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Full Length Article

Less precise motor control leads to increased agonist-antagonist muscle activation during stick balancing

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ABSTRACT

Human motor control has constraints in terms of its responsiveness, which limit its ability to successfully perform tasks. In a previous study, it was shown that the ability to balance an upright stick became progressively more challenging as the natural frequency (angular velocity without control) of the stick increased. Furthermore, forearm and trunk agonist and antagonist muscle activation increased as the natural frequency of the stick increased, providing evidence that the central nervous system produces agonist-antagonist muscle activation to match task dynamics. In the present study, visual feedback of the stick position was influenced by changing where subject focused on the stick during stick balancing. It was hypothesized that a lower focal height would degrade motor control (more uncertainty in tracking stick position), thus making balancing more challenging. The probability of successfully balancing the stick at four different focal heights was determined along with the average angular velocity of the stick. Electromyographic signals from forearm and trunk muscles were also recorded. As expected, the probability of successfully balancing the stick decreased and the average angular velocity of the stick increased as subjects focused lower on the stick. In addition, changes in the level of agonist and antagonist muscle activation in the forearm and trunk was linearly related to changes in the angular velocity of the stick during balancing. One possible explanation for this is that the central nervous system increases muscle activation to account for less precise motor control, possibly to improve the responsiveness of human motor control.

1. Introduction

Like other physical systems, human motor control has constraints that limit its ability to successfully perform tasks. For instance, balancing an upright yardstick on your fingertip is possible, but not a pencil. The reason for this stems from the rate at which the pencil tends to fall is higher than the yardstick. Stated differently, the pencil has a higher natural frequency than the yardstick. Because human motor control has limits in its responsiveness, when the system being controlled exceeds a critical frequency it will exceed the limits in control and the system will become unstable. Frequency related limitations in control can be expressed in terms of control bandwidth. Control bandwidth reflects limits in terms of both low and high frequency cut-offs – but for most situations, it is the high frequency cut-off that is problematic. A system with a higher, high

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frequency cut-off is more responsive and can stabilize faster moving objects than a system with a lower, high frequency cut-off. Readers interested in learning more about control bandwidth are referred to Phillips and Harbor (2000).

In a recent stick balancing study, it was shown that the forearm and trunk muscle activation changed with task dynamics (Reeves, Pathak, Popovich, & Vijayanagar, 2013). Task dynamics were modified by adjusting the height of a mass affixed to the stick. As the mass was lower, the natural frequency of the stick increased. During stick balancing, muscle activation in both the agonist and antagonists were linearly related to the natural frequency of the stick (Reeves et al., 2013). It was suggested that changes in muscle activation was used to regulate control bandwidth by making human motor control more responsive through reducing compliance in muscles and tendons (Reeves et al., 2013). Although, increased agonist-antagonist muscle activation does not change the net torque acting about a joint, it does increase joint stiffness (De Serres & Milner, 1991; Franklin & Milner, 2003; Hogan, 1985; Milner, 2002), which would allow for higher frequency control input to be applied to the object being stabilized.

Aside from task dynamics, precision in human motor control could also influence the angular velocity of stick balancing. For instance, noise (e.g., poorer visual resolution, increased muscle force variability) will degrade human motor control (Kasai, Yahagi, & Shimura, 2002; Maeda, Nakamura, Otomo, Higuchi, & Motohashi, 1998; Missenard, Mottet, & Perrey, 2008), which in the case of stick balancing would increase the angular velocity of the stick. And as with changes in task dynamics (changes in natural frequency of the stick), increased angular velocity from less precise motor control could exceed the high frequency limits in control bandwidth leading to task failure (i.e., the stick falls over).

In the present study, we investigated the effects of less precise human motor control on task stability. We also explore the connection between less precise human motor control on muscle activation to determine if there is evidence that the central nervous system increases control responsiveness through muscle coactivation. To this end, we needed a method to adjust control precision during stick balancing. Based on preliminary work, we found that focusing lower on the stick during stick balancing made the task more challenging. It is believed that looking lower on the stick reduces visual resolution in tracking the stick (see (Reeves, Narendra, & Cholewicki, 2011) for possible explanation). It is also possible that, in addition to increase visual uncertainty (i.e., noise), longer delays in visual feedback may be present at lower focal heights thus making motor control less responsive. To confirm that changing focal height degrades control, we tested the hypotheses that (1) the probability of successfully balancing the stick decreases as focal height decreases, and (2) the average angular velocity of the stick (expressed in terms of frequency) increases as focal height decreases. Finally, we tested the hypothesis that (3) the level of muscle activation in the forearm and trunk in both agonist and antagonist increases as the angular velocity of the stick increases. If these hypotheses are correct, it suggests that the central nervous system adjusts muscle activation to not only task dynamics, as was indicated in the previous stick balancing experiment (Reeves et al., 2013), but also to the precision of human motor control.

2. Materials and methods

The same study population and experimental set-up used in a previous study investigating changes in task dynamics (Reeves et al., 2013) was used for the current study investigating changes in control precision.

2.1. Subjects

Nine healthy subjects with no history of neurological, musculoskeletal upper extremity, or spinal disorders participated in the study (see Table 1 for subject characteristics). The study was approved by Michigan State University's Biomedical and Health Institutional Review Board. Subjects gave informed consent prior to study participation.

2.2. Task

Stick balancing was performed with a weight (mass 1.9 kg) attached to an aluminum rod (length 105 cm, mass 0.4 kg). The base of the stick was connected to a pivot joint connected to a low-friction cart (mass 1.2 kg) that translated along a track (Fig. 1a). Subjects were instructed to move the cart to keep the stick upright. The center-of-mass of the weight was located at a height of 100 cm along the stick with the pivot joint representing the origin. To confine the task, the stick balancing apparatus was enclosed in a frame that was 85 cm long and 55 cm high (Fig. 1b).

Table 1
Mean age, height, and weight (standard deviation) of subjects.

	Males	Females
Number	6	3
Age (years)	34.0 (±11.4)	24.3 (±6.3)
Height (cm)	179 (±8)	165 (±2)
Weight (kg)	83.2 (±3.6)	65.8 (±8.2)