INTRODUCTION

Human walking is a complex skill involving the coordination between upper and lower body motion. As walking velocity increases there is increased counter-rotation between the thorax and pelvis, along with increased arm swing and hip excursion. The arm and contralateral leg move more in-phase, while the arm and ipsilateral leg demonstrate a more out of phase pattern with increased walking velocity. Furthermore, torso and pelvic rotation becomes tightly coupled, while arm movement frequency synchronizes more with stride frequency at higher walking velocities (Wageenaar & Beek, 1992; Wagenaar & van Emmerik, 2000).

Published findings have shown that reduced arm movement amplitude during over-ground walking, leads to adaptive decreases in transverse rotation of the trunk, hip excursion, stride length, and walking velocity (Jackson et al., 1983; Eke-Okoro et al., 1997; Sigg et al., 1997). However, the question remains as to how reduced arm movement amplitude impacts arm motion on the opposite side, and the phasing, and frequency relations between arm and leg movements.

METHODS

Ten healthy (ages 21 to 24) healthy subjects were recruited. Subjects walked on a treadmill while systematically increasing the belt velocity (0.22, 0.40, 0.63, 0.85, 1.10, 1.30, 1.52 m/s) and then decreasing it (same increments) under three different conditions: 1. no arm constraint 2. right arm constrained 3. left arm constrained. The arm was constrained by placing the arm in a sling and securing it to the thorax.

3D kinematic data were collected through a Skill Technologies® 6D Research System. The total range of movement amplitudes for arms, thorax, pelvis, and legs was calculated by subtracting the minimal angular displacement from the maximal angular displacement. The shoulder and hip angle time-series data were used to compute the point estimates of relative (PERP) phase between ipsilateral and contralateral limb pairs. We determined if the power in arm movement frequency was higher at stride or step frequency during walking. Movement frequencies and corresponding power in shoulder and hip angle were estimated by calculating the power spectral density function of the shoulder and hip angle time series.

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P_1 - P_2 = \frac{P_1}{P_1 + P_2}
\]

P1 represents the power (from power spectral analysis) of arm movement frequency at stride frequency, while P2 represents the power of arm movement frequency at step frequency.
Statistical analysis revealed no significant differences in dependent measures between same ascending and descending velocity levels. Therefore, data from the decreasing velocity levels was combined with the increasing velocity levels. The effects of systematically varying walking velocity and arm constraint were evaluated by a within-group analysis of variance with repeated measures. A Bonferonni Test with a 0.01 significance level was used for post-hoc comparisons.

RESULTS

The constrained arm movement amplitude was significantly (p < .0001) decreased as compared to non-constrained arm motion, and did not significantly increase with walking velocity. When one arm was constrained, the non-constrained arm movement amplitude was significantly greater above 1.10 m/s (p < .000001), as compared to arm swing during walking with no constraint.

As walking velocity increased the non-constrained arm movement frequency was more strongly synchronized with the stride frequency (p < .0001; Figure 1). However, with a significant reduction in arm movement amplitude the constrained arm was unable to synchronize with the stride frequency as walking velocity increased.

Arm constraint also led to significant (p < .0001) decreases in transverse rotation of the torso and pelvis. Moreover, subjects increased hip excursion, but decreased stride frequency as they attempted to maintain the spatial temporal relations when walking at a constant velocity.

DISCUSSION

In sum, the results from the present study demonstrate flexibility of the coordination dynamics of walking to meet constraints imposed on the movements of body segments. However, the data suggest that the ability to modify arm movement amplitude, along with frequency, is necessary for synchronization with the stride frequency at higher walking velocity. Considering, slower walking velocity in patients with severe upper extremity dysfunction (e.g., stroke) may be due to inability to alter coordination patterns at higher walking velocities. Future studies should investigate the underlying dynamics of arm dysfunction and adaptations during treadmill and over-ground walking.

REFERENCES