was 2.15 times greater than the biological arms natural frequency, suggesting that little mechanical energy can be harnessed to drive biological arm swing. Indeed, we find that the swinging amplitudes predicted from a horizontally driven pendulum match well with the swinging amplitudes of the passive mechanical arms but not the biological arms (Fig. 4c, d). Note that across step frequencies, the changes in the amplitude of biological arm swing were much greater than the amplitude predicted from a horizontally driven pendulum. Overall, our data are consistent with the established theory of forced, lightly damped pendulums and provides a reasonable explanation as to why passive mechanical arm swing does not match the amplitude of biological arm swing. In conclusion, we find that human arm swing is not primarily passive but can be characterized as a hybrid system of active muscular actuation and passive pendulum dynamics.

4 Open questions

1) Is the linearized approximation for the equation of motion for a horizontally driven pendulum adequate to describe the dynamics of biological arm swing? 2) Why don't humans walk at a step frequency that matches the biological arm's natural frequency? 3) What kind of mathematical models would better describe the active and passive contributions to biological arm swing during human walking?

References

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