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Muscle contributions to center of mass excursion in ankle and hip strategies during forward body tilting

Shinya Ogaya [a,*], Yusuke Okita [b], Satoshi Fuchioka [a]

[a] Course of Physical Therapy, School of Comprehensive Rehabilitation, Osaka Prefecture University, 3-7-30, Habikino, Habikino-shi, Osaka 583-8555, Japan
[b] Physical Medicine and Rehabilitation Unit, Istituto Ortopedico Rizzoli via G. C. Pupilli 1 (ospedale), Bologna 40136, Italy

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ABSTRACT

Humans employ two distinct strategies to maintain balance during standing: the ankle and hip strategies. People with a high fall risk tend to alter their motion patterns during forward body tilting from a hip to an ankle strategy. Improved knowledge regarding how muscles control the center of mass (COM) during balancing would facilitate clinical assessment. The present study aimed to investigate individual muscle contributions to COM motion during forward body tilting with both ankle and hip strategies in 16 healthy adults. While standing, participants were instructed to oscillate their bodies and touch anterior and posterior targets at 0.5 Hz. The anterior target was positioned at the sternum height level in a HIGH and 5% lower in a LOW condition to induce ankle and hip strategies, respectively. The muscle tension force was calculated from measured angle data using a two-dimensional, muscle-driven forward simulation model. Muscle contributions to COM acceleration during forward body tilting were calculated via induced acceleration analysis. Long hamstrings were found to increase upward-contributing action and forward COM acceleration in the LOW condition during forward tilting. In contrast, the contribution of the soleus to backward COM acceleration was reduced. These results imply that the contribution of hamstrings to forward COM acceleration is disadvantageous to fore-aft COM control and balance recovery during forward body tilting.

1. Introduction

In humans, the standing posture is controlled by muscle activations to oscillate the body forward and backward to achieve intended motions such as reaching out or balancing. Two strategies, the ankle and hip strategies, are commonly used to control sagittal plane motion of the human body to regain balance (Horak and Nashner, 1986). In the ankle strategy, balance is maintained or restored mainly by movement of the body around the ankle as a single inverted pendulum, while in the hip strategy it is restored mainly by movement of the body around the hip (Horak and Nashner, 1986). Owing to the delayed onset of ankle plantar flexor activation (Romero and Stelmach, 2003), older people with the fear of falling or impaired physical functioning are thought to be familiar with the hip strategy against perturbation for compensation of impairment of ankle muscle function (Horak and Nashner, 1986; Okada et al., 2001).

The ankle and hip dominant motion patterns can be also observed in reaching and the elderly tend to adopt the hip strategy (Liao and Lin, 2008). The hip strategy accompanies smaller forward center of mass (COM) translation than the ankle strategy (Wernick-Robinson et al., 1999), as shown in Fig. 1, and low contraction of ankle plantar flexion muscle will be found while recovering the posture from the forward body tilting because a less forward excursion of COM requires a smaller ankle plantar flexion torque to restore the balance (Tyler and Karst, 2004). The smaller fore-aft COM translation in the fore-aft direction employed in the hip strategy may efficiently recover the balance from the forward tilting posture with less dependence on the ankle muscle. However, greater hip flexion in the hip strategy moves COM downward due to greater trunk bending at the forward body tilting posture (Liao and Lin, 2008). Therefore, in the hip strategy, greater vertical COG translation will bring the COM upward for recovering from a forward trunk bending to an upright posture and will require muscle force to compensate for the smaller ankle plantar flexor force. A previous study that investigated the fall incidence in older women aged over 70 years reported that approximately 17% of falls occurred during reaching or leaning (Nachreiner et al., 2007). Controlling COM excursion is essential for recovering the balance after forward body tilting because reaching or leaning are frequently performed during daily activities. Although the two strategies display different muscle

* Corresponding author. Fax: +81 72 9502130.
E-mail address: ogaya@rehab.osakafu-u.ac.jp (S. Ogaya).

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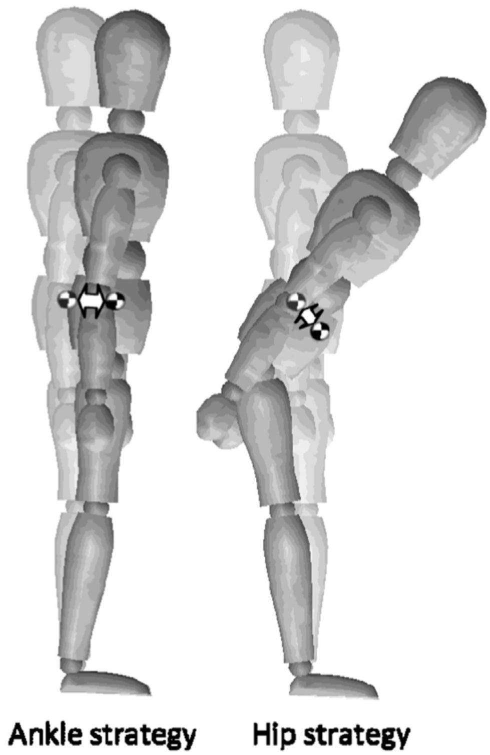

Fig. 1. Different COM excursions in the ankle and hip strategies. The figures on left and right show motions in the ankle and hip strategies, respectively.

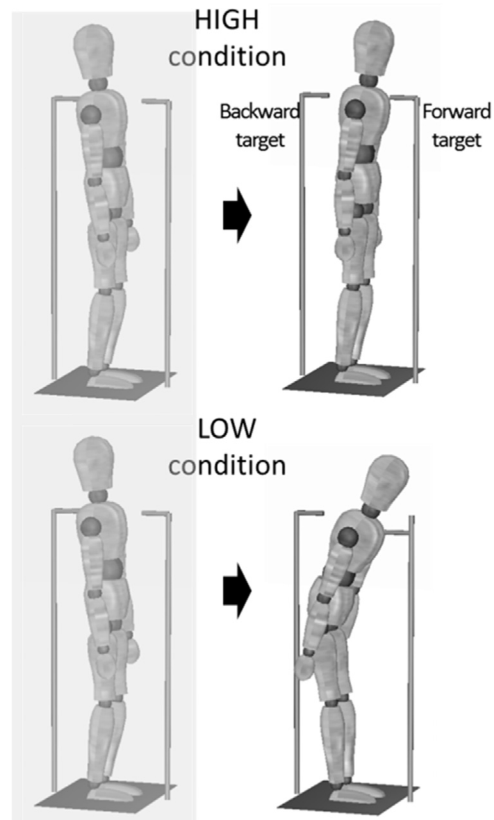

Fig. 2. Illustration of the HIGH and LOW experimental conditions. The distance from the sternum to the anterior target was set to 5% of the sternum height, and the distance from the subject's back to the posterior target was also set to 5% of the sternum height. The anterior target height was set to 100% of the sternum height in the HIGH condition and 95% in the LOW condition. The posterior target height remained at 100% of sternum height in both conditions. This study mainly analyzed forward tilting motions (right figure).

contributions for the control of COM excursion during the forward body tilting motion related to the fall, it is unclear how COM is controlled by the muscles to recover the balance from forward body titling to the upright posture in the ankle and hip strategy (Fig. 2).

Postural stability in these two strategies has mainly been discussed in the context of COM excursion; in contrast, COM regulation has not been assessed. A better understanding of how muscles control COM would enable discussions of dynamic postural balance stabilization in hip and ankle strategies. In particular, an analysis of muscle contribution on COM motion recovering from forward body tilting in the hip strategy might provide significant information about identification of key muscle for balance control or risk of falling in people who use hip strategy.

Previous studies have implemented a model-based simulation analysis to reveal a comprehensive and quantitative picture of the contributions of muscles to joint moment or COM acceleration (Anderson and Pandy, 2003; Hamner et al., 2010; Jansen et al., 2014; Steele et al., 2013). A number of researchers have offered considerable insights in this area with respect to COM regulation during gait or running. These mathematical analyses can be used to investigate the individual contributions of muscles to COM regulation during balance recovery from a forward tilting posture. In addition, the establishment of a direct connection between muscle actions and balancing strategies represents an important step in an understanding of balancing mechanics.

Regarding COM motion, the hip strategy would feature less forward displacement of the upper trunk during forward tilting than that of the ankle strategy. During experimental analysis, both strategies could be induced by the placement of targets at different heights in front of the upper trunk; subjects would then bend their trunks to touch these targets with their sternum. The present study analyzed voluntary forward body tilting motions on the basis of a two-dimensional muscle-actuated body model to reveal differences between the ankle and hip strategies in terms of muscle contributions to COM motion.

2. Methods

2.1. Measurement protocols

Sixteen healthy young people (gender: 8 men, 8 women; age: 21.2 ± 1.0 years old; height: 1.65 ± 0.09 m; weight: 59.6 ± 8.4 kg) participated in this study. Subjects were excluded if they had neurological or musculoskeletal impairments or a history of lower limb surgery. There were no subjects who frequently suffer from ankle sprains or a lower limb injury. The study protocol was approved by the local institutional ethics review committee, and the subjects provided written informed consent to participate.

First, participants were instructed to stand quietly with their feet 200 mm apart on a force plate (Kistler, Winterthur, Switzerland) with a sampling rate of 100 Hz and body weight was measured. Next the height of the top edge of the subject's sternum (sternum height) was measured from the floor, and targets with a 25 mm diameter were placed in front of and behind the subject's upper body at a distance 5% of the sternum height between upper trunk and the target. The upper ends of the anterior target were positioned at 100% of sternum height (HIGH condition) or 95% of sternum height (LOW condition; Fig. 1). The abilities of the HIGH and LOW conditions to induce the ankle and hip strategies, respectively, were ensured during our preliminary examination tests to investigate the effect of target height to motion pattern prior to experimental measurement. The end of the posterior target was consistently positioned at 100% of sternum height.

Although this study focused on forward tilting, muscle activations or COM excursion are known to correlate with the motion speed. Therefore, fore-aft oscillating body motions were recorded under a speed restriction, and data captured during forward body tilting was set as the main analytical target. Participants were instructed to touch the anterior target with their manubrium of sternum restrictedly but posterior target with any part of their back at 1-Hz intervals (determined via metronome) while their feet remained fixed to the floor, resulting