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Role of arm motion in feet-in-place balance recovery

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ABSTRACT

Although considerable arm movements have been observed at loss of balance, research on standing balance focused primarily on the ankle and hip strategies. This study aimed to investigate the effect of arm motion on feet-in-place balance recovery. Participants stood on a single force plate and leaned forward with a straight body posture. They were then released from three forward-lean angles and regained balance without moving their forefeet under arm-swing (AS) and arm-constrained (AC) conditions. Higher success rates and shorter recovery times were found with arm motion under moderate balance perturbations. Recovery time was significantly correlated with peak linear momentum of the arms. Circumduction arm motion caused initial shoulder extension (backward arm movement) to generate reaction forces to pull the body forward, but later forward linear momentum of the arms helped move the whole body backward to avoid forward falling. However, greater lean angles increased difficulty in balance recovery, making the influences of the arms less significant. Since arm motions were observed in all participants with significantly enhanced performance under moderate balance perturbation, it was concluded that moving the arms should also be considered (together with the ankles and hips) as an effective strategy for balance recovery.

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1. Introduction

Maintaining balance is important in daily living. To investigate balance recovery strategies, single or compound inverted pendulum models were commonly employed (Hof, 2007; Rietdyk et al., 1999; Runge et al., 1999). Although balance strategies including shoulder flexion/extension have been identified (Crenshaw and Grabiner, 2014), previous studies on feet-in-place balance have focused primarily on lower body movements usually characterized by the ankle and/or hip strategies (Rietdyk et al., 1999; Runge et al., 1999).

In balance recovery with stepping, compensatory arm movements have been observed in walking with unexpected tripping (Marigold et al., 2003; Roos et al., 2008) and on a moving surface (Allum et al., 2002; McIlroy and Maki, 1995). Researchers have argued that these arm reactions are functionally modulated with balance recovery rather than simply generic startled responses (Corbeil et al., 2013; Grin et al., 2007; Pijnappels et al., 2010). More specifically, distinct movement patterns observed in different age groups have led to the protective and preventive arm movement strategies adopted by older and younger adults, respectively (Roos et al., 2008).

The protective strategy basically involves grasping handrails or nearby objects (Maki and McIlroy, 1997), or reaching forward for self-protection in anticipation of an unsuccessful recovery (Roos et al., 2008). On the other hand, the preventive strategy generally includes adjusting center of mass (CM) position/velocity and body angular momentum. Although the overall effect of arm movements on CM displacements was considered small previously (Patla et al., 2002), upper limbs were later found to play an important role in balance by shifting body CM to the opposite direction (Marigold et al., 2003). In addition, whole body CM velocity was changed significantly by arm movements in healthy adults (Grin et al., 2007) and in spinocerebellar ataxia (SCA) patients (Küng et al., 2009). Arm movements could also allow more time for executing stepping to regain balance (Cheng et al., 2014). Furthermore, reactive torques could be generated by the arms to act against excessive angular momentum of the body (Allum et al., 2002; Roos et al., 2008). Asymmetric arm movements were also shown to postpone the transfer of arm angular momentum to the trunk in the transverse plane and to facilitate body orientation in preparation for landing the recovery foot after tripping (Pijnappels et al., 2010).

Although arm motions have been shown to affect balance recovery after tripping, thorough exploitation of their effects might not be possible because in most studies stepping was allowed. That is, due to various mechanisms which could be

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employed in maintaining balance (Hof, 2007), segment counter-rotation strategies would not be truly demanded unless the option of changing the support area was removed. In addition, some results were obtained from pre-designed experimental procedures which might not represent realistic situations. For example, voluntary arm abduction on only one side (either in the same or opposite side of platform roll) rather than natural reaction (possibly moving both arms) was instructed in balance recovery (Grin et al., 2007). The present study hypothesized enhanced rate of successful recovery (the primary dependent variable) when arm motions were allowed in feet-in-place balance recovery, and aimed at investigating the mechanisms of possibly altered balance performance due to arm motion. To clearly identify the role of arms in addition to the ankle and hip strategies, stepping was not allowed. This approach of constraining feet motion was also employed to examine exclusively the effect of joint torques on balance recovery with mathematical modeling (Kuo and Zajac, 1993) or experimental testing (Runge et al., 1999).

2. Methods

2.1. Participants

Twelve male students (height 1.72 ± 0.04 m; mass 66.5 ± 9.80 kg; age 23.86 ± 1.88 yrs) voluntarily participated in this study. None of them reported noticeable musculoskeletal/neurological disorders within the past six months. Before conducting this study, research objectives with detailed experimental procedures were approved by the University Research Ethics Committee for Human Behavioral Sciences. Each participant was given an information sheet outlining experimental procedures and the associated risks/benefits. Written informed consent form was obtained from each participant.

2.2. Experimental setup and protocol

Participants stood on a single force plate in bare foot, and leaned forward with a straight body posture supported by a custom-made safety harness system attached to the shoulder and back with a control cable (Fig. 1). This tether-release method has been a common way to simulate forward leaning and falls caused by different intensities of balance perturbations (Grabiner et al., 2005; Hsiao-Wecksler and Robinovitch, 2007). There was a large soft foam mat in front of the force plate to provide additional protection. Initial lean angles were 7.5°, 10°, and 12.5° from the vertical line measured by a laser line pointer (KML-3000, LASIC ELECTRO-OPTICS Co., Taiwan) projecting a beam through the line connecting the ankle and shoulder markers onto an enlarged protractor. These lean angles were chosen because the requested movement was to recover balance using extensive body movements without stepping. With smaller angles balance could be recovered effortlessly, and with larger angles taking a step became inevitable. The purpose of having different lean angles was to compare the effect of arm swing under various intensities of balance perturbation. Balance was recovered under arm-constrained (AC) and arm-swing (AS) conditions. In AC trials, the arms were fixated in front of the chest by elastic bandages, and participants recovered balance by moving only the rest body segments. In AS trials the arms were folded in front of the chest to hold the same initial posture as in AC conditions. After releasing the tether the arms could move freely and, to ensure natural responses, no instructions were given regarding the way to move the arms or lower limbs (Corbeil et al., 2013). At the moment of release the heels also left the ground, and balance was successfully recovered if forward falling could be stopped without stepping. Participants performed balance recovery six times for each lean angle/arm movement condition. Positions of both heels were marked before and after each trial. To avoid sliding or having small foot movements, participants were asked to repeat a seemingly successful trial if heel displacement (on either side) exceeded 0.01 m. Randomized lean angle/arm swing conditions with a 1-min break in between were used to reduce the effect of learning and fatigue. Participants were given 10 min to practice regaining balance under all three lean angles and both arm movement conditions prior to actual experiments.

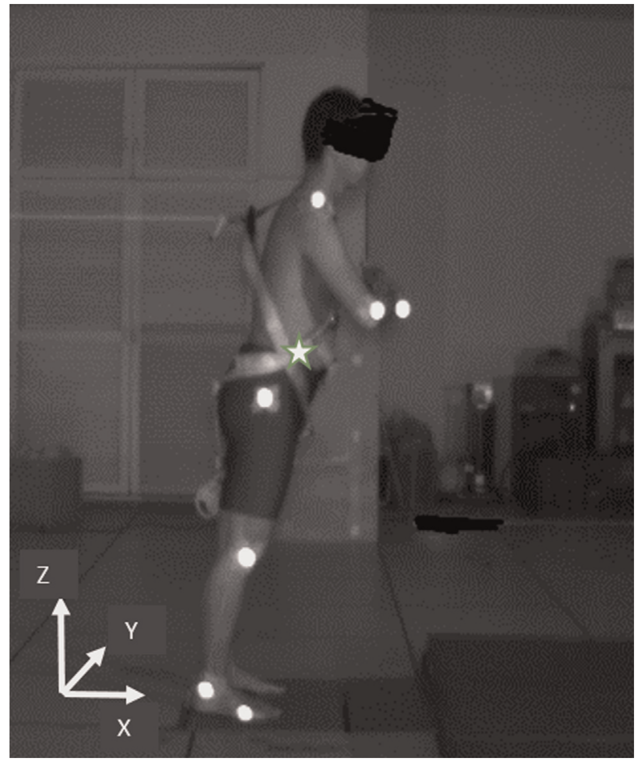

Fig. 1. Experimental setup. Participants stood on a single force plate in bare foot, and leaned forward while maintaining a straight body posture using a tether-release system. They were then released from three forward-lean angles and regained balance without moving their forefeet. The forward, left, and upward directions were set to coincide with the laboratory-fixed *X–Y–Z* coordinates. The star symbol denotes whole body CM position.

2.3. Data analysis

Each participant's forward, left, and upward directions were set to coincide with the laboratory-fixed *X–Y–Z* coordinates. Thirteen active markers were placed bilaterally at the 5th metatarsal phalangeal joints, ankles, knees (lateral femoral epicondyles), femur greater trochanters, sacrum, acromions, elbows, and wrists. Marker positions were recorded using two Visualeyez motion tracking systems (VZ4000, Phoenix Technologies Inc., Canada) placed at both sides of the participants. Joint angles were calculated using the tracking system's built-in VZAnalyzer software. Ground reaction forces (GRF) were measured using an AMTI force plate (BP400600-2000, Advanced Mechanical Technology Inc., Massachusetts, USA) and filtered by a Butterworth 4th-order zero phase-lag low-pass filter with a cutoff frequency of 50 Hz. Success rate of balance recovery (which was not subject-specific) was defined by the number of successful trials divided by total trials in the same condition. The sampling rates of force data and motion data are 1000 Hz and 100 Hz, respectively. The recovery time (RT) was defined as the duration from tether release to the instant when the

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