

ARM MOTION COUPLING DURING LOCOMOTION-LIKE ACTIONS: AN EXPERIMENTAL STUDY AND A DYNAMIC MODEL

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INTRODUCTION

Arm swinging during human locomotion has been viewed as a consequence of coupling between hypothetical pattern generators for the lower and upper extremities [5,6]. Stable patterns of modulation of the upper and lower extremity muscles are also observed in standing subjects when they rhythmically swing their arms [1,2]. *The aim* of our study has been to explore the interactions between rhythmic motor patterns produced by a hypothetical neural oscillator and a voluntary motor command unrelated to the ongoing rhythmic action, such as stopping one of the arms voluntarily. We expected that effects of the command for the discrete voluntary action on the rhythmic action of the other arm could be described with a new constraint on the neural oscillator without a change in the coupling between the arms.

METHODS AND PROCEDURES

Eight healthy right-handed subjects performed an out-of-phase arm-swinging task while stepping in place or while standing (STEP and STAND *Task*) at individually defined Natural (0.9-1 Hz) and Fast (1-1.1 Hz) *Speed*. The subjects stopped the right or left arm (*Side*) in response to an auditory signal while trying to keep the rest of the movement pattern unchanged. Eight blocks of 15 trails (24 s each) corresponding to the *Task* x *Speed* x *Side* design, were performed randomly. A four-camera ProReflex motion analysis system was used to capture the position of six passive reflective markers placed over the shoulder,

elbow, and wrist joints at 240 Hz. The amplitude and cycle duration of arm swing during 3 cycles before and after STOP (*Pre-Stop*, *Post-Stop*) were quantified. Standard methods of parametric statistics were used.

RESULTS AND DISCUSSION

After the voluntary STOP of one arm movement, the continuing arm showed an increase in its amplitude in all the subjects, for both arms, during both STEP and STAND tasks, and under both natural and fast speeds (Fig.1).

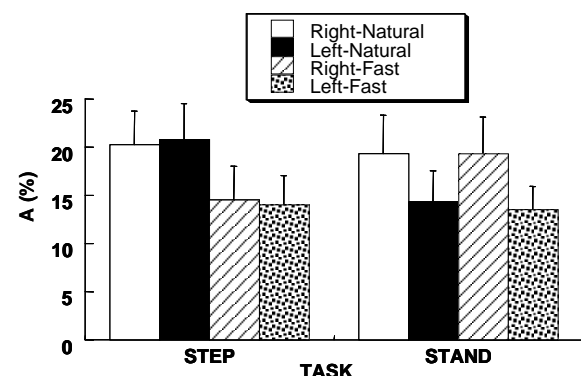


Figure 1: An increase in the amplitude of arm movement (A, in % to the pre-stop arm amplitude) after the other arm stopped swinging. Averaged across subjects data with standard error bars are plotted.

The increase in amplitude (ΔA) between the pre-STOP and post-STOP was, on average, $16.9 \pm 2.9\%$. A four-way ANOVA with the factors *Period* (*Pre-Stop*, *Post-Stop*), *Task* (*Stand*, *Step*), *Side* (*Right*, *Left*), and *Speed* (*Normal*, *Fast*) on A showed significant effects of *Period*, *Task*, and *Side* ($F_{[1,115]} > 14$; $p < 0.001$) without other effects. There

was higher A after the stop as compared to prior to the stop, during standing as compared to stepping, and in the left arm as compared to the right arm. The cycle duration showed only a significant effect of *Task* ($F_{[1,116]} = 9.8$, $p < 0.01$): On average, the arm cycle duration during stepping was about 5% lower than during standing.

Mathematical Model. Each arm motion was modeled with a single Van der Pol oscillator:

$$\begin{aligned} \ddot{x}_1 + v_1 \dot{x}_1 ((x_1^2 + \dot{x}_1^2 / \omega_1^2) - A_1^2) + \omega_1^2 x_1 &= f_1(x_1, \dot{x}_1, x_2, \dot{x}_2) \\ \ddot{x}_2 + v_2 \dot{x}_2 ((x_2^2 + \dot{x}_2^2 / \omega_2^2) - A_2^2) + \omega_2^2 x_2 &= f_2(x_1, \dot{x}_1, x_2, \dot{x}_2) \end{aligned} \quad (1)$$

Here x_1 and x_2 are α_{ARM} angles of the two upper extremities, ω_1 and ω_2 are prescribed frequencies and A_1 and A_2 are amplitudes parameters. Parameters v_1 and v_2 determine the strength of mechanisms stabilizing the desired oscillatory pattern. To make anti-phase oscillation of x_1 and x_2 stable and functions f_1 and f_2 symmetrical with respect to x_1 and x_2 we used the coupling functions from the Haken-Kelso-Bunz model [3], and simplified it by reducing the number of free parameters:

$$\begin{aligned} f_1(x_1, \dot{x}_1, x_2, \dot{x}_2) &= -b_1 \dot{x}_1 (x_1 - x_2)^2 \\ f_2(x_1, \dot{x}_1, x_2, \dot{x}_2) &= -b_2 \dot{x}_2 (x_2 - x_1)^2 \end{aligned} \quad (2)$$

Here parameters b_1 , and b_2 determine the properties of the coupling between the two arms. Different values of ω_1 and ω_2 in (1) may lead to significant desynchronization [3]. For simplicity we assumed that the prescribed frequencies are set by the CNS to equal values, $\omega_1 = \omega_2 = \omega$. All other parameters were allowed to differ for the two limbs. The final equations are:

$$\begin{aligned} \ddot{x}_1 + v_1 \dot{x}_1 ((x_1^2 + \dot{x}_1^2 / \omega_1^2) - A_1^2) + \omega_1^2 x_1 &= -b_1 \dot{x}_1 (x_1 - x_2)^2 \\ \ddot{x}_2 + v_2 \dot{x}_2 ((x_2^2 + \dot{x}_2^2 / \omega_2^2) - A_2^2) + \omega_2^2 x_2 &= -b_2 \dot{x}_2 (x_2 - x_1)^2 \end{aligned} \quad (3)$$

The model (3) was capable to produce cyclic changes of the x_1 and x_2 similar to the experimental data (Fig.2).

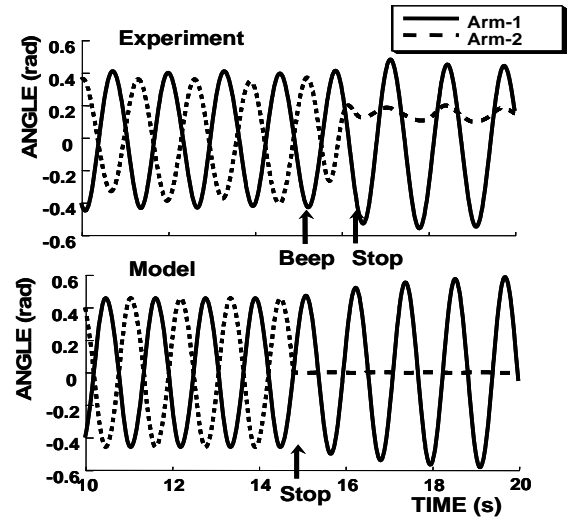


Figure 2: Experiment: a representative example of the arm sway trajectory. The arrows show the Beep and Stop moments. **Model:** Results of the simulation with the parameters defined using the average experimental values. The arrow shows the time of introducing the constraint $x_2 = 0$. Note the increase in the amplitude of the continuing arm motion in both panels.

Our experiments have shown strong coupling effects between the two arms. This effect was nearly symmetrical between the left and right arms. It was similar in magnitude in the tasks that did and did not involve simultaneous rhythmic leg movement (marching in place). We were able to model the effect using a simple dynamic model with two coupled non-linear oscillators, similar to the one suggested by Haken et al. (1985).

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ACKNOWLEDGEMENTS

Supported by NIH grant NS-035032.