# ALTERATION IN COMMUNITY-DWELLING OLDER ADULTS' LEVEL WALKING FOLLOWING PERTURBATION TRAINING

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## Abstract

While perturbation training is promising in reducing fall-risk among older adults, its impact on altering their spontaneous gait pattern has not been investigated. The purpose of this study was to determine to what extent older adults' gait pattern would be affected by exposure to 24 repeated slips. Seventy-three community-dwelling older adults (age: 72.6 ± 5.4 years) underwent 24 repeated-slip exposure induced by unannounced unlocking and relocking of low-friction sections of a 7-m pathway upon which they walked. Full body kinematics and kinetics were recorded during the training. The gait parameters and the center of mass (COM) stability against backward balance loss were compared before and after the training. The results revealed that the training reduced fall incidence from 43.8% upon the novel slip to 0 at the end of training. After the training, subjects significantly improved gait stability by forward positioning of their COM relative to the base of support without altering gait speed. This forward COM shift resulted from a shortened step at the end of single stance and forward trunk leaning during double stance. They also adopted flat foot landing with knee flexed at touchdown (with an average change of 6.9 and 4.1 degrees, respectively). The perturbation training did alter community-dwelling older adults' spontaneous gait pattern. These changes enabled them to improve their volitional control of stability and their resistance to unpredictable and unpreventable slip-related postural disturbance.

## Keywords

stability; fall prevention; adaptation; slip; postural disturbance

## Introduction

Falls pose a significant health threat to elderly and a serious economic burden to the society (Baker and Harvey, 1985; Tinetti, 2003). Falls initiated by slipping account for about 25% of all falls among older people (Holbrook et al., 1984). Backward falls from a slip frequently cause hip fracture that can have devastating consequences (Kannus et al., 1999). Extensive efforts have been directed towards designing and implementing fall prevention programs (Hu and Woollacott, 1994; Rubenstein and Josephson, 2006; Wolf et al., 2003; York et al., 2011).

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None declared.

A newly-emerged paradigm relies on perturbation training to reduce fall-risk (Bhatt et al., 2012; Parijat and Lockhart, 2012; Shimada et al., 2004; Yang et al., 2013). This paradigm focuses on adaptation to perturbation rather than on self-motivated improvements of one's volitional performance. Such perturbation training can reduce fall incidence among older adults from 44% upon the first encounter of a novel slip to 0 upon the final slip during walking (Pai et al., 2010). It has been demonstrated that perturbation training has the potential to produce fall-reduction effects that are not only retainable but also generalizable outside of the training context (Bhatt and Pai, 2009; Parijat and Lockhart, 2012).

While the results from perturbation training are promising (Bhatt et al., 2006b; Parijat and Lockhart, 2012; Shimada et al., 2004; Yang et al., 2013; Yungher et al., 2012), the impact of the slip perturbation training on the temporal and spatial kinematics of regular gait has not been investigated. This is not a trivial issue. Perturbation training may not only improve older adults' reactive control of stability after perturbation onset during recovery, it can also affect the control of stability during volition movement, such as their gait pattern, in a proactive or feed-forward mode (Bhatt et al., 2006b; Marigold and Patla, 2002; Parijat and Lockhart, 2012; Yang et al., 2013). For instance, it was found that after the slip perturbation training, subjects would be able to proactively and reactively adjust their dynamic stability to enhance their resistance to slip-related falls by landing foot flat (Bhatt et al., 2006b; Cham and Redfern, 2002; Marigold and Patla, 2002), flexing knee (Cham and Redfern, 2002), and shortening step length (Bhatt et al., 2006b; Cham and Redfern, 2002) at touchdown upon repeated slips to improve their dynamic stability and hence reduce the incidences of falls. As the first line of defense, effective proactive adjustments in gait can reduce later need for and reliance on reactive correction during an unpredictable and unpreventable event of a slip in everyday living.

What is gait stability and how is it measured? It is defined here as the ability to restore or maintain a person's center of mass (COM) balance in upright posture without resorting to the alteration of the existing base of support (BOS). A step taken by this person is the most common form of such alteration. Unlike the classic definition of the stability (Borelli, 1680), which is only applicable in quiet (quasi-static) standing, the *generalized* conceptual framework characterizes the stability in terms of the motion state (i.e. the position and velocity) that relates the body COM to its BOS (Pai et al., 1994). Mathematical modeling and simulations have been applied to estimate the feasible stability region (FSR) in this COM-BOS-state space (Fig. 1) (Pai and Patton, 1997; Yang et al., 2007), and the results can be distinctively different from those of the static concept (Pai et al., 1998).

Based on this generalized concept, the regular walking consists of alteration of stability recovery (i.e., the state trajectory is either moving towards or staying inside the FSR as the thin dotted line depicted in Fig. 1) followed by an instable period (i.e., it is moving outside and away from the FSR as depicted by the thin dashed line). While the latter is essential to achieve the desired forward mobility, without the former action a person would have fallen onto the ground (Pai, 2003). In forward progression, however, such motion trajectory is clearly *not* intended to ever become backward instability (as allowing one's own motion trajectory to fall inside backward balance loss region in Fig. 1).

The stability is hence measured by the shortest distance from the COM motion state to the boundary of the FSR (Yang et al., 2008a; Yang et al., 2008b), which has two: The limits of stability (LOS) against backward balance loss (the thick solid line in Fig. 1) and those against forward balance loss (the thick dashed line). From this perspective, when a COM motion state lies within the FSR, this person is *not obligated* to alter the existing BOS (Pai, 2003). Nonetheless, a motion state falling outside the posterior LOS (i.e., it would be a negative measurement in Fig. 1) brings instability that a backward step becomes a *necessity*

due to insufficient forward momentum to carry the COM forward to the BOS. Conversely, as the motion state is more forward than the anterior LOS (i.e. a more positive measurement greater than 1 in Fig. 1), a forward step becomes *inevitable* due to the excessive forward momentum (Pai, 2003), even when the COM is still within the BOS (as during the midstance, x = 0.5 in Fig. 1). Based on this generalized conceptual framework (Pai et al., 1994), it is still unclear how slip perturbation training would alter older adults' (unperturbed) step behavior and motion state, more specifically, their control of stability.

The purpose of this study was therefore to determine to what extent older adults' gait pattern would be affected by exposure to 24 repeated slips. We hypothesized that repeated slips would reduce older adults' step length and increase their cadence without altering their gait speed after the training that would improve their stability against any future threats of such postural disturbance.

## Methods

### 2.1 Subjects

One-hundred-thirty-three community-dwelling older adults ( 65 years) were initially recruited. After giving their written informed consent, they were screened for selected drug usage that may alter one's control of stability (e.g. tranquilizers). As safety precautions, older adults who may be at a great risk of fracture during training (based on calcaneal ultrasound body mineral density scan T score < −1.5 (Thompson et al., 1998)), who may have difficulty to follow instructions (the Folstein Mini Mental Status Exam score < 25 (Folstein et al., 1975)), or who may not be able to complete the protocol due to poor mobility (> 13.5 seconds on the Timed-Up-and-Go test (Podsiadlo and Richardson, 1991)) were excluded from the study. Finally, a total of 73 community-dwelling older adults (46 female) were paid to participate in the institutionally approved study. The mean ± SD age, body mass, and body height were 72.6 ± 5.4 years (range: 65 – 90), 75.3 ± 12.9 kg, and 1.67 ± 0.09 m.

### 2.2 Experimental setup and protocol

The details of the perturbation training could be found somewhere else (Bhatt et al., 2006b). Briefly, the perturbation training consisted of 24 repeated slips mixed with 13 nonslip trials in a block-and-random design. The unannounced slips were induced through electronic-mechanical unlocking of a sliding device embedded in a 7-m pathway. The device consisted of two low-friction, movable platforms capable of sliding for 90 cm on the right and 75 cm on the left. Each platform was mounted on a frame supported by two force plates (AMTI, Watertown, MA) to record the ground reaction force in order to trigger the release of the moveable platform and to identify the touchdown or liftoff in analysis (Yang and Pai, 2007). A harness connected with a load cell was employed to protect the subjects while imposing negligible constraint to their movements (Yang and Pai, 2011). The force recorded from the load cell was used to determine whether a fall occurs (Yang and Pai, 2011).

Subjects were informed that they would be performing normal walking initially and would experience simulated slip later without knowing when, where, and how that would happen. They were only told to walk in any manner and at any speed they preferred, and to recover their balance on any slip incidence and then to continue walking. Each subject first underwent approximately 10 walking trials (unperturbed) before the perturbation training protocol as well as four post-training trials. The trial immediately prior to the first slip and the third trial after the last slip trial of the training were selected to represent the pre- and post-training spontaneous walk in order to examine the effect of the perturbation training on a person's gait pattern. Full body kinematics data from 28 retro-reflective markers placed on

the subjects' body and platforms were gathered using an 8-camera motion capture system (MAC, Santa Rosa, CA) synchronized with the force plates and load cell.

### 2.3 Data reduction

The timing for two events in each gait cycle, touchdown (TD) and liftoff (LO), was identified from the vertical component of ground reaction force. Temporal measures included the double (from TD to following LO at the contralateral limb) and single (from LO to the following TD at the ipsilateral foot) stance phase times. The cadence was determined as the reciprocal of the duration from TD to the following TD at the contralateral limb and expressed over 1 minute.

Marker paths were low-pass filtered at marker-specific cut-off frequencies (ranging from 4.5 to 9 Hz) using fourth-order, zero-lag Butterworth filters (Winter, 2005). Locations of joint centers, heels, and toes were computed from the filtered marker positions. Spatial measurements included the step length, and the angles of trunk, knee, as well as foot. The step length was calculated as the anteroposterior distance between the right and left heel markers at TD. Trunk angle was calculated between the trunk segment and a vertical axis. Positive trunk angle represents that the trunk leans backward against the vertical line. Knee joint angle was the one formed by thigh segment and the extension line of leg segment with flexion as positive. Foot angle was the angle between the sole and ground where a flat foot corresponded to zero degrees with toe up as positive. Both knee and foot angles were calculated for the leading leg.

The body COM kinematics was computed using gender-dependent segmental inertial parameters (de Leva, 1996). The two components of the COM motion state, i.e. its position and velocity were calculated relative to the rear of base of support (BOS) (i.e. the right heel) and normalized by foot length ($l_{\mathrm{BOS}}$) and $\sqrt{g \times bh}$, respectively, where $g$ is the gravitational acceleration and $bh$ the body height. As aforementioned, the stability was calculated as the shortest distance from the COM motion state to the LOS against backward balance loss (solid thick line in Fig. 1).

All the spatial parameters including the COM stability were computed at both touchdown and liftoff. Finally, the overall effect of the training was also briefly assessed in terms of number of subjects who fell on the first and the last slip trial during the training. A *fall* was identified when the peak load cell force during slip exceeded 30% body weight (Yang and Pai, 2011).

### 2.4 Statistical analysis

Paired *t*-tests were applied to compare the durations of single- and double-stance phases and all other variables (the cadence, the step length, the foot angle, knee angle, and trunk angle) at both touchdown and liftoff between pre- and post-training trials (pre vs. post) to examine whether and to what extend the perturbation training affected them. The difference in incidence of falls was evaluated by McNemar's test. All statistics were performed using SPSS 19.0, and a significance level of 0.05 was used.

## Results

The training significantly reduced the incidence of falls to 0% upon the final (24th) slip down from 43.8% ($\chi^2 = 40.98$, $p < 0.001$) upon the novel slip, which was the first exposure to the slip prior to the following repeated slips. It also produced measureable effects on temporal and spatial aspects of post-training gait pattern. In the post-training gait, they spent about the same amount of time during the double stance ($t(72) = -1.33$, $p = 0.187$, Fig. 2)

but less time during single stance than they did in the pre-training gait ($t(72) = 5.99$, $p < 0.001$, Fig. 2). They had significantly shorter step duration (0.58 *vs.* 0.63 seconds, $t(72) = 3.88$, $p < 0.001$), and faster cadence after the training than they did before the training ($t(72) = -4.55$, $p < 0.001$, Fig. 3).

Training did not alter these subjects' COM velocity ($t(72) = -0.66$, $p = 0.509$ for TD and $t(72) = -1.25$, $p = 0.215$ for LO, Fig. 4-b). Nevertheless, they were able to significantly improve their COM stability against backward balance loss both at the beginning and at the end of the single stance phase ($t(72) = -5.65$, $p < 0.001$ for TD and $t(72) = -7.72$, $p < 0.001$ for LO,, Fig. 4-c). The older adults anteriorly positioned their COM relative to the BOS at both events ($t(72) = -5.02$, $p < 0.001$ for TD, and $t(72) = -6.16$, $p < 0.001$ for LO, Fig. 4-a). Shortened step at the end of the single stance phase ($t(72) = 4.68$, $p < 0.001$, Fig. 3-a) and increased forward leaning their trunk at both events ($t(72) = 2.15$, $p = 0.035$ for TD, and $t(72) = 4.27$, $p < 0.001$ for LO, Fig. 5-a) both contributed to forward shift of the COM position. Finally, subjects adopted a significantly more flatfooted landing pattern ($t(72) = 6.38$, $p < 0.001$ for TD, and $t(72) = 3.39$, p = 0.001 for LO, Fig. 5-c) with a more flexed knee ($t(72) = -3.55$, $p = 0.001$, Fig. 5-b) at touchdown after the training than they did beforehand at the baseline.

## Discussion

The overall results indicated that repeated-slip exposure did alter community-dwelling older adults' gait pattern to improve their posterior stability against postural disturbance threats during walking. In theory, their COM stability can be improved by the options of an increase in the COM velocity and/or by an anterior shift of the COM position relative to the BOS (Pai and Patton, 1997). Apparently, these older adults adopted the latter but not the former. They preferred to reduce step length and increase their cadence by reducing their single stance time without altering their gait speed.

The modification in these subjects' COM position was achieved not only by shortening step length at the end of the single stance phase but also by increasing forward trunk leaning during double stance (Bhatt et al., 2005; Espy et al., 2010). Forward trunk lean could further shift the COM forward whereby the HAT (head, arm, and trunk) segment represents about two thirds of the total body mass (Prince et al., 1997). Clearly, the shortening of step length led to a reduction in the duration of the single stance phase, while forward trunk leaning did not require the shortening of double stance phase. Normally, the increase in cadence from reduced step time could lead to an increase in gait speed in terms of the positive relationship between gait speed and cadence (Latt et al., 2008). In this case, such a tendency was offset by the reduction in step length.

These findings were consistent with previous findings that repeated-slip exposure enabled young adults to proactively improve their stability before slip occurrence (Bhatt et al., 2006b; Pai and Bhatt, 2007). Subjects may adopt a more "cautious gait" with shorter step (Giladi et al., 2005). The shortened step length found in the present study also agrees with the previously reported relationship between step length and slip risk among both young (Cham and Redfern, 2002; Lockhart et al., 2003; McVay and Redfern, 1994; Moyer et al., 2006) and older adults (Lockhart et al., 2003). A long step could increase its severity in case of a slip, because it would require a forceful push off from the trailing limb during double stance phase that in turn would exacerbate the initiation of slip. A long step could also increase the ratio of required shear to normal force at touchdown and hence increase the demand on floor friction at a time when it is being abruptly reduced in a slip (Cham and Redfern, 2002; Gronqvist et al., 2001). To reduce the slip severity and ensure a successful

recovery from a slip, older adults in post-training gait adaptively took shorter step in comparison to their pre-training gait.

A flatfoot and flexed knee landing (with an average change of 6.9 and 4.1 degrees, respectively Fig. 4-b & c) may also reduce the demand on friction from the ground reaction force (Cham and Redfern, 2002). Such technique was thought to be another contributor to a reduced slip velocity, i.e., its severity (Cham and Redfern, 2002). This may be related to a number of reasons. Firstly, the reduced foot angle reduces one's reliance on floor friction for braking forward momentum when the slip occurs, thereby reducing the peak slip velocity the subject experiences during the slip (Bhatt et al., 2006b; Chambers and Cham, 2007). The increase of knee flexion, on the other hand, could increase the damping of the shock after initial foot contact with the floor and therefore reduce the demand on friction.

An age-related speed reduction in gait has been believed to improve safety and stability (Imms and Edholm, 1997). It was also reported that many older adults tend to walk slower after fall incidences (Guimaraes and Isaacs, 1980). Such intuition may not be applicable nor a sound strategy when facing slip-related postural disturbance as demonstrated in the present study. After these older adults learned how to successfully reduce their fall incidence from 44% to 0% in the present study, they did not walk slower as would have been predicted based on the common believe. Rather, they preferred to maintain the same gait speed that was natural to them after their successful adapted to such postural threats. This supported the previous findings that slower walking speeds in fact can be more instable in the event of a slip that could predispose a person to an increased risk of backward balance loss (Bhatt et al., 2005; Espy et al., 2010).

It has been proposed that increased knee flexion and flexor moments are important to the control of the slip velocity and to reduction of falls (Cham and Redfern, 2001; Yang and Pai, 2010). The corrective flexion movements produced by the knee allow subjects to rotate the leg forward and in an attempt to bring the BOS back near the COM (Cham and Redfern, 2001; Yang and Pai, 2010). In addition to the proposed reduction on the demand on floor friction, the flexed knee posture that these older adults adopted could also have the advantage of reducing slip intensity should that occur.

We still do not know whether or to what degree the gait patterns observed in the laboratory are carried over to these older adults' everyday living. We anticipate, however, at the very least they would still retain some of the training effects at home. Such believe is based on the results from systematic studies pertaining to the generalization of the training effect across different limbs (Bhatt and Pai, 2008), between tasks (Wang et al., 2011), outside the environments (Bhatt and Pai, 2009), and even across opposite types of perturbation (Bhatt et al., 2013). Such cumulating evidence indicates that the training-induced adaptive effects do not occur by chance, and are not likely to disappear soon after (Bhatt et al., 2006a; Bhatt et al., 2012).

In conclusion, a single session of perturbation training could alter community-dwelling older adults' spontaneous gait pattern. The changes in the gait pattern enabled them to improve their volitional control of stability and thus improve their resistance to unpredictable and unpreventable slip-related postural disturbance. The findings of the present study could also provide some guidance for the development of clinical gait training paradigm to prevent falls from happening among older adults. While it is remarkable that these significant changes all resulted so rapidly, future studies still need to investigate the degree such changes can be retained among this aging but likely active population.

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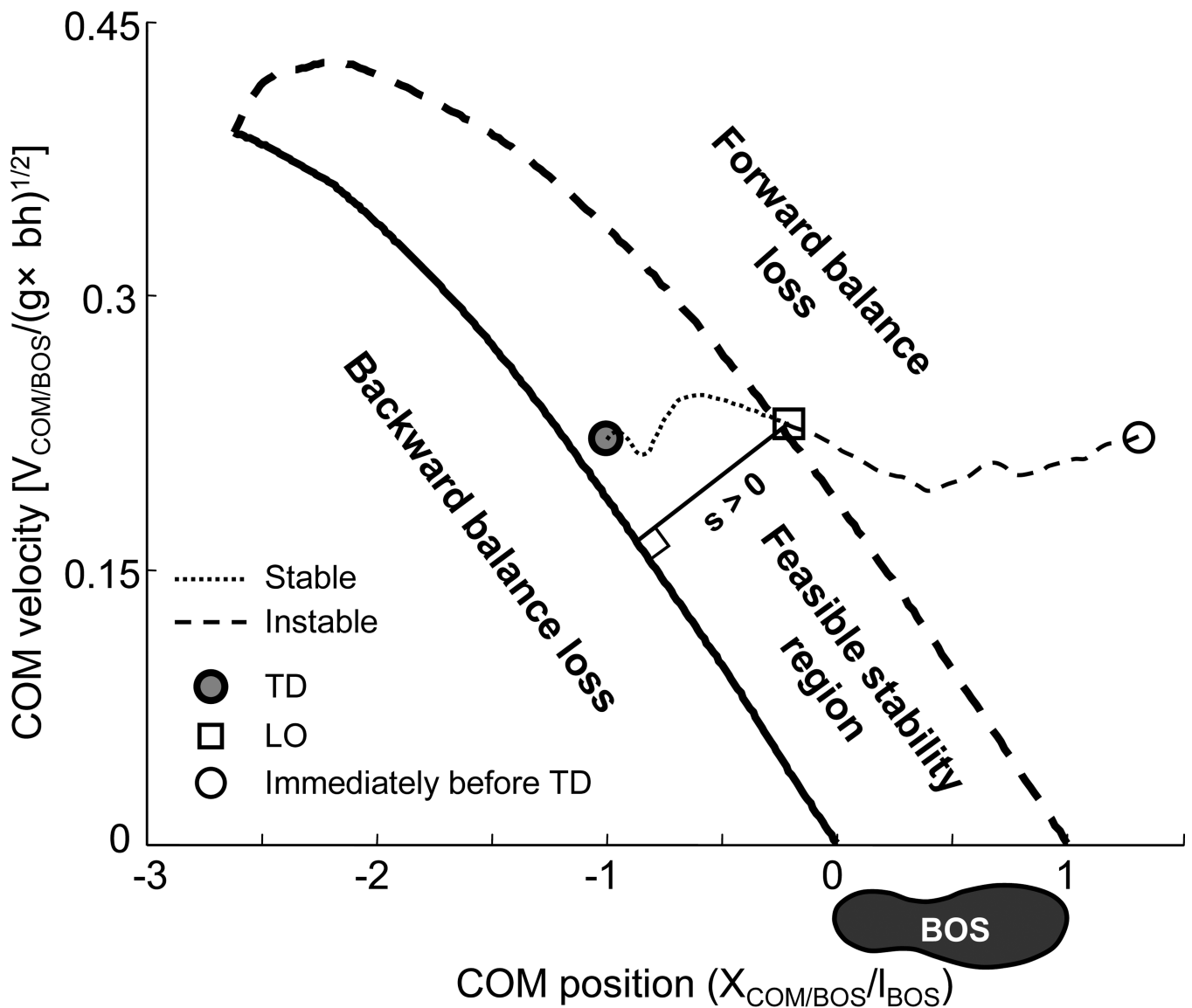
**Fig. 1.**
Schematic illustration of the feasible stability region (FSR), which is enclosed by two boundaries: the limits of stability (LOS) against backward balance loss (the thick solid line) and those against forward balance loss (the thick dashed line). The stability measurement (*s*, the length of the thin solid line) indicates the magnitude of the instantaneous stability of the center of mass (COM) against backward balance loss, and is defined as the shortest distance from the instantaneous COM motion state (i.e., the x-coordinates represents the COM anteroposterior position and the positive y-coordinates indicates its forward velocity) to the corresponding LOS. The regular walking consists of alteration of stability recovery (i.e., the motion state trajectory is either moving towards or staying inside the FSR as the thin dotted line) followed by an instable period (i.e., it is moving outside and away from the FSR as depicted by the thin dashed line) progressing from the touchdown (TD, thick filled circle), through the *contralateral* foot liftoff (LO, thin square), and immediately prior to the *contralateral* foot TD (thin circle). Position and velocity of the COM relative to the base of support (BOS) are dimensionless as a fraction of $l_{BOS}$ and $\sqrt{g \times bh}$, respectively, where $l_{BOS}$ represents the foot length, *g* is gravitational acceleration, and *bh* the body height.

Please note, a single foot was used as the BOS in the stability calculation for the illustration purpose of keeping the COM motion state trajectory continuous during each step cycle.
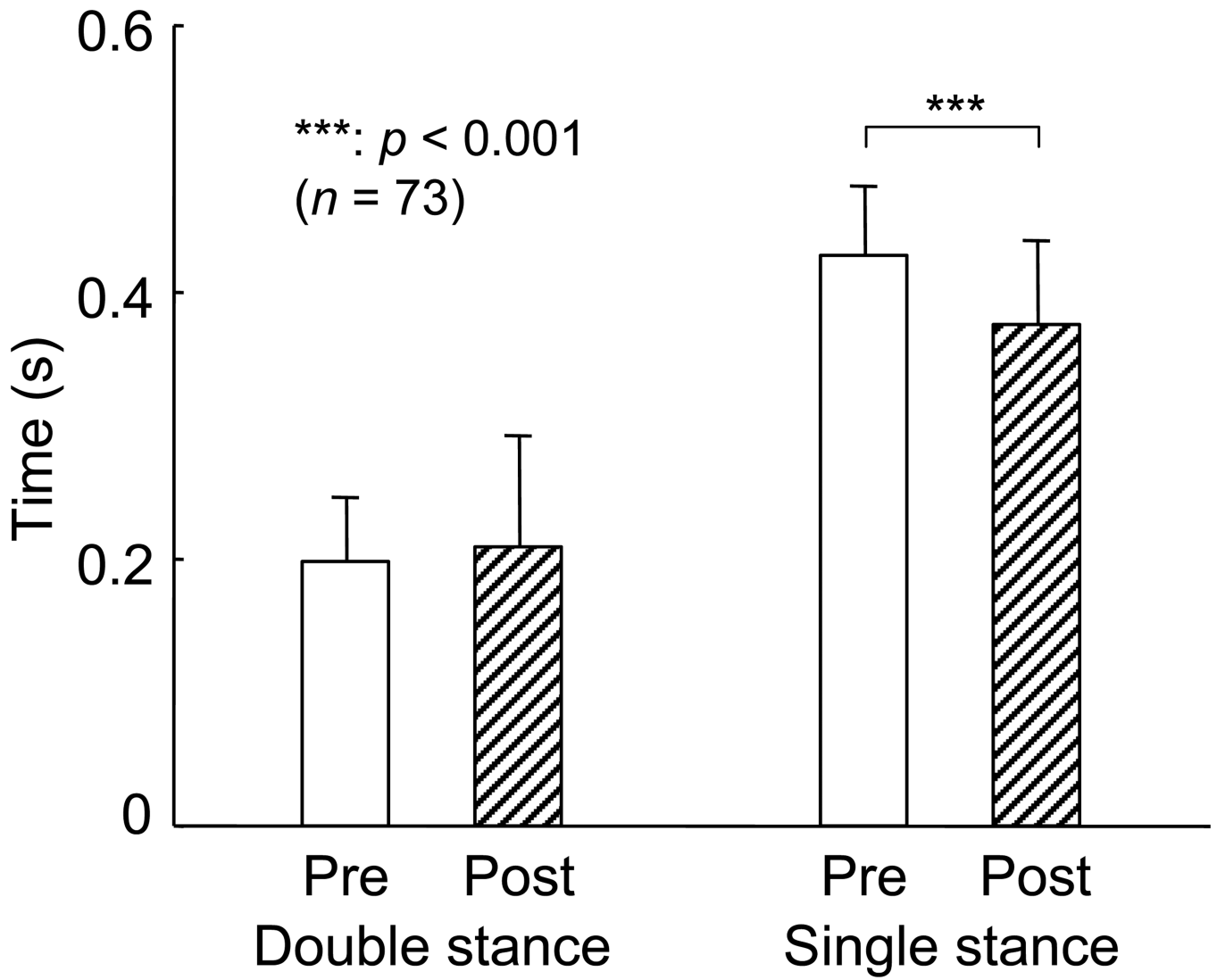
**Fig. 2.**
Group mean (column height) and standard deviation (bar) of the elapsed time in seconds of double and single stance phase during pre- and post-training unperturbed gait among 73 older adults.
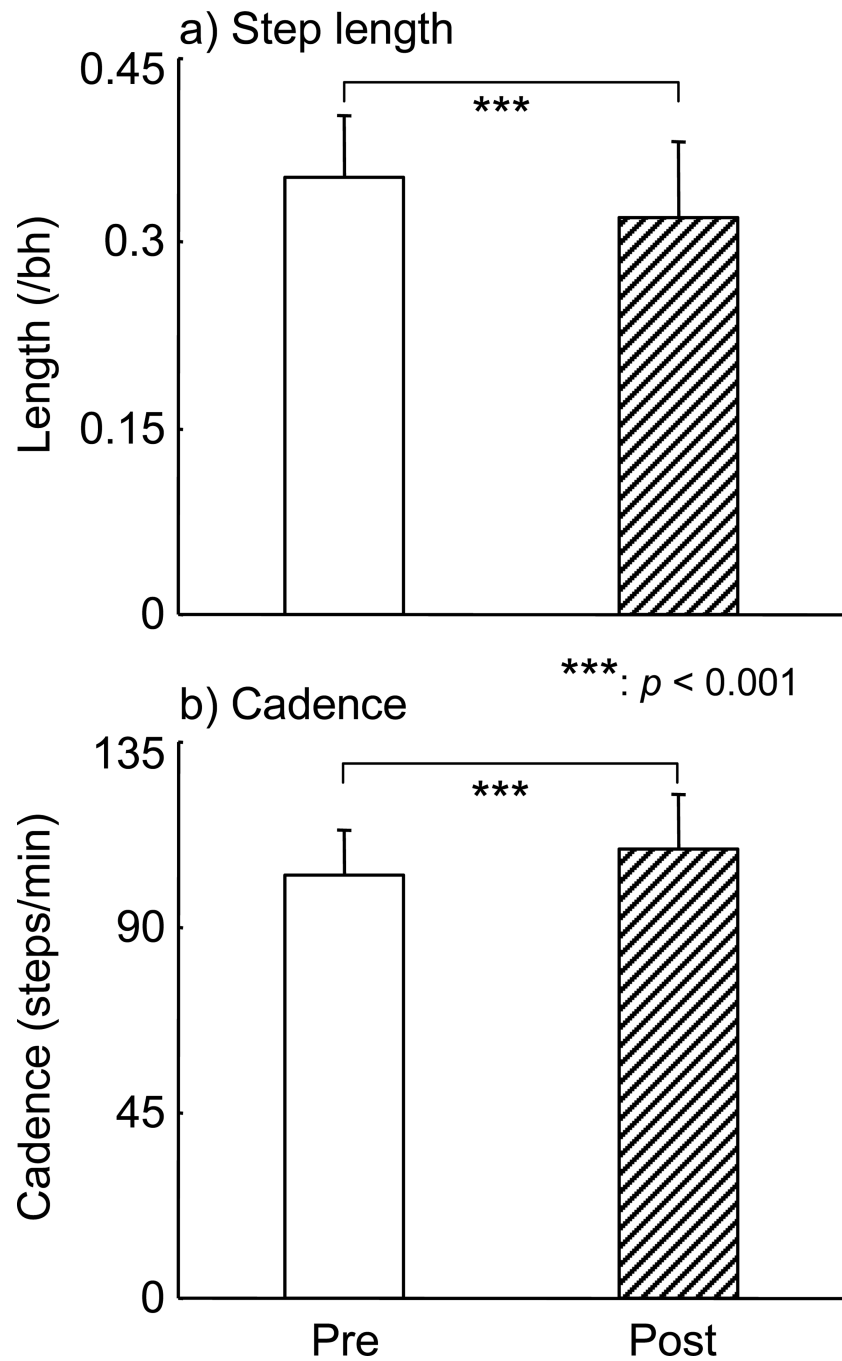
**Fig. 3.**
Comparison of (a) step length and (b) cadence between pre- and post-training gait for 73 older adults. The step length was calculated from the farthest distance of the left-to-right heel (*i.e.*, between their most posterior positions) during stance phase and normalized to the body height (*bh*). The cadence was determined as the reciprocal of the duration from TD to the following TD at the contralateral limb and expressed over 1 minute.
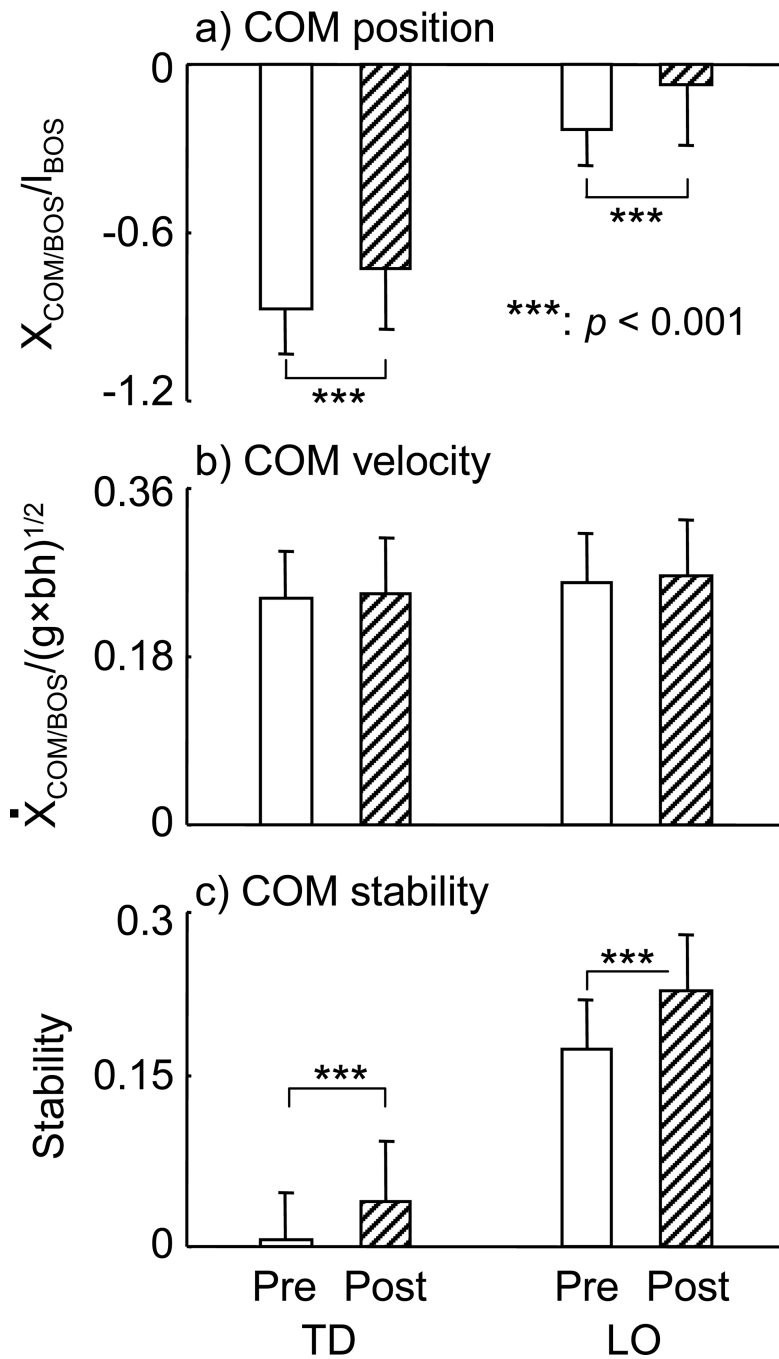
**Fig. 4.**
Comparisons of a) the center of mass (COM) position, b) COM velocity, and c) COM stability between pre- and post-training gait for 73 older adults. Both the COM position and velocity were relative to the rear edge of the base of support (BOS) and respectively normalized by foot length ($l_{BOS}$) and $\sqrt{g \times bh}$, where $g$ represents the gravitational acceleration and $bh$ the body height. Stability was calculated as the shortest distance from the given COM motion state (i.e. its position and velocity) and the computer-predicted boundary against backward balance loss under slip conditions.
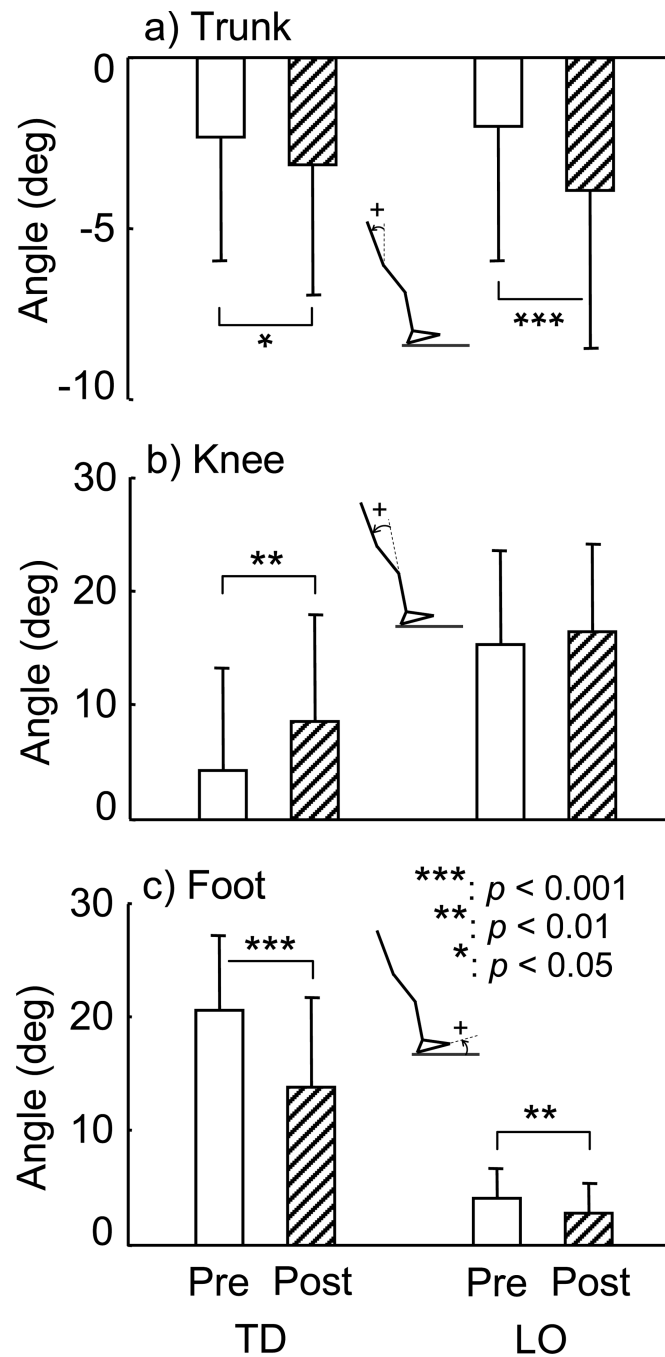
**Fig. 5.**
Comparisons of a) the trunk angle, b) knee angle, and c) foot angle at two essential gait characteristic events (touchdown or TD and liftoff or LO) between pre- and post-training gait. Trunk angle was calculated between the trunk segment and a vertical axis. Positive trunk angle represents that the trunk leans backward against the vertical line. Knee joint angle was the one formed by thigh segment and the extension line of leg segment with flexion as positive. Foot angle was the angle between the sole and ground where a flat foot corresponded to zero degrees with toe up as positive. The knee and foot angles are calculated for the leading leg.