Effect of body configuration at step contact on balance recovery from sideways perturbations

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A B S T R A C T

Compensatory stepping is an important protective mechanism to prevent falling. To recover from sideways perturbations side steps are generally more advantageous than cross-over steps. However, there is lack of understanding of the characteristics of compensatory side steps following sideways perturbations that separate successful recoveries (i.e., no falls) from falls, the most clinically relevant outcome following a balance perturbation. We aimed to identify the critical determinants for successful side stepping after large sideways balance perturbations. Twelve healthy young adults were subjected to large leftward perturbations at varying intensities on a translating sheet. For recovery attempts started with a side step, we determined body configuration variables (frontal-plane leg and trunk angle) at first step contact, as well as spatiotemporal step variables (onset, length, duration, velocity). A logistic regression analysis was conducted to determine the predictive ability of body configuration and spatiotemporal variables on the probability of success (no fall vs. fall); perturbation intensity (peak jerk of translating sheet) and a random effect for individual were also included in the model. In the final model, leg angle and peak jerk were retained as predictors of successful balance recovery and these variables correctly classified the recovery outcome in 86% of the trials. This final 'body configuration' model yielded a −2 log likelihood of −36.3, whereas the best fitting model with only spatiotemporal variables yielded a −2 log likelihood of −45.8 (indicating a poorer fit). The leg angle at a given perturbation intensity appears to be a valid measure of reactive side step quality. The relative ease of measuring this leg angle at step contact makes it a candidate outcome for reactive stepping assessments in clinical practice.

1. Introduction

Falls and their physical and psychosocial consequences are a major health problem in the aging population. Compensatory stepping is an important protective mechanism to prevent falling in daily life. More insight into the critical determinants for successful stepping responses may help identify people at risk of falling and develop targeted interventions to prevent falls.

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Stepping responses following sideways perturbations are of particular interest, because sideways falls increase the odds of hip fractures by at least threefold compared to forward or backward falls (Hayes et al., 1993; Nevitt & Cummings, 1993). To recover from sideways perturbations, individuals generally choose between side stepping or cross-over stepping (Maki, Edmondstone, & McIlroy, 2000). During a cross-over step, the limb unloaded by the perturbation passes the other foot on either the anterior or posterior side. This strategy, however, allows for a rather limited extension of the base of support into the direction of the perturbation, thus also limiting its effectiveness for arresting the impending fall. Indeed, in a group of people with Parkinson's Disease, cross-over steps resulted in a fall more frequently than did side steps (King & Horak, 2008). Furthermore, a cross-over step also carries the risk of limb collisions, which is particularly evident in the elderly (Mille et al., 2013; Mille, Johnson, Martinez, & Rogers, 2005). Side stepping is therefore regarded a more advantageous strategy for recovering from large sideways perturbations, but its execution is complicated by the fact that the limb that is initially loaded by the perturbation needs to be quickly and actively unloaded to allow taking a step. Indeed, it appears that people have difficulties employing this strategy at perturbation intensities large enough to induce real falls, despite its greater effectiveness in arresting the impending fall (Feldman & Robinovitch, 2007).

For expressing the quality of stepping responses following sideways perturbations, previous studies have mainly used spatio-temporal variables (Hilliard et al., 2008; King & Horak, 2008). Step length appears to be an important determinant of successful balance recovery, as older fallers took a shorter step than non-fallers to recover from sideways perturbations (Hilliard et al., 2008). Such variables, however, do not take into account the position and/or velocity of the center of mass (COM) relative to the base of support at the time of step contact. Various methods have been developed that include approximations of COM position/velocity for assessing the quality of balance correcting steps in the anteroposterior direction (Hof, Gazendam, & Sinke, 2005; Honeycutt, Nevisipour, & Grabiner, 2016; Vallee, Tisserand, & Robert, 2015; Yang, Anderson, & Pai, 2008). These methods have been successful in distinguishing between single and multiple stepping responses (Carty, Cronin, Lichtwark, Mills, & Barrett, 2012b; Maki & McIlroy, 1999) and in identifying individuals with a higher risk of falling (Salot, Patel, & Bhatt, 2016). In addition, in our study in healthy young participants, we found that a simple biomechanical model describing body configuration at step contact (Hsiao & Robinovitch, 2001) accurately discriminated between successful balance recovery and true falls following backward perturbations (Weerdesteyn, Laing, & Robinovitch, 2012). The angle of the stepping leg (relative to the vertical) together with the trunk inclination angle at step contact (both including an approximation of the COM position) had significantly greater discriminative ability than any combination of spatiotemporal step variables (Weerdesteyn et al., 2012). However, similar studies have not yet been conducted for step recoveries from sideways perturbations.

In this study, we conducted a secondary analysis on a data set that was originally collected for investigating the effects of compensatory stepping strategies on hip impact velocity and orientation during falls following sideways balance perturbations. The key strength of this study was that it involved healthy young adults responding to highly destabilizing lateral support-surface translations that required at least two steps for successful balance recovery. The participants failed to recover from these perturbations in more than 50% of the trials, thus allowing us to determine characteristics of compensatory steps that separated successful recoveries (i.e., no falls) from actual falls. As side stepping is generally accepted to be the most effective strategy (cf. cross stepping), we aimed to identify the determinants of successful side steps for balance recovery. Our hypothesis was that the quality of the first corrective side step would be a strong predictor of recovery success, similar to our previous observations for backward perturbations (Hsiao & Robinovitch, 2001; Weerdesteyn et al., 2012). In particular, we expected that a model with body configuration variables would better fit the observed recovery outcomes compared to a model with traditional spatiotemporal step variables.

2. Methods

2.1. Participants

Twelve healthy young adults (28.6 ± 9.3 years; 10 males) participated in this study. Written informed consent was obtained from all participants. The protocol was approved by the Research Ethics Board of Simon Fraser University.

2.2. Experimental setup and protocol

Participants stood barefoot in semi tandem stance with the left foot in front and with the left arm lifted forward (average AP and ML distances between left and right mid-foot positions were 426 and 147 mm, respectively). They stood on top of a rubber sheet (LxW = 990 × 890 mm) overlying a firm gymnasium mattress. The rubber sheet could be translated horizontally by means of a linear motor (T4D, Trilogy System Corporation, Webster, TX, USA). The sheet always translated to the participant's right, inducing a leftward loss of balance (Fig. 1).

After familiarization with the experimental setup, participants were subjected to 33 balance perturbations at varying intensities (with peak horizontal velocities of the rubber sheet of 1.6–3.4 m/s, peak accelerations of 12.7–28.9 m/s^2, and peak jerks of 200–473 m/s^3), in random order. The total displacement of the sheet was 1.20 m for all perturbation intensities. The instant of perturbation onset was unknown to the participants. Participants were instructed to do their very best to prevent themselves from falling. A fall was defined as the pelvis coming to rest on the gymnasium mattress. For each trial, the outcome of the recovery attempt was classified as successful (no fall) or fall.

Full-body kinematics (Helen Hayes marker set (Davis, Ounpuu, Tyburski, & Gage, 1991)) were recorded at 200 Hz with an 8-camera 3D motion analysis system (Motion Analysis Inc., Santa Rosa, CA). Four additional markers were placed on the translating rubber sheet.
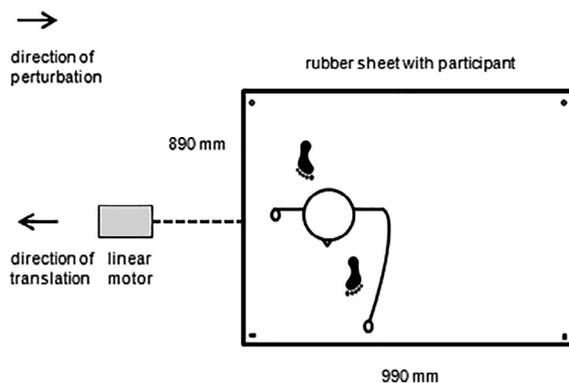
Fig. 1. Schematic (top view) of experimental setup.

2.3. Data analysis

Marker position data were filtered with a second order, low-pass (6 Hz), zero-lag Butterworth filter. Stepping strategy (i.e., side step or no side step) was visually determined for each trial. The start of the perturbation was determined from the velocity profiles of the markers on the rubber sheet. The body configuration (i.e., trunk inclination angle and leg angle) was determined at first step contact (mediolateral velocity of 2nd metatarsal or calcaneus marker < 0.4 m/s). The trunk inclination angle was calculated as the angle in the frontal plane between the vertical and the line connecting mid-shoulder to mid-pelvis. The leg angle was defined as the angle between the vertical and the line connecting mid-pelvis to the 2nd metatarsal of the (first) stepping foot. A leftward tilted trunk and a foot position leftward to mid-pelvis were represented by positive angles (Fig. 2).

As spatiotemporal variables, we determined step onset (mediolateral velocity of the 2nd metatarsal or calcaneus marker > 0.4 m/s), step length (mediolateral displacement between step onset and step contact of the 2nd metatarsal marker of the stepping foot relative to the rubber sheet), step duration, and step velocity (length/duration). In addition, peak velocity, peak acceleration, and peak jerk of the sheet were calculated from marker data as measures of perturbation intensity.

All outcome measures were calculated with a custom-written Matlab Program (Matlab R2011a).

2.4. Statistical analysis

Our analyses were focused on the side steps. We compared body configuration and spatiotemporal variables between successful recoveries, failed recoveries with more than one step, and failed recoveries with one step, using a one-way analysis of variance
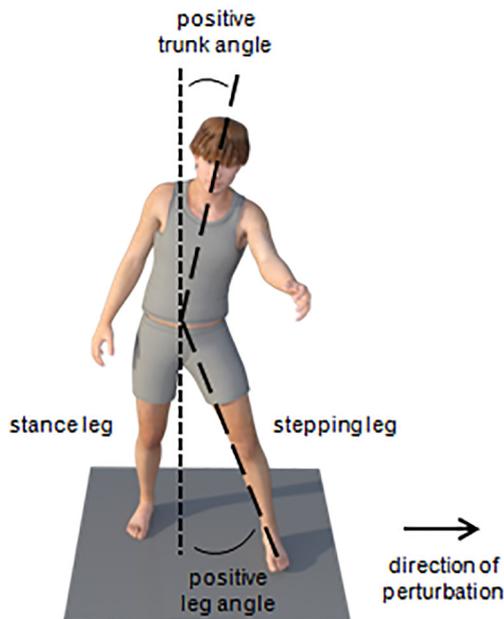

Fig. 2. Definitions of positive leg and trunk inclination angles.

Table 1

Mean and standard deviations for each of the predictors sorted by outcome of the recovery attempt.

	Outcome of recovery attempt		
	Successful recovery (n = 42)	Failed recovery with more than one step (n = 52)	Failed recovery with one step (n = 34)
Peak jerk (m/s^3)	294 (72)[a,b]	385 (62) [a]	362 (66)[b]
Leg angle (degrees)	3.0 (8.3)[a,b]	−7.9 (7.1)[a,c]	−24.0 (12.2)[b,c]
Trunk angle (degrees)	17.5 (6.9)[a]	23.8 (8.0)[a]	21.4 (11.5)
Step onset (s)	0.16 (0.04)[a]	0.14 (0.03)[a,c]	0.16 (0.05)[c]
Step length (cm)	65 (14)[b]	58 (15)[c]	46 (14)[b,c]
Step duration (s)	0.27 (0.03)	0.26 (0.03)	0.26 (0.04)
Step velocity (cm/s)	235 (35)[b]	218 (38)[c]	174 (37)[b,c]

[a] Significant difference between 'successful recovery' and 'failed recovery with more than one step' ($p < 0.01$).

[b] Significant difference between 'successful recovery' and 'failed recovery with one step' ($p < 0.01$).

[c] Significant difference between 'failed recovery with more than one step' and 'failed recovery with one step' ($p < 0.01$).

(ANOVA). Post-hoc tests were performed using Bonferroni corrections. To determine the predictive ability of all side step variables (leg angle, trunk angle, step onset, step length, step duration, step velocity) for recovery outcome (no fall vs. fall), a backward logistic regression analysis was conducted. Peak jerk was also included as an independent variable for perturbation intensity and was selected over peak velocity and peak acceleration because it yielded a greater Nagelkerke R^2 for recovery outcome. Model selection was based on $p < 0.05$ for entry and $p > 0.10$ for removal. Because individuals contributed repeated measures (i.e., trials) to the model, a random effect for individual was added. We also determined the best model fit (in terms of -2 log likelihood) when only body configuration variables (i.e., leg angle and trunk angle) and when only spatiotemporal step variables (i.e., onset, length, duration and velocity) were included. Furthermore, Pearson correlation coefficients were calculated between body configuration and spatiotemporal variables. Statistical analyses were performed in SPSS (version 20.0) and RStudio (version 1.0.136). P < 0.05 was considered statistically significant.

3. Results

Thirteen of the 396 trials were omitted from the analyses due to problems with data recording (9 trials) or an inability to determine stepping strategy (2 trials) or recovery outcome (2 trials) from the 3D motion data. Of the remaining 383 trials, participants used a side-stepping strategy in 205 trials. Seventy-six of the 205 side-step trials were excluded from further analysis, because the participant stepped outside of the translating sheet on the stationary mat (which, thus, helped them recover balance; 47 trials); the pelvis rotation at the moment of perturbation onset was larger than 45 degrees (i.e., perturbation direction is more forward or backward instead of sideward; 16 trials); essential marker data were missing at first step contact (12 trials) or at perturbation onset (1 trial). Participants successfully recovered balance in 42 of the 129 included trials (on average 33%, varying from 0 to 67% between individuals). To successfully recover balance, participants always needed at least two steps.

Table 1 shows the average values for the body configuration and spatiotemporal step variables in successful trials, failed trials with more than one step, and failed trials with one step. In general, we observed larger leg angles, smaller trunk angles, larger step lengths and higher step velocities in successful compared to failed trials.

When all variables were entered into the logistic regression model to predict recovery outcome, leg angle ($p < 0.001$) and peak
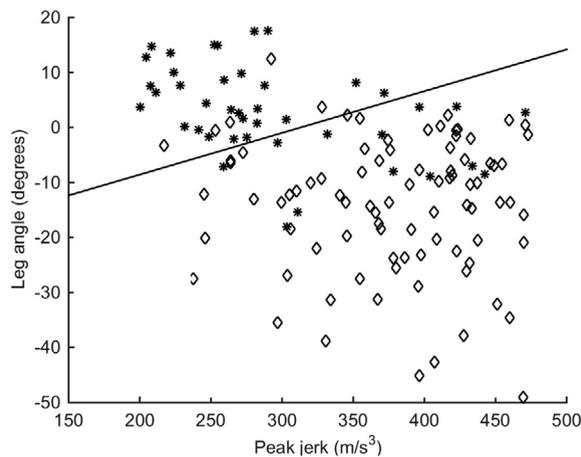
Fig. 3. Leg angles and peak jerks for successful (asterisks) and failed (diamonds) balance recovery attempts initiated with a side-stepping strategy. The line represents the combination of angle and jerk with 50% probability to recover balance successfully.

Table 2
Results of the backward logistic regression analysis for the side-stepping strategy.

	Mean (SD)	Odds ratio (95% CI)[*]	p value
Body configuration variables (−2 log likelihood = −36.3)			
Leg angle (degrees)	−8.5 (13.7)	1.368 (1.154–1.621)	< 0.001
Peak jerk (m/s³)	350 (77)	0.977 (0.962–0.991)	0.001
Spatiotemporal variables (−2 log likelihood = −45.8)			
Step length (cm)	57 (16)	1.114 (1.052–1.178)	< 0.001
Peak jerk (m/s³)	350 (77)	0.967 (0.953–0.981)	< 0.001

   [*] The odds ratio is calculated for an increase in the independent variable of one unit. In case of the leg angle as independent variable, it means that with an increase in leg angle of 1.0 degrees, the odds of successful balance recovery will increase by 1.368.

jerk ($p = 0.001$) were retained in the final model. For 111 of the 129 trials (86%) the outcome of the recovery attempt was correctly classified based on leg angle and peak jerk (Fig. 3), according to the equation:

$$\text{Probability of success} = 1 - \left(\frac{1}{1 + e^{7.434 + 0.313 * leg\ angle - 0.024 * peak\ jerk}} \right)$$

An increase in leg angle of 1.0 degrees increased the odds of successful balance recovery by 1.368 (Table 2). To maintain the same probability of success, larger leg angles (i.e., more positive) were required when peak jerk increased.

A −2 log likelihood value of −36.3 reflects the goodness-of-fit of this model based on leg angle and peak jerk. The best fitting model using only spatiotemporal variables yielded a −2 log likelihood of −45.8 (i.e., poorer fit) and included step length ($p < 0.001$) and peak jerk ($p < 0.001$) as significant predictors of success (Table 2). For 106 of the 129 trials (82%) the successfulness of the recovery attempt could be correctly classified based on step length and peak jerk.

Significant correlations were observed between leg angle and spatiotemporal variables ($r = 0.31–0.66$), except for leg angle and step onset (Table 3). The trunk angle was significantly correlated with step onset ($r = -0.30$) and step duration ($r = 0.23$). The strongest correlation between body configuration and spatiotemporal variables was found between leg angle and step velocity ($r = 0.66$), with larger step velocities yielding more positive leg angles.

4. Discussion

The aim of this study was to identify determinants of the first side step that could predict whether or not the participant would ultimately fall following a large sideways balance perturbation. In line with our hypothesis, we found that the quality of the first side step was a predictor for the outcome of the recovery attempt, with a greater angle of the leg at step contact and perturbation intensity being the strongest predictors of successful recovery.

We found that the angle of the stepping leg at first step contact was associated with recovery outcome following large sideways perturbations, and more so than any of the spatiotemporal variables. This result is in line with our previous work on backward stepping (Weerdesteyn et al., 2012). Although the leg angle moderately correlated with step length and velocity, it apparently provided more salient information on the quality of the recovery step. This can be explained by the leg angle better reflecting the position of the foot relative to the COM, and the stabilizing moment provided by the foot contact force. Several other approaches have been published to model the relationship between COM position/velocity and the base of support for quantifying dynamic stability (Hof et al., 2005; Pai & Patton, 1997; Vallee et al., 2015), yet the present method is much easier – as the leg angle at a given perturbation intensity can be determined from a single frontal 'screenshot' – while still being very accurate in predicting recovery outcome. We, therefore, feel that this method may be particularly useful in assessments of reactive step quality in a clinical environment. Yet, it cannot be excluded that information on the velocity of the COM at foot landing (which is not taken into account in either the body configuration or the spatiotemporal step variables) may further improve the prediction of recovery outcome. In addition, the leg angle only takes into account the leg movements that occurred in the frontal plane (i.e., direction of perturbation), whereas out-of-plane stepping movements or axial rotations in the trunk may also influence the likelihood of successful balance recovery.

Table 3
Pearson correlations between body configuration variables and spatiotemporal variables for the side-stepping strategy.

	Trunk angle	Step onset	Step length	Step duration	Step velocity
Leg angle	−0.09	−0.04	0.63[**]	0.31[**]	0.66[**]
Trunk angle	–	−0.30[**]	0.05	0.23[**]	−0.04
Step onset	–	–	−0.36[**]	−0.50[**]	−0.22[*]
Step length	–	–	–	0.74[**]	0.92[**]
Step duration	–	–	–	–	0.44[**]

  [*] $p < 0.05$.
  [**] $p < 0.01$.

In addition to the leg angles, average trunk inclination angles also differed between successful and failed trials with more than one step (see Table 1). Previous work on forward perturbations has emphasized the importance of controlling the trunk angle for maintaining stability during balance recovery (Carty, Mills, & Barrett, 2011; Grabiner, Koh, Lundin, & Jahnigen, 1993; Owings, Pavol, & Grabiner, 2001; Pavol, Owings, Foley, & Grabiner, 2001). Similarly, in our previous work on backward stepping, the trunk angle was a significant predictor of recovery outcome, albeit much weaker than the leg angle (Weerdesteyn et al., 2012). In the present study, however, the trunk angle did not come out as a significant predictor of sideward balance recovery.

Although the leg angle in combination with perturbation intensity accurately predicted the outcome of the recovery attempt for sideways perturbations, the classification accuracy of the model (86% of trials correctly classified) was substantially lower than for backward perturbations (96% correct) (Weerdesteyn et al., 2012). In addition, in our previous study the body configurations in incorrectly classified trials (i.e., discrepancy between model prediction and actual outcome of recovery attempt) closely approached the 50% probability values, whereas in the present study some of these trials were relatively distant from the equiprobability line (as indicated by the line in Fig. 3). Such deviant trials may be due a faulty second step rendering the recovery attempt unsuccessful, despite a "good" first side step; for instance when a limb collision occurred during the second cross-over step (Maki et al., 2000). It must be mentioned, though, that there was only one failed recovery trial where the first step was well above the 50% probability line (the uppermost diamond in Fig. 3), so it appears that successful recovery is highly likely following a good first side step (i.e., large leg angle). In contrast, a poorer leg angle did not necessarily preclude successful recovery, as there were several trials in which our participants managed to avoid falling despite leg angles being lower than −10 degrees (and at considerable distance from the 50% probability line). This reflects that a good second step may effectively compensate for a relatively poor first step. Yet, the leg angle of the first side step needs to be sufficiently large to allow taking additional steps, as evidenced by the poorer average leg angles in unsuccessful trials with only one step compared to those with more than one step (Table 1).

The lower percentage correctly classified recovery outcomes for side stepping compared to backward stepping may also be due to differences in the ability of the stepping leg to generate force (or absorb energy) after foot landing. When stepping backwards, the leg usually lands with the joints in relatively extended configurations that, combined with their anatomy and end range of motion, cause the stepping leg to act like a relatively stiff strut (Weerdesteyn et al., 2012). In contrast, when stepping sideways, the leg usually lands with the joints (and particularly the knee) in a more flexed position. This leg configuration allows the quadriceps muscles to absorb energy by contracting eccentrically, similar to their role in arresting a forward fall (Carty, Barrett, Cronin, Lichtwark, & Mills, 2012; Carty, Cronin, Lichtwark, Mills, & Barrett, 2012a; Karamanidis & Arampatzis, 2007; Madigan & Lloyd, 2005). Thus, inter-trial and inter-individual differences in joint torques (with only a limited role for torques around the ankle joint) produced after foot landing may explain the residual variance in recovery outcomes. Unfortunately – and inherent in the use of thick mattresses to ensure falling safely – our experimental setup did not permit recording ground reaction forces to quantify these joint torques.

Another limitation is related to the present study concerning a secondary analysis of a data set that was originally collected for addressing another research question. The semi-tandem starting position that was used (i.e., standing with the left leg in front of the right leg) with the left arm lifted forward does not reflect a 'natural' stance. In addition, the rather small translating rubber sheet that we used may also be mentioned as a limitation, as the foot landing outside the sheet resulted in the exclusion of a relatively large number of trials (47 of the 205 side steps).

The key strength of our study was that we applied perturbations that were strong enough to induce true falls in healthy young adults, which allowed us to identify the characteristics of compensatory side steps following sideways perturbations that separate successful recoveries (i.e., no falls) from falls, as the most clinically relevant outcome following a balance perturbation. The angle of the stepping leg with the vertical at first step contact was identified as a strong determinant of success, more so than any of the spatiotemporal step variables. At a given perturbation intensity, we expect the leg angle to be a valid measure for the quality of a reactive side step regardless of age and disease, but further research should focus on the generalizability of our results to other populations. In future studies, it would also be of interest to identify *how* people achieve favorable leg angles at foot contact, as this could provide targets for interventions aimed at improving side step quality. Importantly, the simplicity of assessing the leg angle at a given perturbation intensity may allow its application in novel balance tests for clinical use.

Financial disclosure

Declaration of Competing Interest

None.

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