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# INCORPORATING VOLUNTARY UNILATERAL KNEE FLEXION INTO BALANCE CORRECTIONS ELICITED BY MULTI-DIRECTIONAL PERTURBATIONS TO STANCE

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**Abstract—Positive effects on lateral center of mass (CoM) shifts during balance recovery have been seen with voluntarily unilateral arm raising but not with voluntarily bilateral knee flexion. To determine whether unilateral voluntary knee movements can be effectively incorporated into balance corrections we perturbed the balance of 30 young healthy subjects using multi-directional rotations of the support surface while they simultaneously executed unilateral knee flexion. Combined pitch and roll rotations (7.5° and 60°/s) were presented randomly in six different directions. Subjects were tested in four stance conditions: balance perturbation only (PO); cued flexion of one knee only (KO); combined support surface rotation and cued (at rotation onset) flexion of the uphill knee, contralateral to tilt (CONT), or of the downhill knee, ipsilateral to tilt (IPS). Outcome measures were CoM motion and biomechanical and electromyography (EMG) responses of the legs, arms and trunk. Predicted measures (PO+KO) were compared with combined measures (CONT or IPS). Unilateral knee flexion of the uphill knee (CONT) provided considerable benefit in balance recovery. Subjects rotated their pelvis more to the uphill side than predicted. Downhill knee bending (IPS) also had a positive effect on CoM motion because of a greater than predicted simultaneous lateral shift of the pelvis uphill. KO leg muscle activity showed anticipatory postural activity (APA) with similar profiles to early balance correcting responses. Onsets of muscle responses and knee velocities were earlier for PO, CONT, and IPS compared to KO conditions. EMG response amplitudes for CONT and IPS conditions were generally not different from the PO condition and therefore smaller than predicted. Later stabilizing responses at 400 ms had activation amplitudes generally equal to those predicted from the PO+KO conditions. Our results suggest that because EMG patterns of anticipatory postural activity of voluntary unilateral knee flexion and early balance corrections have similar profiles, the CNS is easily able to incorporate voluntary activation associated with unilateral knee flexion into automatic postural responses. Furthermore, the effect on movement strategies appears to be non-linear. These findings may have important implications for the rehabilitation of balance deficits.** 

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*Abbreviations:* AL, anterior lateral; ANOVA, analysis of variance; AP, anterior–posterior; APA, anticipatory postural adjustment; CoM, center of mass; CONT, contralateral to tilt; EMG, electromyography; Glut Med, gluteus medius; IPS, ipsilateral to tilt; IRED, infrared emitting diode; KO, knee only; KOC, knee only contralateral; KOI, knee only ipsilateral; Lat, medio-lateral; LPo, lateral posterior; Para, paraspinal; PO, perturbation only; PoL, posterior lateral; SEM, standard error of the mean.

**Key words: balance corrections, postural control, muscle responses, CNS motor programs.**

Adequate balance recovery plays a critical role in preventing falls (Maki et al., 2007). For rehabilitation focused on fall avoidance, it is important to know how involuntary or automatic movements of the extremities influence balance control and how additional voluntary movements of the arms and legs may aid balance corrections. Some insights may be obtained by initiating voluntary body motion during quiet stance and studying the subsequent influence on human postural stability. Several studies showed that early anticipatory postural adjustments (APAs) seen just prior to main voluntary contractions in the leg and arm muscles help to offset the destabilizing influence of later voluntary movements (Hughey and Fung, 2005; Nashner and Cordo, 1981; Pozzo et al., 2001). This approach, however, provides no direct information on the influence of APAs of voluntary movements on balance corrections. An approach that might provide this information would be to examine automatic balance corrections triggered by a perturbation to stance when these are supplemented with additional voluntary limb movements designed to enhance balance recovery. To achieve stability, the voluntary movements should presumably have similar metrics to those of automatic responses.

Compensatory arm movements have been shown to play a major role in balance recovery (Allum et al., 2002; Carpenter et al., 2004; McIlroy and Maki, 1995). Examples include grasping a handrail (McIlroy and Maki, 1995) to recover balance or breaking the fall by stretching out the arms in the direction of fall (Allum et al., 2002). It has been suggested that automatic arm responses aid center of mass (CoM) stabilization over the base of support (Küng et al., 2009a) and/or act as a protective "damping" mechanism in the event of an impending fall (Maki and McIlroy, 2006; Allum et al., 2002). The role of lower limb responses in balance recovery has also been investigated. The main focus was, however, on comparing in-place versus stepping reactions. Stepping reactions expand the base of support in the direction of falling. Thereby, the range of CoM displacement that can be accommodated without loss of stability is increased (Maki and McIlroy, 1997). It is an open question whether balance-correcting responses in the legs, which consist of flexing the uphill and extending the downhill knee (Allum et al., 2008; Küng et al., 2009a) can be enhanced using triggered voluntary movements.

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By comparing independent voluntary activation and automatic postural responses elicited during unexpected perturbations, insights into how the CNS integrates feedforward and feedback information into balance corrections can be obtained. Although they found a number of marked dissimilarities between voluntary and automatic postural responses, Nashner and Cordo (1981) also found similarities in response latencies when voluntary movements were well-practiced, executed in a predictable direction and performed under conditions of postural stability. These studies, however, were restricted to the sagittal plane. When laterally directed movements were studied, more dissimilarities were found between these two kinds of responses (Hughey and Fung, 2005). This effect appeared to be due to the different goals and biomechanical constraints of voluntary activation compared to automatic postural responses resulting from unexpected balance perturbations. For example, during voluntary leg lifts, co-contractions of hip muscles aid stiffening of the pelvis position and thereby reduce medial–lateral movements (Hughey and Fung, 2005). In contrast, the response to a lateral support-surface tilt is to roll the pelvis into the perturbation direction and the trunk in the opposite direction (Allum et al., 2008; Bakker et al., 2006). Thus a dissimilarity between laterally directed voluntary activation and balance control responses appears to be the amount of pelvis stabilization. If a voluntary leg movement is to aid balance control it would seem important that the voluntary movement and the automatic balance correction have a similar muscle response synergy and movement strategy.

Following this line of reasoning, a number of authors have developed the approach of examining whether voluntary movements can be integrated in balance corrections and thereby aid these corrections. Burleigh et al. (1994) showed that there is a similarity between the automatic postural responses to an external perturbation and APAs of voluntary movements. The main difficulty of integrating the latter into balance corrections is that the muscle forces of APAs and voluntary movements may, at the same time, provide sensory inputs that disturb the internal reference needed to plan balance corrections following perturbations to stance (Massion, 1992). An example of this occurs during integration of voluntary bilateral knee bending into the balance correcting strategy (Oude Nijhuis et al., 2007). For a forward tilt of the support surface, Oude Njihuis and colleagues (2007) found that bilateral voluntary knee flexion can be well integrated into the balance correction. But they also found strong support for the notion that the additional APAs created by voluntary movements can disrupt the balance correcting strategy (Oude Nijhuis et al., 2007) by opposing the attempt of the CNS to create oppositely directed limb movements during balance corrections (Hughey and Fung, 2005). The disruption Oude Nijhuis et al. (2007) noted during backward tilts resulted from the dissimilarity between the postural synergy initiating the balance correction and the APAs of bilateral voluntary knee flexion movements. Maintaining balance after a backward tilt of the surface required activation of anterior leg muscles whereas knee flexion is achieved primarily by activation of posterior leg muscles.

In contrast, the incorporation of voluntary activation into balance corrections worked well for voluntary uphill arm raising (Grin et al., 2007). Such voluntary action reduced the lateral downhill motion of the CoM. Given the finding that bilateral knee bending is not well integrated into balance corrections for backward tilts and has no additional stabilizing effect on lateral displacement of the CoM (Oude Nijhuis et al., 2007), the question arises whether voluntary *unilateral* knee bending would be better integrated into balance corrections, especially because uphill knee flexion is fundamental to stable balance during lateral tilts (Allum et al., 2008; Bakker et al., 2006; Küng et al., 2009a).

The purpose of the current study was to examine the interactions between balance corrections elicited by unexpected rotational perturbations of the support surface and synergies due to simultaneously executed voluntary unilateral knee flexion. The question arose how voluntary unilateral knee flexion synergies alter the inter-segmental shaping of automatic balance corrections. It could also be that flexing the downhill rather than the uphill knee might suppress the initial automatic postural responses and thereby also alter the pre-programmed balance correcting response synergy. We presumed that additional knee flexion of the uphill knee would reduce the lateral shift of the CoM and be well integrated into balance corrections but that flexion of the downhill knee would not. Thus an overall aim was to investigate whether the muscle synergies for voluntary knee movements and automatic balance corrections were similar in the leg muscles and whether these were well integrated when performed simultaneously. If voluntary unilateral knee movements improve stability, then this study would provide a basis for patients, with a tendency to fall, to learn an appropriate balance recovery strategy. In those with pathologically reduced knee flexibility, such as patients with cerebellar ataxia (Bakker et al., 2006) or vestibular loss (Allum et al., 2008), such a rehabilitation might prove particularly useful.

## EXPERIMENTAL PROCEDURES

### Subjects

Thirty healthy young subjects without neurologic or orthopedic deficits were recruited for this study (mean±SEM (standard error of the mean): age 25±0.8 years; height 176±1.6 cm; and weight 67±2.1 kg). All subjects gave witnessed, written informed consent to participate in the experiments according to the Declaration of Helsinki. The Institutional Ethical Review Board of the University Hospital of Basel approved the study.

### Protocol

Subjects stood on a servo-controlled platform that could tilt in the pitch and roll directions. The roll and the pitch axis of the platform had the same height equal to the average distance of the ankle joint to the soles of the feet. The subjects' feet were lightly strapped into heel guides fixed to the upper surface of the movable platform. The heel guides were adjusted to ensure that the ankle joint axes were aligned with the pitch axis of the platform and prevented stepping reactions when stance perturbations oc-