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RESEARCH ARTICLE

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Relative stability improves with experience in a dynamic standing task

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Abstract This study tested the hypothesis that subjects improve their relative stability as they learn a dynamic pulling task. Healthy adult subjects practiced making brief horizontal pulls (<300 ms) on a handle to a range of target forces ranging from 20 to 80% of their estimated maximum for 5 days. They were instructed to always keep their feet flat and begin and end their motion in an upright posture. In order to do this, subjects had to develop the appropriate body momentum prior to the pull and then recover their balance following the pull. We analyzed relative stability during balance recovery, using two measures: spatial safety margin (minimum distance of the center of pressure, COP, to the edges of the feet) and temporal safety margin (minimum extrapolated time for the COP to reach the edges of the feet). We hypothesized that: (1) spatial and temporal safety margins would be uncorrelated; (2) safety-margin means would increase with practice; and (3) safety-margin standard deviations would decrease with practice. Two experiments were conducted: one where subjects practiced three force targets and positioned their initial COP in a small window, and one where subjects practiced two force targets with no initial COP constraint. Results showed that spatial and temporal safety margins were correlated but shared less than 6% variance, indicating that they reflected different aspects of control. Safety-margin averages increased with practice and standard deviations decreased with practice, indicating that the stability of balance control in the execution of this task became more robust. We suggest that the nervous system could use safety margins in both feedback and feedforward control of balance.

Key words Human · Posture · Motor learning · Constraints · Balance control · Robust control

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Introduction

Falling is often a precipitating cause of death (Winter 1995), yet it is not always clear how and why falls occur. Standing activities involve simultaneous goals (e.g., keep the feet still, lift an object, avoid slipping, avoid leaning too far, keep upright, etc.). Consequently, it is difficult to understand what the nervous system's objectives are, how they are met, or whether they can change with experience. In this paper, we focus on two measures of relative stability and whether these measures show improvement when subjects practice a dynamic standing task.

There is conflicting evidence in the literature about how balance changes with experience. Some studies suggest that in dynamic standing activities, behavior begins cautiously and becomes more risky. Subjects who were repeatedly pushed from behind progressively increased their center of mass displacements (Brown and Frank 1997). Over longer periods, astronauts tend to show post space-flight reduction in stability (Collins et al. 1995; Paloski and Nicholas 1996). However, other studies suggest that subjects become more cautious with experience. Dancers instructed to abduct one leg laterally could execute a single fluid motion with little center-of-mass motion, while non-dancers moved their leg and then corrected their balance (Mouchino et al. 1992). Gymnasts performing a back flexion task showed a distal-to-proximal pattern in leg-muscle EMG that resulted in a single fluid motion, while novices did not (Pedotti et al. 1989). Moreover, only the gymnasts could adapt to a narrow base of support by suppressing their gastrocnemii early in the task. Such results indicate that appropriate postural coordination may take a long time to acquire.

A limitation of these studies is that a mechanically well-founded measure was not used to track changes in stability. This may be because it is difficult to apply the term stability to balance (Slotine and Li 1991), and there are many different ways to fall (slipping, stumbling, etc.). The nervous system must also contend with unexpected disturbances and inaccuracies in the sensorimotor system. Moreover, the balance-control system exhibits considerable variability. Variability can be dangerous because outlier behaviors can exceed the limits of stability. In other words, the stability must be robust to noise, disturbances, and inaccuracies. Therefore, what is required is a measure of *relative stability* that indicates whether someone is more or less likely to become unstable.

Recent modeling studies support using a constraint-based approach for measuring relative stability in dynamic balance control (Pai and Patton 1997). Pai and Patton (1997) used a pendulum model of the center of mass to identify a *feasible range* of dynamic variables for balance control. Beyond the boundaries to this feasible range, the feet must move to regain balance. The model did this by calculating how several biomechanical and physiological constraints influence the feasible range (e.g., avoid slipping, stumbling, leaping, or exceeding one's strength limits). A subsequent study introduced *safety margins* (i.e., the minimum distance to the boundaries) as measures of relative stability and supported their validity with empirical data (Patton et al. 1999a). Safety margins quantify how far a subject is from a dangerous situation, and therefore measure the relative stability or how robust the system is to disturbances or inaccuracies. Patton et al. (1999a) demonstrated that under normal conditions when subjects maintain balance, the center-of-pressure (COP) safety margin (minimum distance of the COP to either the heel or the toe) is also a valid measure of relative stability because it directly measures how large a perturbation would be necessary to initiate a fall.

Others have suggested that the COP safety margin (also called "stability margin") is a measure of relative stability (Gurfinkel 1973; Hinton 1995; Koozekanani et al. 1980; Murray et al. 1967; Paloski and Nicholas 1996). Paloski and Nicholas (1996) suggested that, when the nervous system detects that the COP safety margin is nearing zero, a new motor-control program might be triggered. Other stability measures have been derived from the COP, such as excursions, velocities, and spectral characteristics (Aggashyan et al. 1973; Black et al. 1982; Collins and DeLuca 1993; Diener et al. 1984; Geursen et al. 1976; Goldie et al. 1989; Kolleger et al. 1989; Patla et al. 1992; Prieto et al. 1996; Riley et al. 1995; Schieppati and Nardone 1991; Stevens and Tomlinson 1971). Such measures typically assume that the goal of balance control is to minimize the excursion of the center of mass and COP. In contrast, safety-margin measures make no such assumptions of minimization. Instead, safety margins describe how far a person is from an unstable condition.

Although the above studies refer only to the distance-to-edge (spatial safety margin), the present study also considers the time-to-edge (temporal safety margin). We consider the temporal aspects of safety margins because stability can be threatened if the COP is rapidly moving towards the edge of the foot, even if there is a large spatial safety margin. Time is a critical consideration because reflex loops and muscle activation dynamics have appreciable delays (Hogan 1990). Therefore, the nervous system must allow time to react to common disturbances. The appropriate avoidance actions can be initiated through feedforward control by using ongoing sensory information to predict future locations of the COP. Therefore, while large spatial safety margins may provide a safe distance from dangerous circumstances, large temporal safety margins should make the system even more robust.

Several researchers have examined temporal safety margins of the COP in standing balance. David Lee originally suggested that the timing of motor control might be governed by a general estimation of time-to-contact (tau) (Lee 1976). Tau was hypothesized as a control variable for preparing for an impending impact, such as catching an object or landing from a jump. This concept has been generalized to other motor control tasks (see (Slobounov et al. 1997 for a review). A few have suggested applying tau to the COP in balance control, using an estimate of the COP's time to reach the edge (Carello et al. 1985; Koozekanani et al. 1980; Paloski and Nicholas 1996; Riccio and Stoffregen 1988; Slobounov et al. 1997). Slobounov et al. (1997) suggested that the nervous system might use temporal safety margins to control balance.

Investigations have not evaluated and compared both spatial and temporal safety margins in the same study, so it remains to be seen whether the spatial and temporal safety margins are correlated. Because they have different metrics (space and time), one might expect that these measures are uncoupled. On the other hand, it is possible that spatial and temporal safety margins are always correlated. Trajectories near a boundary (a small spatial safety margin) could also take less time to reach the boundary (a small temporal safety margin). If the two measures were highly correlated, only one would be sufficient for measuring relative stability. Therefore, the correlation between spatial and temporal safety margins needs to be determined prior to evaluating any changes with practice.

It is also not clear whether average safety margins tend to increase, decrease, or stay the same with practice. Increasing average safety margins would improve relative stability, and balance control would be more robust to disturbances and inaccuracies in the sensorimotor system. Decreasing safety margins would indicate that subjects begin cautiously, but then learn to maneuver closer to dangerous circumstances without falling.

In addition to averages, it is not clear whether trial-to-trial *variability* of the safety margins increase, decrease, or stay the same with practice. The probability of falling would be lower if safety margins became more consistent, because there would be fewer outliers that result in dangerous situations. Decreases in variability are common in motor learning (Schmidt 1988). Hence, variability should decrease if subjects learn to become more stable as they become skilled at performing a task. However, if subjects learn to maneuver closer to dangerous circumstances without falling, variability should increase.

Two experiments were conducted to resolve whether spatial and temporal safety margins are uncorrelated and whether they change when subjects practice a dynamic standing task. The task required subjects to generate a rapid pull on a handle to target forces while maintaining balance. Experiment 1 controlled initial COP and presented three target forces, while experiment 2 did not control initial COP and presented only two target forces. Our specific hypotheses were: (1) spatial safety margins and temporal safety margins are uncorrelated; (2) safety margin averages increase with practice; and (3) safety margin standard deviations decrease with practice. Changes were evaluated over a short time scheme (first day of practice) and a long time scheme (5 days of practice).

Materials and methods

Experiment 1. Constrained initial COP, three force targets, 5 days of practice

Ten healthy adults (23–49 years old; eight female, two male) with no history of orthopedic or neurological disorders volunteered to train for five separate days on the standing horizontal-pull task. Before participating, each subject signed a consent form that conformed to federal and university guidelines. Subjects warmed up with light stretching to reduce the possibility of injury.

Subjects stood freely on a force platform, holding a handle with both hands (Fig. 1). They were instructed to make brief, horizontal pulls straight backwards on the handle while keeping their feet flat on the floor and their forearms parallel to the floor at all times. Subjects were told to begin and end the trial in an upright and quiet posture. Before each pull, the COP location and a target were displayed to the subject on a monitor. To start the trial, the subject had to position the COP at a location 40±5% of the distance from the heel to the toe. They initiated the movement any time after an audible cue, but the pulling force they generated had to abruptly begin and end with zero force. All subjects found they needed to develop posterior momentum before starting to pull in order to generate sufficient force. They then recovered their balance after rebounding from the pull. The present analysis focused on this balance recovery phase of the motion.

The instructions were to try to make an impulse-like pull with a rise time of less than 150 ms to a magnitude matching various peak-force targets. Each trial's peak-force target was 20, 40, or 80% of the subject's estimated maximum based on a linear regression with height and weight (Lee et al. 1990). Subjects made 36 pulls to each target on the first four days. On day 5, subjects made 21 pulls to each target and also produced pulls to 10%, 50%, 60%, and 95% targets. The subjects were given verbal feedback on the duration and magnitude of the pull after completing the trial. A "fading" feedback schedule was used to inform the subjects about their performance (100% feedback on day 1, decreasing to 0% feedback by day 5). No feedback about COP was given during or after the initiation of the trial.

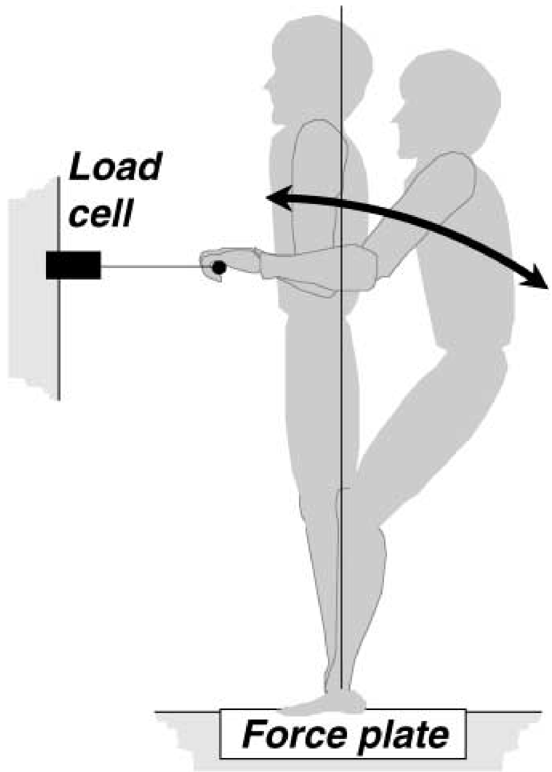

Fig. 1 Biomechanical Task. Subjects made large, horizontal, impulse-like pulls on a handle to different target forces

Experiment 2. Unconstrained initial COP, two force targets, 1 day of practice

Experiment 2 was the same as experiment 1, with the following exceptions. Nine additional healthy adults (21–27 years old; all female) volunteered for experiment 2. Subjects in experiment 2 had not participated in experiment 1. Each made 60 pulls to each of two targets (35% and 65% of their estimated maximum). Subjects had no restrictions on the initial COP location, and feedback was given after every trial about the duration and magnitude of the pull.

Instrumentation and data processing

Ground reaction forces and moments were recorded with an AMTI force plate, and pulling forces were recorded with an 1100 N Sensotec load cell. Collection frequency was 200 Hz. COP records were conditioned with a third order, two-pass Butterworth filter (cutoff frequency of 6 Hz), and then differentiated with a three-point, central differentiation algorithm. The bold line in the top of Fig. 2 illustrates a typical COP trajectory. The onset of the balance recovery phase was determined by locating when the pulling force dropped within the 95% confidence interval on the baseline force recorded on the load cell. The end of the balance-recovery phase was determined by locating when the center-of-mass velocity had returned to within 5% of the maximum (see Lee and Patton 1997 for details).

Safety margin measures

Spatial safety margins were evaluated by computing the nearest distance-to-edge of the COP to either the heel or the toe (Fig. 2, center). *Temporal safety margins* were evaluated by computing the time-to-edge of the COP using multiple predictive extrapolations (thin lines in Fig. 2, top). We assumed that future COP locations were best predicted using the current COP and its derivatives with respect to time. Future COP locations were estimated using a second-order, truncated Taylor series expansion:

$$COP(t+\Delta t) = COP(t) + \dot{COP}(t)\Delta t + \tfrac{1}{2}\ddot{COP}(t)\Delta t^2 \quad (1)$$

where t is the current time and Δt is the predicted jump into the future. Future COP locations were estimated for increasing intervals of Δt (0.01 s) until the heel or toe was reached (Fig. 2, thin lines). The time required to reach the nearest edge (heel or toe) defined the predicted time-to-edge. Note that because the trajectories become horizontal at times, the time-to-edge approaches infinity, resulting in the spikes. The minimum of all predicted times-to-edge defined the temporal safety margin for that trial. We assumed that equation 1 (based on position, velocity, and acceleration) was sufficient to characterize the extrapolation. Higher order approximations (third or above) are theoretically more accurate because they can represent more of the signal, but were not used for several reasons. First, each increasing order contributes a smaller amount to the accuracy because the frequency content of biological signals such as COP are inherently dominated by low frequencies. Second, noise increasingly contributes errors as each higher order derivative is calculated in discrete time. Third, we assumed that the nervous system is incapable of considering COP jerk and higher derivatives in predicting future COP locations. Finally, similar second-order predictors have been used in the analysis of time-to-edge (Slobounov et al. 1997).

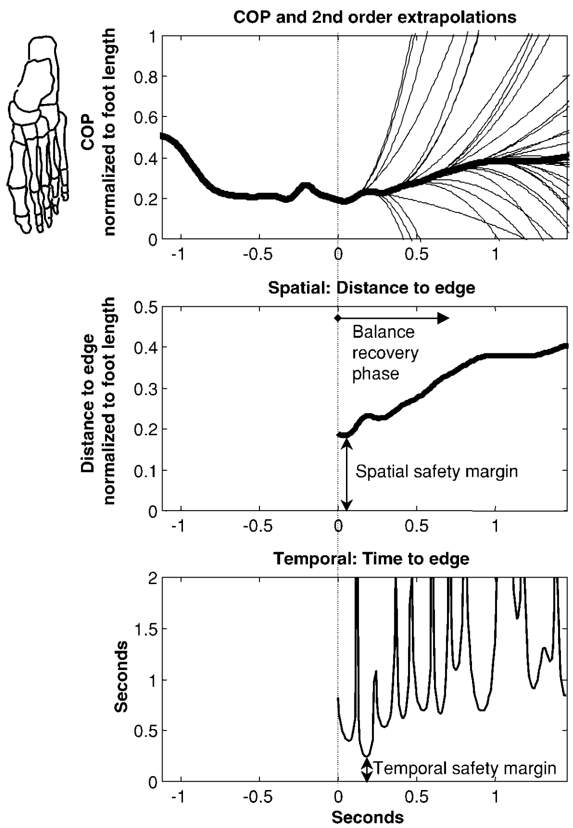

Fig. 2 Definitions of the spatial and temporal safety margins for a typical trial. The *upper plot* shows the center-of-pressure (*COP*) trajectory (*bold curve*) and the second-order extrapolations (*thin lines*). Distance-to-edge is shown in the *center figure*; its minimum defines the spatial safety margin. Time-to-edge is shown in the *lowest figure*; its minimum defines the temporal safety margin. The vertical line indicates the initiation of the balance recovery phase (see Fig. 3

Analyses

Pearson correlation coefficients (r) assessed the linear dependence between spatial and temporal safety margins to determine if the two measures provided the same information about balance. Repeated-measures, multivariate analyses of variance tested the null hypotheses that neither force nor experience influenced the safety margins. Peak force was normalized with respect to estimated maximum. For experiment 1, normalized peak force was used to group trials into seven cells, each spanning a 10% range (from 15–25% through 75–85% of maximum). Data were grouped to determine the effect of five days of practice (day 1 vs. day 5) Additionally, data were grouped to determine the effect of a single day of practice (first half vs. last half of the trials from day 1). For experiment 2, normalized peak force was used to group trials into two force levels (30–40% and 60–70% of maximum), and data were grouped to determine the effect of a single day of practice. If a statistical cell contained fewer than three trials, the block was eliminated from the analysis. This occurred in experiment 1, where trials with forces above 55% were missing for some subjects for the within-day-1 analysis. This was because it took several days for some individuals to learn how to generate the larger pulls. The significance threshold for all statistics was set at an alpha level of 0.05. The Huynh-Feldt conservative adjustment of degrees of freedom was used for conditions showing non-normal distributions (Huynh and Feldt 1976). Power calculations were run on each measure to determine probability of type-II error.

Results

General observations

Figure 3 shows ensemble-averaged trajectories for a typical subject. This subject developed posterior momentum, made a brief pull that reversed the center-of-mass motion, and then recovered balance (Fig. 3, top). This pattern was consistent across all subjects. Median COP trajectories were between 35.6% and 53.0% of the dis-

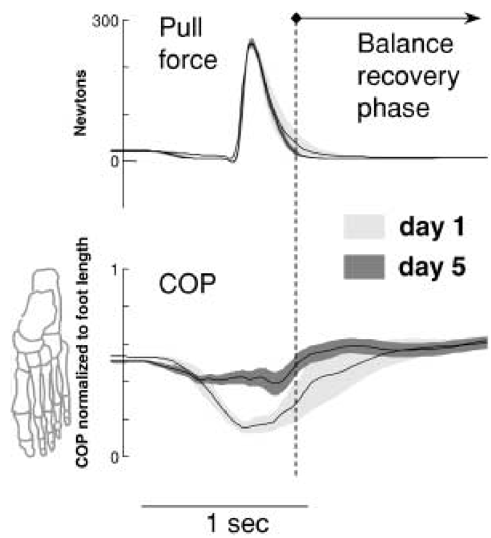

Fig. 3 Typical time records of pulling force and center of pressure (*COP*) for 40% pulls of a single subject. *Lines* indicate ensemble averages, and *shaded areas* indicate 95% confidence intervals. Trials were aligned at the instant of maximal pulling force. For this reason, the line indicating the initiation of the balance-recovery phase is shown for the average pull of day 5 only

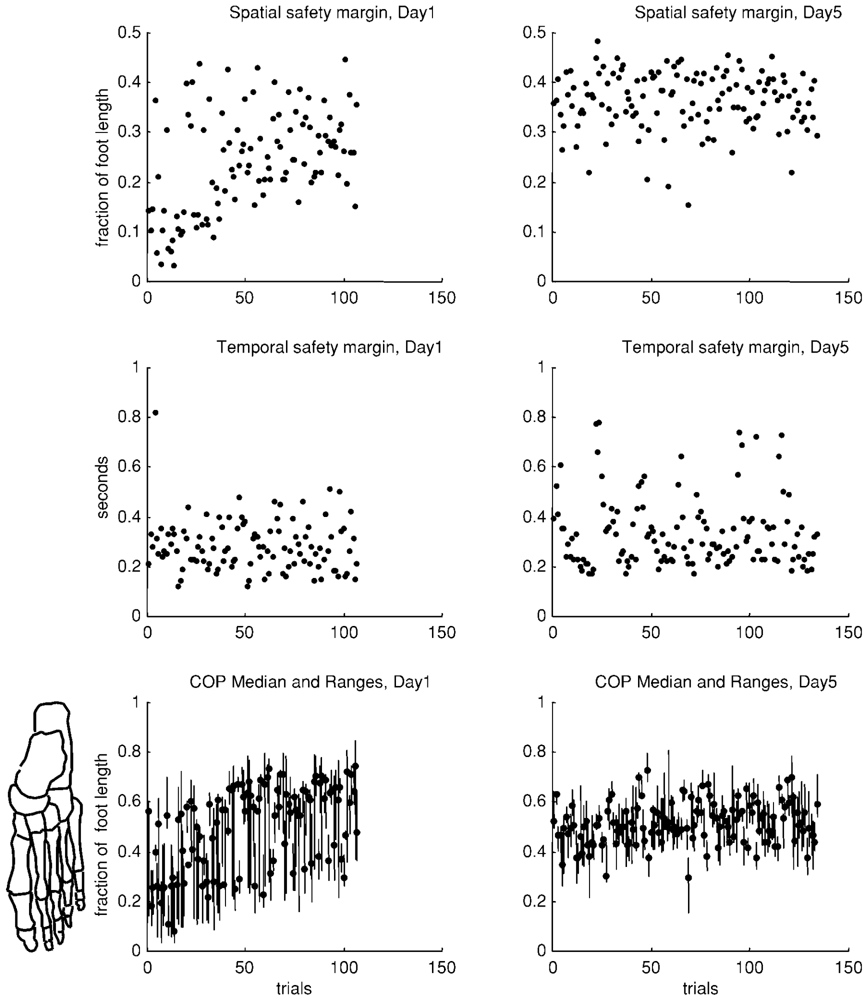

Fig. 4 Learning curves of the spatial safety margin, temporal safety margin, and center-of-pressure (*COP*) median and range evaluated over the balance-recovery phase for one subject from experiment 1 for all trials at all pulling forces. *Top figures* show spatial safety margins versus trial for day 1(*left*) and day 5 (*right*). *Center figures* show temporal safety margins versus trial for day 1 (*left*) and day 5 (*right*). *Bottom figures* show the COP median (*dots*) and the COP range (*wings*) versus trial for day 1 (*left*) and day 5 (*right*)

tance from the toe to the heel during the balance-recovery phase. Both spatial and temporal safety margins showed significant changes with experience, described in detail below. However, we first evaluated the relationship between the two safety margins to determine if each provided unique information.

Do spatial and temporal safety margins reflect different features of stability?

Pearson correlations showed that spatial and temporal safety margins reflected different features of balance control. If spatial and temporal safety margins were highly correlated, they would provide redundant information about balance and it would be unnecessary to analyze how both measures change with experience. However, Pearson correlations between spatial and temporal safety margins were weak (average r=0.23; ranging from –0.01 to 0.42) although significant (P<0.05). Thus on average, the two measures shared less than 6% of common variance.

Do spatial and temporal safety margins change with practice?

Results of both experiments showed that practice increased the average spatial and temporal safety margins (Table 1). Learning curves for a typical subject from experiment 1 are shown in Fig. 4. Spatial safety margins increased more dramatically than temporal safety margins, especially on day 1 (Fig. 4, top plots). The average of the temporal safety margin increased between day 1 and day 5, mainly because the maximum temporal safety margins were often higher on day 5 (Fig. 4, center left and right plots). The COP occupied more anterior positions after practice, which shifted the median closer to the center of the foot (dots on the bottom left plot of Fig. 4). The COP's range decreased by day 5 (see the vertical lines on the bottom of Fig. 4). Not all subjects showed such pronounced changes with practice, however, so the following sections describe the group results in more detail.

Experiment 1. Changes across five days

Five days of practice increased spatial safety margins interactively with pulling force. Specifically, an increase

Table 1 ANOVA results of practice effects on spatial and temporal safety margins

	Experiment 1				Experiment 2	
	5 days of practice (day 1 vs. day 5)		1 day of practice (day 1 early trials vs. day 1 late trials)		1 day of practice (day 1 early trials vs. day 1 late trials)	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Spatial safety margin	* ↑ interactively with force [F(3.20,28.77)=3.06; P=0.0412]	* ↓ [F(1,8)=11.94; P=0.0086]	* ↑ [F(1,9)=6.72; P=0.0291]	*↓ [F(1,9)=5.71; P=0.0405]	* ↑ [F(1,8)=7.79; P=0.0235]	↓ [F(1,8)=1.05; P=0.3358]
Temporal safety margin	↑ [F(1,9)=4.11; P=0.0731]	[F(1,8)=2.24; P=0.1724]	↑ [F(1,9)=2.06; P=0.1846]	[F(1,9)=1.04; P=0.3348]	* ↑ [F(1,8)=5.54; P=0.0464]	↑ [F(1,8)=2.46; P=0.1552]

*P<0.05 (statistically significant)

was observed for pulling forces above 40% (Fig. 5, upper left plot; Table 1). This interaction effect indicated that spatial safety margins for all force levels converged onto roughly the same value by day 5 (about 32% of foot length). The average increase in the spatial safety margin after five days of practice was 2% of foot length. The standard deviation of the spatial safety margin was significantly lower on day 5 than on day 1, indicating that the subjects became more consistent with practice (Fig. 5, upper right plot; Table 1). Neither the average nor the standard deviation of the temporal safety margins changed significantly, either alone or interactively with pulling force (Fig. 5, lower two plots; Table 1). However, there were marginally significant increases in average temporal safety margins after five days of practice (P=0.0731; Table 1).

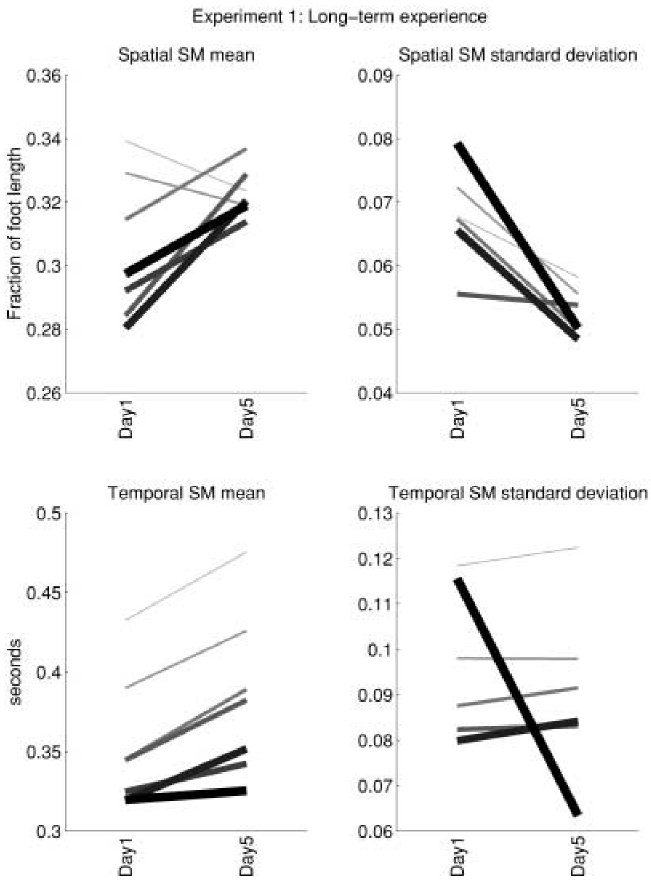

Fig. 5 Effects of five days of practice on safety margins (*SM*) for experiment 1. Spatial (*upper plots*) and temporal (*lower plots*) averages (*left plots*) and standard deviations (*right plots*) are shown. Seven pulling-force levels (20–80% of maximum) are represented as *lines of increasing thickness*

Experiment 1. Changes within one day

Only the four lowest force levels (20–50% of maximum) had enough trials to sustain statistical analysis within day 1. Spatial safety margins for these pulls increased within day 1, by an average of 3% for these force levels (Fig. 6, upper left plot; Table 1). This contrasts with the finding that spatial safety margins for the two lowest force levels did not increase further after five days of practice. The standard deviation of the spatial safety margin also decreased within day 1, indicating that the subjects became more consistent with practice (Fig. 6, upper right plot; Table 1). Similar to five days of practice, neither the average nor the standard deviation of the temporal safety margins changed significantly within day 1 (Fig. 6, lower two plots; Table 1).

Two factors may have influenced the results of experiment 1. First, initial COP was constrained, which may have inhibited natural movements. Second, statistical cells representing higher forces (55% and above) had to be eliminated from the analysis of changes within day 1 because too few trials were obtained. Therefore, in experiment 2, we relaxed constraints on the initial COP location and required subjects to pull to only two force levels, one low (35%) and one high (65%). Consequently, a larger number of trials were available at each force level.

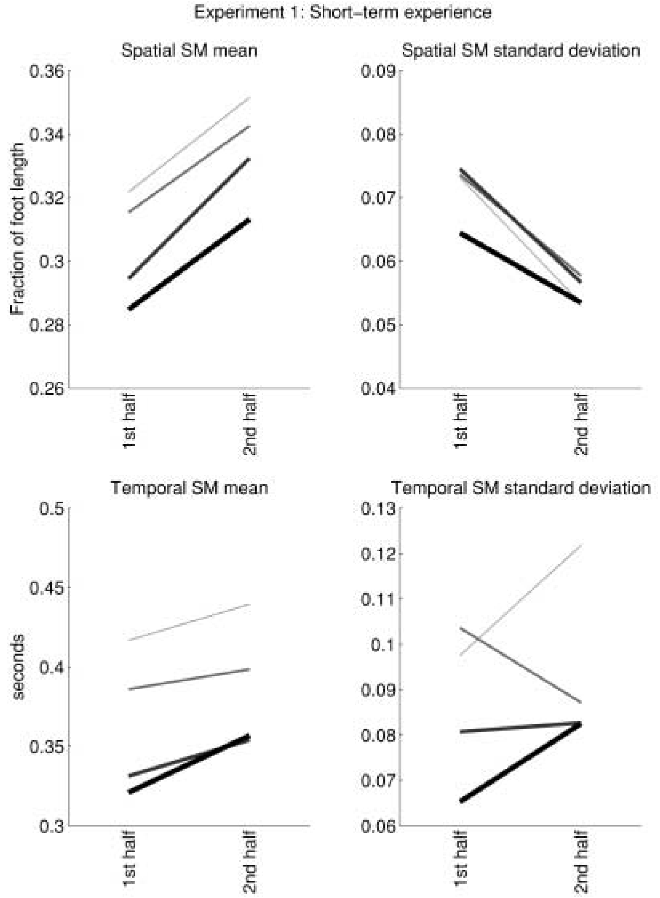

Fig. 6 Effects of one day of practice on spatial (*upper plots*) and temporal (*lower plots*) safety margins (*SM*) for experiment 1. Averages (*left plots*) and standard deviations (*right plots*) are shown. Four pulling-force levels (20–50% of maximum) are represented as *lines of increasing thickness*

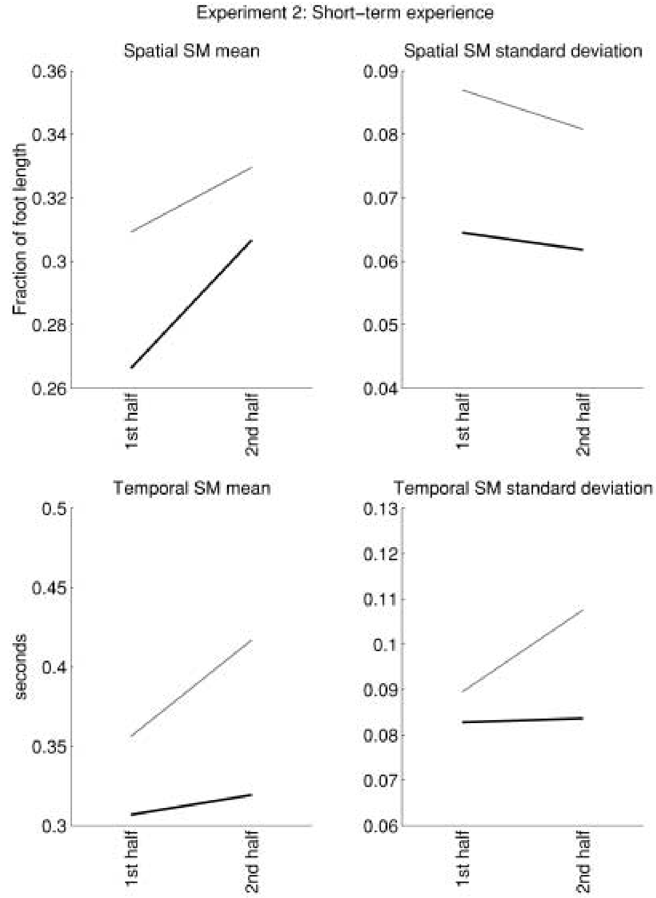

Fig. 7 Effects of one day of practice on spatial (*upper plots*) and temporal (*lower plots*) safety margins (*SM*) for experiment 2. Averages (*left plots*) and standard deviations (*right plots*) are shown. Two pulling-force levels (35 and 65% of maximum) are represented as *lines of increasing thickness*

Experiment 2. Changes within one day

Experiment 2 replicated some of the results seen for day 1 of experiment 1 (Fig. 7; Table 1). Within this single day of practice, spatial safety margins increased significantly at both force levels, by an average of 3% of foot length (Fig. 7, upper left; Table 1). In contrast to experiment 1, standard deviations of the spatial safety margin did not decrease significantly (Fig. 7, upper right plot; Table 1). Hence, the spatial safety margins did not become more consistent with practice. Also unlike experiment 1, temporal safety margins significantly increased an average of 37 ms (Fig. 7, lower left; Table 1). Standard deviations of the temporal safety margin did not decrease significantly with practice (Fig. 7, lower right; Table 1).

Changes in safety margins were not due to learning a "more efficient" strategy

Although the practice-related changes in safety margins during balance recovery are consistent with the hypothesis that learning is associated with increasing relative stability, the changes in safety margins could have also been due to subjects learning a more efficient strategy of using their body momentum and gravitational forces rather than muscle activity to recover balance. Two lines of evidence argue against that alternative. First, the mechanical work done by the ankle joint would be reduced if changes in COP safety margins were wholly due to increased efficiency. We tested this hypothesis and found the opposite to be true: work was unchanged after five days of practice for the low force pulls and *larger* for the high force pulls [force-practice interaction $F(1,9)=31.72$; $P=0.0003$]. Second, if efficiency had increased, then momentum and ankle torque should have been lower after practice. However, as reported previously, neither momentum nor ankle torque changed significantly with practice (Lee and Patton 1997).

Discussion

These two experiments provided evidence that spatial and temporal safety margins are uncorrelated, that safety-margin averages increased with practice, and that safety-margin standard deviations decreased with practice. The next three sections discuss these results, followed by sections considering implications of motor variability and control strategies that the nervous system may use to avoid falling.

The practice-related improvements in relative stability in this study are consistent with the hypothesis that learning is associated with increasing spatial and temporal safety margins to control balance. However, the increases in safety margins and decreases in their variability could arise from changes in other controls by the CNS, such as learning a strategy that relies more on momentum to recover balance. The data did not support that particular hypothesis, but the data do not exclude the possibility that other controls could be the ultimate source of changes in safety margins that accompany practice. One approach to the question of whether the CNS uses a safety margin control strategy would be to test a crucial underlying assumption of this hypothesis, namely that the CNS is capable of real-time monitoring and use of distance- and time-to-edge information. To our knowledge, that capacity has not yet been demonstrated directly. Regardless of the particular neural mechanisms that mediate practice effects (e.g., whether the CNS monitors safety margins), the present study clearly showed that practice improved relative stability during balance recovery in the pulling task.

Spatial and temporal safety margins are different measures

The fact that spatial and temporal safety margins shared less than 6% of their variance suggests that each may play a unique role in stability. This observation is consistent with modeling efforts that found that stability is influenced by center-of-mass position (a spatial parameter), *and* center-of-mass velocity (a spatio-temporal parameter) (Pai and Patton 1997). Although it may seem that the spatial and temporal safety margins should be strongly correlated, consider the following two extreme examples. If the COP were close to but moving away from the edge, the spatial safety margin would be low and the temporal safety margin would be high. A disturbance toward the edge would easily result in instability in this case, but only the spatial safety margin would correctly indicate poor relative stability. Likewise, if the COP were located in the center of the foot, but moving rapidly towards the edge, only the temporal safety margin would correctly indicate impending instability. Using a combination of spatial and temporal safety margins thus allows more potential dangers to be detected.

It may be possible to improve the extrapolation method used to determine the temporal safety margin. Our second-order extrapolation method was consistent with a previous study (Slobounov et al. 1997). A first-order extrapolation appeared overly simple, and noise artifacts prevented our using at a third-order extrapolation. We obtained the most systematic results from the present approach. Alternative conditioning and extrapolation methods (such as Fourier, cubic, bicubic, or cubic spline approximations) may produce better estimates of the temporal safety margin.

It is important to distinguish temporal safety margins in this study from the “virtual time-to-contact” measures presented by Slobounov and colleagues (Slobounov et al. 1997, 1998). They measured virtual time-to-contact at each instant in time, in the same way we measured time-to-edge in this study. However, the temporal safety margin used in our study selected the *minimum* time-to-edge. While Slobounov and colleagues (1997) reported averages and standard deviations of virtual time-to-contact, they did not report their minima. Consequently, their average virtual time-to-contact for anterior-posterior sway (grand mean of 450 ms) is not directly comparable to our temporal safety margin (grand mean of 350 ms). Interestingly, we found comparable averages for our time-to-edge (the extrapolated trajectories in the top plot of Fig. 2; average of about 400 ms), but we believe the critical measure to be the *minimum* (fastest time-to-edge, or temporal safety margin). Slobounov et al. (1997) also found that virtual time-to-contact was smaller for faster motions, which is similar to our finding that safety margins decreased with the faster motions associated with higher pulling forces.

One may argue that safety margins measured relative to the heel should be excluded in this task, due to the fact that the subject is not in danger of falling backward because he or she can pull on the handle. However, the subject was instructed to avoid pulling on the handle during balance recovery as well as to try not to step. Subjects were told they failed on a trial if they pulled on the cable to avoid falling backward or took a step to avoid falling forward. Thus, backward and forward falling forward were both equally penalized.

It is important to mention that safety margins derived from the COP cannot *completely* quantify relative postural stability. Under certain conditions, such as leaning too far or too fast, it is not feasible to recover balance even though the COP may be well-centered under the foot. One can theoretically maintain the COP under the center of the foot and still fall. However, to prevent a fall, the COP must travel beyond the center of mass for at least an instant to generate torques that accelerate the center of mass away from the limits to stability (Patton et al. 1999a; Winter 1995). Hence, for tasks in which balance is fully recovered (as in the current study), the COP safety margins should be the most sensitive indicator of relative stability.

The COP ranges are somewhat related to the functional base of support in quiet standing (Blaszczyk et al. 1994; King et al. 1994; Lee and Deming 1988). In these studies, researchers characterized COP loci for different postures. King found that, for healthy young subjects who leaned forward and backward as far as they could, the static range was approximately 60% of the foot length, which compares reasonably well with the range seen in this task (Fig. 4, lower left plot).

Effects of practice on safety margins

The average spatial safety margin increased with practice in all analyses, while the standard deviation decreased in experiment 1. Temporal safety margin averages increased significantly only in experiment 2, but showed only a marginally significant increase across five days of practice in experiment 1. Spatial safety margins increased at lower force levels (20–65%) in the first day of practice and showed further increases after five days only at higher force levels (40–80%). Hence, spatial safety margins increased more rapidly for lower force pulls and took longer to increase at higher force pulls. This may be because the higher force pulls, which involve faster motions, were more difficult for novices to produce.

There are several reasons why temporal safety margins significantly increased only in experiment 2. First, increasing temporal safety margins may be easier to learn if initial COP is not constrained, because subjects are allowed to begin the motion from a posture that is more familiar to them. Second, it may be that five days was not long enough for subjects in experiment 1 to learn how to increase their temporal safety margins for multiple pulling forces. Subjects from experiment 2 had to pull to only two targets and practiced each target more often within the first day than did subjects from experiment 1. This additional practice may have enabled subjects from experiment 2 to learn how to increase their temporal safety margins more quickly. This possibility is supported by the observation that the average temporal safety margin increased across five days (Fig. 5, lower left plot), albeit only marginally (P=0.0731; Table 1). A final explanation for why temporal safety margins increased significantly only in experiment 2 may be that intrasubject variability differed in the two experiments. A larger dataset should resolve this.

Variability and a safety-margin control strategy

Large COP excursions are not a stability problem if safety margins are sufficiently high. Such variations in COP might reflect noise in the system about an equilibrium point, but could also reflect the dynamic requirements of the task (Lee and Patton 1997). Moreover, subjects may learn to keep safety margins large enough to remain stable (McCullum and Leen 1989; Riccio 1993). When distance-to-edge and time-to-edge are sufficiently large, no corrective response is needed and trajectories may appear to be random. When either drops below a threshold, a corrective response could be triggered. To use a safety margin-triggered control strategy, the nervous system would need to calculate current distance-to-edge and time-to-edge. Such a safety-margin-control strategy would be robust to many disturbances and inaccuracies in the sensorimotor system and may not require constant monitoring.

Studies on quiet standing support such a threshold-triggered control strategy (Collins and DeLuca 1994). They suggested that, after a sufficient amount of time has passed or a large enough displacement of the COP has occurred, different control modes were activated. In another motor task (manual tracking using a joystick), Hanneton and colleagues similarly found evidence supporting the triggering of stereotyped corrective movements when variables exceeded a safety margin (Hanneton et al. 1997). Such considerations may provide insight into rehabilitation of sensory impairments, such as the so-called noise-enhanced sensory function techniques, where sensory detection of subthreshold stimuli can be enhanced by artificially introducing noise into the system (Chow et al. 1998).

The temporal safety margins in this study were long enough (average ≥300 ms) to allow the nervous system time to employ all available reflex mechanisms, plus longer-latency information processing to control balance via a “safety margin control strategy”. Specifically, the temporal safety margin exceeded delays associated with reflex [~80–100 ms for visuo-spinal, proprioceptive, and vestibulospinal reflexes (Nashner and Berthoz 1978)] and simple reaction-time control mechanisms (Schmidt 1988). The temporal safety margins thus afford the nervous system with sufficient time to allow the muscles to actuate a change in the direction of the body, even with its considerable inertia, using both feedback and feedforward control mechanisms. This type of control can be considered optimal in terms of its robustness to noise and disturbances in the system.

The practice-related improvements in relative stability observed in this study agree with other modeling and experimental studies that focus on the consideration of noise in understanding how people move. The effects of signal-dependent noise (Harris and Wolpert 1998) and sensory-dependent noise (Kuo et al. 1998) have been shown to be critical in predicting motor patterns in reaching, eye movements and postural dynamics. This study showed changes in spatial and temporal margins (increased averages; decreased standard deviations) that occurred with practice, suggesting that subjects adaptively increased their noise-robustness.

This study furnished evidence that relative stability improves with practice of a standing task. More recent studies provide evidence that relative stability is a motivational factor in motor learning and whether such measures as distance-to-edge and time-to-edge are actively monitored by the nervous system (Patton et al. 1999b). We assert that it is crucial to consider the role of noise and uncertainty when modeling or conducting experiments on motor learning.

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