Altered Plantar-Receptor Stimulation Impairs Postural Control in Those With Chronic Ankle Instability

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Context: Postural control as assessed via time-to-boundary (TTB) measures has been shown to be impaired in those with chronic ankle instability (CAI). Foot orthotics have been shown to improve postural control, although it is not clear if this is via mechanical or sensorimotor mechanisms. Objective: To assess the effect of textured shoe inserts that provide no mechanical support on postural control as assessed by TTB measures in subjects with CAI. Design: A crossover design to examine the effects of a textured insole on postural control in individuals with unilateral CAI. The independent variables were vision (eyes open, eyes closed) and texture (textured insole, sham insole, control). Setting: Laboratory. Participants: 20 physically active individuals, 12 men, 8 women, age 18–45 y (21.5 ± 5.51) with self-reported CAI. Intervention: Each subject balanced in shod single-limb stance with eyes open and eyes closed under 3 conditions (control, sham, and textured insole). The order of testing under the 3 shoe conditions and 2 vision conditions was counterbalanced. Main Outcome Measures: The mean of TTB minima and the standard deviation of TTB minima in the mediolateral (ML) and anteroposterior directions. Results: There were significant reductions in TTB ML magnitude and variability found in the textured condition compared with the control and sham conditions. In the textured condition, subjects failed significantly more trials than any other condition. Conclusions: Stimulating the plantar surface of the foot, via a textured insole, has an effect in the broad spectrum of postural-control maintenance in individuals with CAI.

Keywords: sensorimotor, balance, constraints

Injuries occurring at the ankle complex, mainly to the lateral ligaments, are among the most common injuries in athletics. It is estimated that in the United States nearly 23,000 ankles are sprained on a daily basis and that 85% of those sprains affect the lateral ligaments. It has been well established that the primary risk factor for suffering an ankle sprain is a previous history of sprains. The longstanding residual symptoms of an ankle sprain affect over 70% of those who suffer an ankle sprain. The phenomenon of recurrent ankle sprains and longstanding symptoms caused by repetitive bouts of lateral ankle instability has been defined as chronic ankle instability (CAI).

CAI has been associated with a variety of sensorimotor impairments, one of the most studied being deficits in postural control. Deficits in single-limb postural control have been identified in those with CAI with the use of instrumented measures, but there has been limited consistency in these findings across studies. One of the major contributing factors to this inconsistency has been the wide variety of instrumented measures used. Across studies, however, based on several recent meta-analyses, there appears to be a very real postural-control deficit in those with CAI compared with healthy controls. Recently, a novel instrumented measure known as time to boundary (TTB) has consistently found deficits in those with CAI. TTB is a measurement technique that provides a contextual analysis of the relationship between center-of-pressure (COP) excursions and the base of support in which those excursions occur. The resulting TTB variables provide an estimation of the amount of time a person has to make postural corrections and the variability in strategies used to make them. Those with CAI have been shown to have less time to make postural corrections and lower variability in the strategies than healthy subjects, indicating impaired postural control.

Until recently, the link between these TTB deficits and CAI remained unclear. However, recent evidence suggests that altered somatosensory input from the lateral ankle-joint receptors may be a contributing factor. In a recent study, healthy subjects who underwent lateral ankle-joint anesthesia displayed deficits in TTB similar to those with CAI. There is also evidence to suggest that the sensorimotor system selectively reweights sensory input based on the availability of reliable information.
to maintain postural control.\textsuperscript{17} Taken together, those with CAI may rely more on other available inputs in the somatosensory system, namely, the musculotendinous receptors in the triceps surae and the receptors in the plantar surface of the foot. However, the reduction in reliable inputs may be related to the reduction in time to make corrections and the reduction in strategies to make them.

In order for the central nervous system to produce effective motor patterns to maintain postural control, sensory input must be generated from the various mechanoreceptors in the lower extremity.\textsuperscript{18} It has been previously demonstrated that sensory reweighting occurs in the presence of pathology.\textsuperscript{19,20} Specifically, those with low back pain have been shown to shift reliance on information from paraspinal muscles to ankle-muscle receptors compared with healthy subjects.\textsuperscript{19} These individuals also appear to display more rigid postural-control strategies than their healthy counterparts.\textsuperscript{19,20} It is possible that the sensorimotor system dynamically shifts reliance away from the affected area toward other available receptors. A similar dynamic regulation of sensory inputs might be a factor associated with postural-control alterations in those with CAI.

There may also be dynamic regulation of somatosensory input in other sources of information. Because the soles of the feet are the only points of contact between the body and the ground during single- and double-limb stance, it has been suggested that information from the plantar cutaneous mechanoreceptors may be important in postural control.\textsuperscript{21} Plantar cutaneous mechanoreceptors provide input to the central nervous system regarding the production of ankle torque, weight transfer, velocity of limb loading, and nature of the support surface.\textsuperscript{22} In a recent study, the use of textured insoles in healthy subjects did not lead to a change in single-limb-stance postural control.\textsuperscript{23} This indicated that although information from the plantar cutaneous receptors was compromised, there were other adequate sources of input available to maintain postural control. However, in a population that may have alterations in other sources of input, this may not be the case.

In the absence of contextual input from the lateral ankle-ligament receptors, those with CAI may dynamically reweight information to the plantar cutaneous receptors to maintain postural control. To gain more relevant information from these receptors, those with CAI may have to move closer to the boundaries of support to elicit appropriate postural responses. However, if plantar-receptor information becomes compromised in addition to the altered input from the lateral ankle-joint receptors, those with CAI may not have enough relevant input to appropriately execute the movement goal of maintaining single-limb stance.

Currently, there is no evidence of the effects of reweighted information from the plantar receptors on postural control in individuals with CAI. The independent variables were vision (eyes open, eyes closed) and texture (textured insole, sham insole, control). The dependent variables were measures of TTB, specifically, the mean and the standard deviation of the minima.

A crossover design was used to examine the effects of a textured insole on unipedal postural control in individuals with unilateral CAI. The independent variables were vision (eyes open, eyes closed) and texture (textured insole, sham insole, control). The dependent variables were measures of TTB, specifically, the mean and the standard deviation of the minima.

### Methods

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### Subjects

Twenty physically active subjects (12 men, 8 women; age 21.5 ± 5.5 y, height 175.6 ± 9.0 cm, weight 80.2 ± 17.2 kg) participated in this study. All were physically active and in good general health but self-reported having CAI based on a history of at least 1 sprain with a history of recurrent giving way, 4 or more “yes” answers on the Ankle Instability Instrument,\textsuperscript{24} self-reported disability as assessed by scores of less than 90% on the Foot and Ankle Disability Index (FADI),\textsuperscript{25} and 88% on the FADI sport subscale.\textsuperscript{26} The average FADI and FADI sport scores were 82% ± 9% and 62% ± 15%, respectively. The subjects in this study reported a mean of 9 ± 7 previous sprains, with 4.7 ± 5.6 months since the last significant sprain. Subjects were excluded from this study if they had suffered an acute ankle injury in the last 3 months, a history of other lower extremity injury in the last 12 months, a prior history of lower extremity surgery, suffered a concussion within the last 3 months, or suffered from any peripheral neuropathies or had a vestibular disorder. The study was approved by the appropriate university institutional review board, and informed consent was obtained from all subjects participating in this study.

### Instrumentation

Postural control was assessed with the AccuSway Plus balance platform (Advanced Mechanical Technology, Inc, Watertown, MA). COP measures were calculated from the composite 3-dimensional forces and moments arising from the foot–force-plate interaction through Balance Clinic software (Version 1.0, Advanced Mechanical Technology). COP data were sampled at 50 Hz and filtered through a fourth-order, zero-lag low-pass filter with a cutoff frequency of 5 Hz.

### Materials

Two types of insoles were used. The first was a textured insole made of clear plastic with raised points, 4 points/cm\(^2\), with an overall thickness of 3 mm.\textsuperscript{27} These insoles
were made of the matting material used to hold plastic mats to carpet. The second was a sham insole with no texture made of closed-cell foam with an overall thickness of 3 mm. Each trial was performed with the insole in the subject’s own shoe, but subjects were provided with a standard pair of nylon socks. The last condition was a control condition in which each subject performed single-limb-stance testing without any insert.

**Testing Procedures**

All subjects performed all testing procedures in accordance with a previously established protocol. Each subject’s foot was meticulously positioned in the center of the force-plate surface grid for each testing condition. The subjects were instructed to maintain single-limb stance for 6 conditions: the 3 conditions with eyes open (texture insole, sham insole, and control) and the 3 conditions with eyes closed. The control condition consisted of no insert in the shoe. To reduce any order effects, the 6 different protocols were designed and cycled through the study so that the first subject and the seventh subject would complete the study in the same order. Before the testing, the subjects were instructed to maintain single-leg stance with their arms folded across their chest and with their nonstance leg in 30° of hip flexion and 45° of knee flexion. Each trial lasted for 10 seconds and there were 3 trials per condition. A trial was terminated and repeated if the subject touched down with the nonstance limb, moved the arms from across the chest, attempted to gain better balance by hooking the nonstance leg onto the stance leg, or opened the eyes during eyes-closed tests or if the stance foot shifted out of position on the force plate. The number of failed trials was recorded and used for secondary analysis.

**Data Reduction**

TTB quantifies the spatiotemporal relationship between the COP and the base of support in the anteroposterior (AP) and mediolateral (ML) directions. To calculate TTB, the length and width of each subject’s foot was measured (in cm). By modeling the foot as a rectangle, the anterior, posterior, medial, and lateral boundaries of the base of support were identified. TTB analysis specifically examined the relationship between adjacent COP data points and the respective boundary of the foot. Therefore, each COP data point yields a TTB value in both the AP and ML directions. Rather than examining all values in the TTB series, the TTB minima were identified, which represent the times when the subject had the lowest TTB values. These values represented the times when the subjects had little time to make postural corrections to avoid colliding with the boundaries of support. The absolute TTB minimum represents the lowest single TTB value, the mean of TTB minima represents the average time a subject had to make a correction when balance was most precarious, and the standard deviation of TTB minima represents the variability of TTB values. The standard deviation of TTB minima is believed to present the level of constraint on the sensorimotor system. Less variability is indicative of fewer solutions used to make postural corrections. The mean and the standard deviation of TTB minima were calculated separately for the AP and ML directions for each trial. The mean of 3 trials of each condition for each variable was calculated and used for statistical analysis.

**Statistical Analysis**

To examine the effects of textured insoles on TTB measures of postural control, separate 2 × 3 ANOVAs with repeated measures were employed for each dependent variable. Independent variables included vision (eyes open, eyes closed) and texture (control, sham, textured insole). Dependent variables included the mean of TTB minima and the standard deviation of TTB minima in the ML and AP directions. If significant interactions were found, Fisher’s least-significant-difference tests were used to determine significant differences among pairwise comparisons.

Alpha level was set a priori at $P \leq .05$. All statistical analyses were performed with SPSS software, version 13.0 (SPSS Inc, Chicago, IL).

**Results**

Means and standard deviations for all TTB measures are listed in Table 1. A significant vision-by-texture interaction for the mean of TTB minima in the AP direction was found ($P = .05$). Post hoc comparisons revealed that during eyes-open trials, the mean of TTB minima in the AP direction was significantly lower with the textured insoles than in the control and sham conditions ($P < .05$). When vision was removed, there was no difference between any of the texture conditions.

There was a significant main effect for texture for the mean of TTB minima in the ML direction ($P = .01$). Post hoc comparisons revealed that the mean of TTB minima in the ML direction significantly decreased with the textured insole compared with the control or sham ($P < .05$). There was no difference between control and sham conditions.

There was a significant main effect for texture for the standard deviation of TTB minima in the ML direction ($F_{2,38} = 3.66, P = .04$). Post hoc tests revealed that the standard deviation of TTB minima in the ML direction significantly decreased with the use of the textured insole compared with control and sham conditions ($P < .05$). There were no differences between the control and sham conditions. There were no significant differences for the standard deviation of TTB minima in the AP direction for any of the textured conditions.

Finally, there was a significant main effect for vision for all TTB measures. When vision was removed, the mean and the standard deviation of TTB minima in the ML and AP directions significantly decreased ($P < .001$) regardless of texture condition.
Table 1  Time-to-Boundary (TTB) Measures in the Mediolateral (ML) and Anteroposterior (AP) Directions, s, Mean ± SD

<table>
<thead>
<tr>
<th>Time to Boundary (s)</th>
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<tr>
<td></td>
<td>Eyes Open</td>
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<td>Eyes Closed</td>
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<td></td>
<td>Control</td>
<td>Sham</td>
<td>Texture</td>
<td>Control</td>
<td>Sham</td>
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<tr>
<td>Mean of TTB ML minima*</td>
<td>4.6 ± 1.6</td>
<td>4.3 ± 1.4</td>
<td>4.0 ± 1.0</td>
<td>1.9 ± 0.5</td>
<td>2.1 ± 1.8</td>
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<td>Mean of TTB AP minima</td>
<td>14.2 ± 3.7</td>
<td>13.6 ± 3.8</td>
<td>12.2 ± 3.1†</td>
<td>5.6 ± 1.2</td>
<td>5.7 ± 1.1</td>
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<tr>
<td>Standard deviation of TTB ML minima*</td>
<td>3.8 ± 2.0</td>
<td>3.2 ± 1.6</td>
<td>2.8 ± 0.8</td>
<td>1.6 ± 0.7</td>
<td>2.0 ± 0.8</td>
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<tr>
<td>Standard deviation of TTB AP minima</td>
<td>9.4 ± 3.2</td>
<td>8.7 ± 3.1</td>
<td>8.1 ± 3.3</td>
<td>3.6 ± 0.8</td>
<td>3.8 ± 0.8</td>
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*Significant main effect in TTB ML measures with the textured insole (P < .05). The textured condition was significantly lower than both the control and sham conditions.
†Significant interaction in TTB AP measures with textured insole in eyes-open but not eyes-closed condition (P = .05). The textured condition was significantly lower than both the sham and control conditions with eyes open.

Discussion

The primary finding of this study was a significant reduction in the mean and standard deviation of TTB minima with the use of textured insoles. The reduction in standard deviation of TTB minima shows a potentially detrimental effect of textured insoles on the sensorimotor system’s ability to control single-limb stance. We hypothesized that altering sensory stimuli to the sole of the foot would lead to a decreased ability of the sensorimotor system to effectively reweight sensory inputs available to maintain single-limb stance.

TTB ML magnitude significantly decreased when participants wore textured insoles compared with the control condition and the sham condition, but there was no significant difference between the control and sham conditions. Likewise a significant reduction was found in the standard deviation when comparing texture with sham and texture with controls. These findings indicate that the textured condition was the cause of the reduction in ML control of single-limb stance. This reduction in the standard deviation of the TTB minima indicates that the sensorimotor system in these subjects was significantly more constrained in the texture condition than in the other conditions.13,14,29 In this case, we speculate that the impaired postural control was the result of the altered information from the plantar cutaneous receptors because of the stimulation from the textured insoles.

Significant impairments in TTB measures of postural control have been found in people with CAI.13 Freeman et al30,31 originally hypothesized that this phenomenon was the result of damage to the lateral ankle complex—an inversion sprain—resulting in a deafferentation of the lateral ligaments of the ankle. A recent investigation32 demonstrated significant alterations in TTB after lateral ankle-ligament anesthetization in healthy subjects. The authors of that study speculated that in the absence of information from lateral ankle-ligament receptors, healthy subjects spontaneously reweighted sensory inputs to place greater reliance on input from the plantar cutaneous and musculotendinous receptors to maintain postural control. This suggests a more dynamic central regulation of inputs. Dynamic sensory reweighting has been demonstrated in healthy individuals with the removal or confounding of visual, vestibular, or somatosensory information.17 In addition, it has been demonstrated that there is sensory reweighting of somatosensory input in pathological populations compared with healthy adults.19,20 Based on the evidence from these studies combined with recent evidence of gait initiation33 and termination,34 alterations in those with CAI—the dynamic regulation at the spinal and/or supraspinal levels—may be the key to better understanding the etiology of CAI.

Those with CAI have been shown to demonstrate significantly less TTB magnitude and variability, especially in the AP direction.13,14 To maintain postural control in the absence of information from the lateral ankle-ligament afferents, those with CAI may reweight sensory information specific to AP excursions to control upright stance, with a cost. To enhance the information provided by the musculotendinous receptors in the triceps surae complex and the tibialis anterior, as well as the plantar cutaneous mechanoreceptors in the soles of the feet, larger and more predictable excursions are needed in the AP direction. This would result in lower TTB magnitude and variability in the AP direction but preserved stability in the ML direction. This dynamic regulation affords CAI subjects the ability to maintain single-limb stance, but not as effectively as healthy subjects.13,14 The individual contributions of musculotendinous inputs and their role in maintaining postural control in those with CAI warrant further systematic exploration.

In the current study we altered this afferent input to the plantar cutaneous mechanoreceptors with the use of textured insoles. When worn in the shoe, these insoles stimulated the plantar cutaneous receptors differently than either the control or sham conditions. This may have resulted in a loss of boundary-relevant information in the AP direction to maintain postural control. The sensorimotor system could no longer effectively reweight the other available inputs, and consequently TTB magnitude in the AP and ML directions and variability in the ML
direction were compromised. The CAI subjects had more failed trials in the textured-insole condition (2.5 ± 3.0) than the sham condition (1 ± 1.3; \( P = .04 \)). In a previous study on healthy individuals, these textured insoles were shown to have no effect on single-limb stance compared with a control condition.\(^{23} \) Based on these findings, it is possible that the changes reported\(^{13,14} \) in TTB AP in those with CAI are evidence of dynamic reweighting of available inputs in the presence of decreased information from ankle receptors.

The findings of this study have potential clinically relevant implications. Based on the model proposed here, those with CAI may place greater reliance on inputs available, namely, the plantar cutaneous receptors. Although TTB is a laboratory-based measure, evaluating the ability to maintain single-limb stance with eyes closed in a clinical environment may provide an important measure. Determining the ability to balance on 1 limb with eyes closed in the presence of various interventions such as taping or wearing insoles may help clinicians determine which interventions are more functionally advantageous to patients with CAI.

There are a few limitations to our study. The assessors and the subjects were not blinded to the treatment conditions. We did, however, counterbalance the testing order and believe that we controlled for any potential bias that could have been introduced by order effect. Second, the subjects we used were young, physically active men and women in a narrow age range. These findings may not be generalizable to the larger population of patients with CAI. Third, there was no period of accommodation with regard to the textured insoles. Perhaps wearing the insoles for an extended period of time would alter the TTB profiles in single-limb stance. An additional confounding variable in this study might have been discomfort associated with wearing the textured insoles. We did not account for perceived pain or discomfort caused by the insoles. Future investigations would benefit greatly by exploring the perceived level of noxious stimulation as a potential covariate in postural-control alterations.

We recommend that future studies examine the effects of various types of textural material on measures of postural control and function in those with CAI. In addition, interventions to address the potential reweighting of the plantar-receptor information in the maintenance of postural control, gait, and other aspects of function in those with CAI warrant further investigation. The plantar receptors appear to play an important role in the maintenance of function in this population, and the potential benefit from advantageously augmented information must be systematically investigated.

In conclusion, we have found evidence to support the theory that stimulating the plantar surface of the foot, via a textured insole, has an effect on the broad spectrum of postural-control maintenance in individuals with CAI. Specifically, the plantar cutaneous receptors may play an important role in providing relevant, reweighted information to patients with CAI.

### References