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 percent 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.

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. Danzer 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 (Mouchnino, 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., 1999). 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. (1999) demonstrated that under normal conditions when subjects maintain balance, the 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 (Aghashayan, et al., 1973; Black, et al., 1982; Collins and DeLuca, 1993; Diener, et al., 1984; Geursen, et al., 1976; Goldie, et al., 1989; Kollegger, et al., 1989; Patla, et al., 1992; Prieto, et al., 1996; Riley, et al., 1995; Schiappati 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 supraspinal, reflexive, preprogrammed feedback loops, and muscle activation dynamics all 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 in jumping, landing, or lifting. 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) should 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 experience) and a long time scheme (across 5 days of practice).

METHODS

Experiment 1 – constrained initial COP, three force targets, 5 days of practice

Ten healthy adults (23-49 years old; 8 female, 2 male) with no history of orthopedic or neurological disorders volunteered to train for five separate days on the standing horizontal pulling 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 (Figure 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 milliseconds to a magnitude matching various peak force targets. Each trial’s peak force target was 20, 40, or 80 percent 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.

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 sixty 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 1100N Sensotec load cell. Collection frequency was 200 Hz. COP records were conditioned with a third order, 2-pass Butterworth filter (cutoff frequency of 6 Hz), and then differentiated with a 3 point, central differentiation algorithm. The bold line in the top of Figure 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 (Figure 2, center). Temporal safety margins were evaluated by computing the time-to-edge of the COP using multiple predictive extrapolations (thin lines in Figure 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:

\[
\text{COP}(t + \Delta t) = \text{COP}(t) + \frac{\partial\text{COP}(t)}{\partial t}\Delta t + \frac{1}{2!}\left(\frac{\partial^2\text{COP}(t)}{\partial t^2}\right)(\Delta t)^2 + \frac{1}{3!}\left(\frac{\partial^3\text{COP}(t)}{\partial t^3}\right)(\Delta t)^3 + \cdots
\]

where \(t\) is the current time and \(\Delta t\) is the predicted jump into the future. Future COP locations were estimated for increasing intervals of \(\Delta t\) (0.01 seconds) until the heel or toe was reached (Figure 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 time-to-edges defined the temporal safety margin for that trial. We assumed that Equation 6.1 (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]).

Analyses

Pearson correlation coefficients (2) assessed the linear dependency 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 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
RESULTS

General observations

Figure 3 shows ensemble-averaged trajectories for a typical subject. This subject developed posterior momentum, made a brief pull that reversed center of mass motion, and then recovered balance (Figure 3, top). This pattern was consistent across all subjects. Median COP trajectories were between 35.6% to 53.0% of the distance 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 ($p < .05$). Thus, on average, the two measures shared less than 6% of common variance.

Five days of practice increased spatial safety margins interactively with pulling force. Specifically, an increase was observed for pulling forces above 40% (Figure 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 (Figure 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 (Figure 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).

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

<table>
<thead>
<tr>
<th></th>
<th>EXPERIMENT 1: 5 days of practice (Day1 vs. Day5)</th>
<th>EXPERIMENT 1: 1 day of practice (Day1 early trials vs. Day 1 late trials)</th>
<th>EXPERIMENT 2: 1 day of practice (Day1 early trials vs. Day 1 late trials)</th>
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<tbody>
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<td>Average</td>
<td>Standard deviation</td>
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<td>4 days</td>
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<td>$[F(3.20, 28.77)$ =3.06; $p=0.0412$</td>
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<td>$[F(1,9) =2.24; p=0.1224$</td>
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<td>$[F(1.9) =5.21; p=0.0235$</td>
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<td>$[F(1.9) =1.04; p=0.3348$</td>
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Figure 2: Definitions of the spatial and temporal safety margins for a typical trial. The upper plot shows the COP trajectory (bold curve) and the second order extrapolations (thin lines) are shown. 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.

Figure 3: Typical time records of pulling force and 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.

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 Figure 4. Spatial safety margins increased more dramatically than temporal safety margins, especially on Day 1 (Figure 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 (Figure 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 Figure 4). The COP's range decreased by Day 5 (see the vertical lines on the bottom of Figure 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 within one day.

Only the four lowest force levels (20 to 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 (Figure 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 5 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 (Figure 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 (Figure 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 Day1 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.

Experiment 2 replicated some of the results seen for Day 1 of Experiment 1 (Figure 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 (Figure 7, upper left; Table 1). In contrast to Experiment 1, standard deviations of the spatial safety margin did not decrease significantly (Figure 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 (Figure 7, lower left; Table 1). Standard deviations of the temporal safety margin did not decrease significantly with practice (Figure 7, lower right; Table 1).

Chances 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 also could have 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 due wholly to increased efficiency. We tested this hypothesis and found the opposite to be true: work was unchanged after 5 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 & 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. 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 due wholly to increased efficiency. We tested this hypothesis and found the opposite to be true: work was unchanged after 5 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 & Patton, 1997).
effects (e.g., whether the CNS monitors safety margins) the present study clearly showed that that practice improved relative stability during balance recovery in the pulling task.

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., 1999; 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 (Blassczak, 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 (Figure 4, lower left plot).

**Effects of practice on safety margins**

The average spatial safety margin increased with practice in all analyses, while it's standard deviation decreased only in Experiment 1. Temporal safety margin averages increased significantly only in Experiment 2, but showed only a marginally significant increase across 5 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 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 (Figure 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 intransitability 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 a 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 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 allow the nervous system with sufficient time to allow the muscles to actuate a change in the direction of the body, even with 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. Additional studies are underway to determine whether 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. We assert that it is crucial to consider the role of noise and uncertainty when modeling or conducting experiments on motor learning.

REFERENCES


