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Gait & Posture

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Short communication

Time-to-boundary analysis of postural control following acute lateral ankle sprain

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ABSTRACT

Background: Acute lateral ankle sprain (ALAS) impairs unipedal balance both with the injured and uninjured limb, suggesting that balance during bipedal stance may also be compromised. However, a previous study failed to find such impairment because of poorly sensitive balance outcomes. Time-to-boundary (TTB) analysis may be sensitive enough for detecting latent deficits in bipedal balance following ALAS.

Research question: We aimed to examine postural stability during bipedal stance in patients with ALAS using TTB outcomes, and to determine bilateral deficits in unipedal balance.

Methods: Twenty-seven patients with ALAS and 26 persons without a history of ALAS participated. ALAS was operationally defined as a traumatic injury to the lateral ligaments of the ankle joint occurring within 24–72 h. Both limbs of the control group were side-matched to those of the patients as either injured or uninjured limbs. All participants performed 3 trials of bipedal stance with eyes open and closed. Next, they completed 3 trials of unipedal stance on both the injured and uninjured limbs in both visual conditions. Order of limb and visual condition for each limb was randomly selected. Means and standard deviations of TTB minima in the anteroposterior and mediolateral directions were computed to assess balance, with lower values indicating poorer balance.

Results: Independent t-tests revealed significant group differences for almost all measures ($p < 0.001$ to 0.021), indicating that the ALAS group presented poorer bipedal balance. For unipedal balance, there were no significant group-by-limb interactions for all measures ($p > 0.05$), indicating no side-to-side differences in the ALAS group. However, group main effects were found for all measures ($p = < 0.001$ to 0.048), showing poorer unipedal balance in the ALAS group.

Significance: TTB analysis revealed impaired balance during both unipedal and bipedal stance conditions following ALAS. These results support the emerging hypothesis that centrally mediated changes in postural control may occur following ALAS.

1. Introduction

There is strong evidence that acute lateral ankle sprain (ALAS) impairs postural control that is critical to joint stability and the prevention of falls/recurrent injuries [1,2]. Specifically, postural stability during unipedal (single-leg) stance is affected, not only with the injured limb but also with the uninjured limb [2–4]. Bilateral deficits following unilateral injury have highlighted centrally mediated changes in postural control that may occur following ALAS. This central mechanism suggests that postural stability during bipedal (double-leg) stance may also be compromised. However, there is little research on bipedal stance stability following ALAS. One previous study [5] examined bipedal stance stability in patients with ALAS by using center-of-pressure (COP) spatial-based measures (i.e. sway index), but failed to find statistically significant deficits. However, a subsequent meta-analysis [6] pointed out that the balance outcome measures that were previously used in that study may not be sensitive enough for detecting postural

control deficits. This argument is supported by subsequent findings on balance deficits during bipedal stance in patients with unilateral chronic ankle instability (CAI), a debilitating condition arising from an initial ALAS [7]. The deficits were discovered using more sensitive COP outcomes that were based on temporal aspects (i.e. velocity). In contrast, such deficits had not been found using COP spatial-based measures in an earlier study [8]. This clearly suggests that it is important to re-examine bipedal stance stability following ALAS with more sensitive measures because bipedal balance deficits associated with CAI likely develop from an initial ALAS.

A newly developed measure, known as time-to-boundary (TTB), incorporates both spatial and temporal aspects, and has been shown to be more sensitive than the traditional measure in patients with CAI [9,10]. However, it is unknown whether TTB is also sensitive enough for detecting postural control deficits due to ALAS. Therefore, the purpose of this study was to determine postural control during bipedal stance in patients with ALAS by using TTB outcomes. Additionally, TTB

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<https://doi.org/10.1016/j.gaitpost.2018.10.002>

Received 9 May 2018; Received in revised form 1 October 2018; Accepted 4 October 2018

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analyses were performed for assessing unipedal stance on either the injured or uninjured limb to determine whether the patients with ALAS enrolled in this study are representative of those presenting bilateral deficits during unipedal stance in previous studies.

2. Methods

A total of 53 participants from the university community were enrolled in the study through referrals and advertisements. The participants comprised 27 patients with ALAS and 26 persons without a history of ALAS. The recruitment methods and criteria for inclusion and exclusion were consistent with those of a previous study [11]. ALAS was operationally defined as a traumatic injury to the lateral ligaments of the ankle joint occurring from 24 to 72 h before the study. Patients with a first-time or recurrent ALAS were included, but those with injury to other areas (i.e. fracture, syndesmotic sprain, and medial sprain) and lateral ankle sprain older than 72 h were excluded. A single licensed clinician screened all participants and evaluated their injured ankles by using a standard ankle-injury evaluation form [11]. Participants who were matched for sex, age, height, and mass were recruited as the control group, and their limbs were side-matched to those of the patients as either injured or uninjured limbs. The demographics of the participants are presented in Table 1. The university institutional review board approved the study, and informed consent was obtained from all participants.

The balance testing procedures and data processing protocol were consistent with previously reported methods [9,10,12]. All participants were asked to perform 3 trials of bipedal stance (Task 1) with eyes open and closed. Next, they completed 3 trials of unipedal stance on both the injured (Task 2) and uninjured (Task 3) limbs in both visual conditions. Order of limb and visual condition for each limb was randomly selected. A total of 18 trials were required, with each trial lasting for 10 s. One practice trial was given in each condition. Trials, where participants were unable to maintain a 10-second balance, were repeated and excluded for statistical analysis. A forceplate (Accusway Plus; AMTI, Watertown, MA, USA) was used to record COP excursions that were sampled at 50 Hz and filtered with a fourth-order, zero-lag, low-pass Butterworth filter with a cut-off frequency of 5 Hz. A custom-made software program (MATLAB; The MathWorks Inc., Natick, MA, USA) was used to compute the study outcomes in the same manner as previously described [9,10,12]: means and standard deviations of TTB minima in the anteroposterior and mediolateral directions. Lower values of TTB outcomes indicate poorer postural control.

Table 1
Subject demographics.

Group	Ankle Sprain (n = 27)	Healthy Control (n = 26)
Sex	14 males, 13 females	14 males, 12 females
Age (yrs)	21.8 ± 3.0	22.3 ± 2.0
Height (cm)	174.5 ± 9.3	172.4 ± 10.2
Mass (kg)	71.7 ± 8.7	68.4 ± 11.9
Ankle swelling (cm) ^a	1.9 ± 0.7	0.07 ± 0.2
VAS score for pain (cm)	2.9 ± 1.1	0
FAAM-ADL (%) ^b	55.5 ± 15.9	99.6 ± 0.8
FAAM-Sport (%) ^c	32.5 ± 19.3	99.8 ± 0.6

Abbreviation: VASvisual analog scale; FAAMFoot and Ankle Ability Measure; ADLactivity of daily living.

^a quantified using the figure-of-eight method by subtracting the average of 3 measurements of uninjured ankle circumference from the average of injured ankle circumference.

^b represents self-reported ankle function perceived during activity of daily living from the time of ALAS (24–72 hours), ranging from 0 to 100% with a lower value indicating poorer ankle function.

^c represents self-reported ankle function perceived during sports from the time of ALAS (24–72 hours), ranging from 0 to 100% with a lower value indicating poorer ankle function.

For bipedal TTB measures, separate independent t-tests were used to determine group differences. Each unipedal TTB measure was assessed using a two-way (group-by-limb) repeated-measures analysis of variance (ANOVA). Additionally, Cohen's d effect sizes and associated 95% confidence intervals (CIs) were calculated and interpreted as follows: values > 0.2 were interpreted as small, 0.5 as moderate, and 0.8 as large [13]. All statistical analyses were performed using SPSS 24.0 (IBM Corp, Armonk, NY, USA) with the alpha level set *a priori* at $p \leq 0.05$.

3. Results

All participants successfully completed all balance tests, except for four patients with ALAS who were unable to perform a 10-second unipedal stance with the injured limb. These patients were excluded from the ANOVA test.

For bipedal postural control, there were significant group differences for almost all measures ($p = < 0.001$ to 0.021). The ALAS group presented lower TTB values than did the healthy control group, indicating poorer bipedal postural control in the patients (Table 2). The group differences seemed to be moderate in the eye-open condition ($d = 0.51$ – 0.75) and became large in the eye-closed condition ($d = 0.84$ – 1.08), with almost all associated 95% CIs not crossing zero, indicating that these observed effects are likely to be true.

For unipedal postural control, there were no significant group-by-limb interactions for all measures ($p > 0.05$); however, significant group main effects were found for all ($p = < 0.001$ to 0.048 , Table 3). These results indicate that unipedal postural control with the injured limb did not differ from that with the uninjured limb in the ALAS group; however, the groups were different after pooling data from both limbs, with the ALAS group showing poorer unipedal postural control. The group differences were close to moderate in the eye-open condition ($d = 0.48$ – 0.73) and became large in the eye-closed condition ($d = 0.92$ – 1.42). These observed effect sizes are likely to be true because most of the associated 95% CIs did not cross zero.

4. Discussion

TTB analysis revealed impaired postural control during both unipedal and bipedal stance conditions in patients with ALAS, with no differences noted in unipedal postural control between the injured and uninjured limbs in the ALAS group. The lower TTB mean in the ALAS group indicates that patients with ALAS may have less time to make a postural correction for maintenance of balance over the base of support. In addition, they may have fewer movement strategies for balance, as reflected by a lower TTB standard deviation. The impairments appeared to be greater in the eye-closed condition than in the eye-open condition for both stance conditions.

The present study confirmed the previous findings of bilateral deficits during unipedal stance following ALAS [2–4], and supports the emerging hypothesis that centrally mediated changes in postural control may occur immediately after ALAS. In addition, the impaired postural control during bipedal stance found in the current investigation presents new supporting evidence for this hypothesis. However, the current study is in conflict with a previous study that failed to find the impairment in patients with ALAS [5]. The discrepancy may be largely explained by the different COP measures used to determine postural control. The COP spatial-based measures used in the previous study overlooked the important temporal aspect of balance, resulting in poor sensitivity [6]. Instead, incorporating both spatial and temporal aspects together in the context of the size of the base of support has been shown to be more sensitive in patients with CAI [9,10], and the current study demonstrates that TTB analysis is also useful in detecting postural control deficits during both the unipedal and bipedal stance conditions in patients with ALAS. In addition, the larger balance disruption in the absence of visual information observed in this study has been previously noted [3,5], and may indicate altered sensory

Table 2
Time-to-Boundary (TTB) measures calculated during 10-sec bipedal standing.

Task	TTB parameter	Group Difference	Ankle Sprain Group	Healthy Control Group	Group Effect Size ^a
Bipedal stance with eyes open	Mean-ML(s)	t(51) = -2.374, p = 0.021	97.90 ± 38.65	121.80 ± 34.40	0.65(0.10, 1.21)
	Mean-AP(s)	t(51) = -2.733, p = 0.009	50.17 ± 11.60	59.86 ± 14.15	0.75(0.19, 1.31)
	SD-ML (s)	t(51) = -2.442, p = 0.018	59.39 ± 22.98	77.34 ± 30.17	0.67(0.12, 1.22)
	SD-AP (s)	t(51) = -1.852, p = 0.070	32.50 ± 9.68	37.56 ± 10.21	0.51(-0.04, 1.06)
Bipedal stance with eyes closed	Mean-ML(s)	t(51) = -3.937, p < 0.001	74.30 ± 32.64	108.27 ± 30.10	1.08(0.50, 1.66)
	Mean-AP(s)	t(51) = -3.048, p = 0.004	33.50 ± 11.19	44.25 ± 14.37	0.84(0.28, 1.40)
	SD-ML (s)	t(51) = -3.139, p = 0.003	46.86 ± 20.89	66.29 ± 24.10	0.86(0.30, 1.43)
	SD-AP(s)	t(51) = -2.813, p = 0.007	21.01 ± 8.57	27.92 ± 9.31	0.77(0.21, 1.33)

Abbreviation: ML, mediolateral; AP, anteroposterior; SD, standard deviation.

^a Cohen's *d* estimate of effect size was calculated between two groups using pooled standard deviation, along with its associated 95% confidence interval.

Table 3
Time-to-Boundary (TTB) measures calculated during 10-sec unipedal stance.

Task	TTB parameter	Group-by-Limb Interaction	Group Main Effect	Side	Ankle Sprain Group	Healthy Control Group	Group Effect Size ^a
Unipedal stance with eyes open	Mean-ML (s)	F _{1,47} = 0.99, p = 0.325	F _{1,47} = 4.69, p = 0.035	Injured	4.20 ± 1.19	4.99 ± 1.15	0.67(0.12, 1.23)
				Uninjured	4.50 ± 1.05	5.05 ± 1.21	0.49(-0.06, 1.03)
	Mean-AP (s)	F _{1,47} = 0.01, p = 0.935	F _{1,47} = 6.37, p = 0.015	Injured	11.74 ± 2.34	13.77 ± 3.15	0.73(0.18, 1.29)
				Uninjured	12.24 ± 2.85	14.23 ± 3.18	0.66(0.11, 1.21)
SD-ML (s)	F _{1,47} = 2.44, p = 0.125	F _{1,47} = 4.82, p = 0.033	Injured	3.45 ± 1.76	4.53 ± 1.27	0.70(0.15, 1.26)	
			Uninjured	3.57 ± 1.66	4.26 ± 1.17	0.48(-0.07, 1.03)	
SD-AP (s)	F _{1,47} = 0.01, p = 0.933	F _{1,47} = 4.13, p = 0.048	Injured	7.93 ± 2.13	9.22 ± 2.13	0.61(0.05, 1.16)	
			Uninjured	8.07 ± 2.46	9.31 ± 2.71	0.48(-0.07, 1.03)	
Unipedal stance with eyes closed	Mean-ML (s)	F _{1,47} = 0.09, p = 0.762	F _{1,47} = 19.56, p < 0.001	Injured	2.26 ± 0.69	3.08 ± 0.79	1.11(0.53, 1.69)
				Uninjured	2.31 ± 0.63	3.18 ± 0.78	1.23(0.64, 1.82)
	Mean-AP (s)	F _{1,47} = 3.62, p = 0.063	F _{1,47} = 23.10, p < 0.001	Injured	5.45 ± 1.45	8.24 ± 2.38	1.42(0.82, 2.02)
				Uninjured	5.94 ± 1.31	8.11 ± 2.12	1.24(0.65, 1.82)
SD-ML (s)	F _{1,47} = 1.83, p = 0.183	F _{1,47} = 20.73, p < 0.001	Injured	1.75 ± 0.70	2.84 ± 0.93	1.33(0.73, 1.92)	
			Uninjured	1.89 ± 0.68	2.76 ± 0.85	1.13(0.55, 1.71)	
SD-AP (s)	F _{1,47} = 0.29, p = 0.592	F _{1,47} = 13.43, p = 0.001	Injured	3.73 ± 1.39	5.12 ± 1.23	1.06(0.48, 1.63)	
			Uninjured	3.93 ± 1.29	5.19 ± 1.45	0.92(0.35, 1.49)	

Abbreviation: ML, mediolateral; AP, anteroposterior; SD, standard deviation.

^a Cohen's *d* estimate of effect size was calculated between two groups using pooled standard deviation, along with its associated 95% confidence interval.

reweighting following ALAS (specifically, increased reliance on the visual system for postural control) [14].

The current study supports previous clinical recommendations against using an uninjured limb as a criterion for normal postural control when assessing unipedal balance in an injured limb following ALAS [2], and suggests global neuromuscular training aimed at both the injured and uninjured limbs. Additionally, bipedal stance instability presents a new rehabilitation area for patients with ALAS. It is critical to rehabilitate both bipedal and unipedal postural control in patients with ALAS to facilitate functional recovery.

Conflict of interest statement

All authors confirm that there are no conflicts of interest associated with this work.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors

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