ARM SWING DURING HUMAN WALKING: ACTIVE AND PASSIVE CONTRIBUTIONS TO A HYBRID SYSTEM

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INTRODUCTION/MOTIVATION

Is arm swing actively driven by muscle forces, a passive pendulum response to body accelerations, or some combination? Scientific interest in human arm swing dates back to the 1800's and was originally described as passive pendulums (noted in [1]). This idea persisted for many years and was later endorsed by prominent biomechanists. For example, Chapman and Ralston [2] observed that the metabolic cost of walking was similar when the arms were free to swing and when the arms were bound to the side of the body. Since arm swing did not demand metabolic energy by the muscles, they concluded that "the arms behave as passive compound pendulums activated by movements at their point of attachment to the shoulder".

In contrast to the idea that the arms act as passive pendulums, others have argued that arm swing is an active movement caused directly by the activation of the shoulder muscles. In particular, Ballesteros et al. found that EMG activity of the posterior deltoid muscle at the shoulder plays the most important role in the backward swinging of the arm as well as decelerating the forward swing at the end of the flexion phase. However, the anterior deltoid remains silent during the forward swing suggesting that passive forces are responsible for the forward swinging motion of the arm.

One would think that the EMG data would have resolved this issue long ago, but the controversy surrounding the underlying mechanism of human arm swing has resurfaced. Recently, Pontzer et al. [4] proposed a passive arm swing hypothesis whereby arm swing is derived by the mechanical energy from the swinging legs, which is transferred through the pelvis and upward through the torso and shoulder girdle. In contrast to Ballesteros et al., they reported simultaneous activation of the anterior and posterior deltoid; leading them to surmise that these muscles act to stabilize the shoulder, not drive arm swing. They also found that restricting arm swing did not affect the metabolic cost of walking, an observation analogous to Chapman and Ralston [2]. These findings led Pontzer et al. to hypothesize that "the power for arm swing is ultimately derived from the swinging legs".

In another recent study, Collins et al. [3] used a three-dimensional passive dynamic walking computer model to show that purely passive arms could swing back and forth like biological arms. They also built passive mechanical arms made of wood or thick rope and provided physical demonstrations of passive arm swinging during human walking. In contrast to Pontzer et al., Collins et al. found that restricting arm swing increased the metabolic cost of walking. As such, they proposed a "cost-benefit" hypothesis whereby shoulder muscles incur a direct metabolic cost to swing the arms but arm swing indirectly reduces the overall cost of walking by reducing the ground moment about the vertical axis. They further reasoned that the direct cost of swinging the arms is negligible since both their walking model and artificial arms could generate passive arm swinging dynamics. These results are very intriguing, however, no attempt was made to match the pendulum characteristics of the passive mechanical arms to those of biological arms. Comparing passive arms that are mechanically similar to biological arms could provide key insights into whether human arm swing could be accomplished by passive dynamics. Although the hypothesis proposed by Collins et al. is fundamentally different from that of Pontzer et al., an underlying theme in both is that arm swing can arise primarily from passive dynamics with little to no muscular effort to drive the arms.

Motivated by these recent findings, we sought to determine if biological arm swing during walking could arise from passive dynamics alone. In line with the physics of forced, lightly damped pendulums, we reasoned that the arms could be made to swing in the presence of a cyclical horizontal force applied to the shoulder joint, the pivot point of attachment of the arm. We studied people walking 1) normally with their biological arms and 2) with passive mechanical arms that matched the pendulum characteristics of their biological arms (Fig. 1).

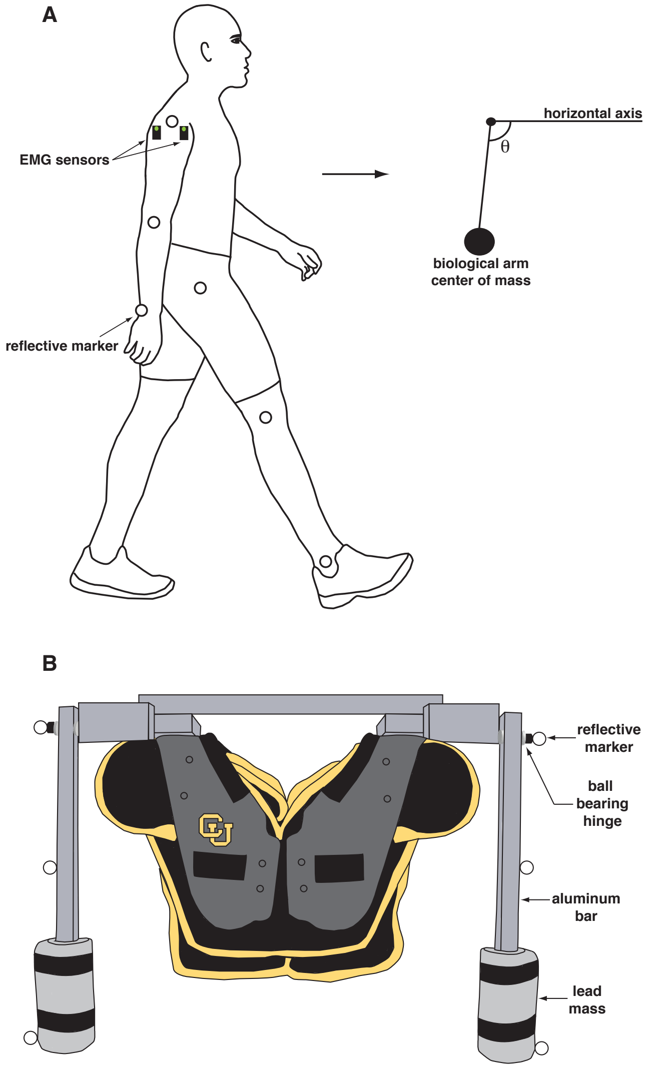

Figure 1. (A) Reflective marker and EMG sensor placement for measurement of biological arm swing, leg swing, and deltoid muscle activity. **(B)** During passive mechanical arm swinging, subjects wore our custom-built device, consisting of a set of football shoulder pads linked to aluminum bars that hung vertically from their pivot point.

OUR APPROACH

Subjects walked on a treadmill at a constant speed (1.25 m/s) across a range of slow and fast metronome enforced step frequencies. As our first test of the passive arm swing hypothesis, we measured anterior and posterior deltoid muscular activity and the amplitude of biological arm swing at 70, 80, 90, 100, 110, 120, and 130% of each subject's preferred step frequency (Fig. 1A). If biological arm swing is the result of purely passive pendulum motion, then we would expect that the force generated against the ground during each step would accelerate the shoulder joint and excite the passive motion of the biological arms, causing 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.

As our second test of the passive arm swing hypothesis, we measured the swinging amplitude of anthropomorphic passive mechanical arms while subjects walked at the range of step frequencies noted above (Fig. 1B). During these experiments, subjects crossed their biological arms across their chest so that the passive mechanical arms were free to swing. If biological arm swing is the result of purely passive pendulum motion, then we would expect that the force generated against the ground during each step would accelerate the mechanical pivot and excite the motion of the pendulum-like passive mechanical arms, causing the swing amplitudes across step frequencies 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.

DISCUSSION

During our talk, we hope to convince the *dynamic walking community* that arm swing during human walking is a hybrid system of active muscular actuation and passive pendulum dynamics. Our muscle activity measurements show that at preferred step frequencies, the backward swing of biological arms is caused by posterior deltoid muscle actions while the forward swing is driven by gravity and passive pendulum dynamics. In addition, based on the linearized equation of motion for pendulum physics, we find that passive mechanical arm swing resembled the resonance behavior of a horizontally driven pendulum, reaching its largest amplitude as step frequency approached the biological arms natural frequency. However, the swinging amplitudes of passive mechanical arms were much less than the biological arms.

REFERENCES

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