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Short Communication

Comparison of the correlations between impact loading rates and peak accelerations measured at two different body sites: Intra- and inter-subject analysis

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ABSTRACT

Background: High average (VALR) and instantaneous vertical loading rates (VILR) during impact have been associated with many running-related injuries. Peak acceleration (PA), measured with an accelerometer, has provided an alternative method to estimate impact loading during outdoor running. This study sought to compare both intra- and inter-subject correlations between vertical loading rates and PA measured at two body sites during running.

Methods: Ground reaction force data were collected from 10 healthy adults (age = 23.6 ± 3.8 years) during treadmill running at different speeds and inclination surfaces. Concurrently, PAs at the lateral malleoli and the distal tibia were measured using synchronized accelerometers.

Results: We found significant positive intra-subject correlation between loading rates and PA at the lateral malleoli ($r = 0.561–0.950$, $p < 0.001$) and the distal tibia ($r = 0.486–0.913$, $p < 0.001$). PA measured at the lateral malleoli showed stronger correlation with loading rates ($p = 0.004$) than the measurement at the distal tibia. On the other hand, inter-subject variances were observed in the association between PA and vertical loading rates. The inter-subject variances at the distal tibia were 3.88 ± 3.09 BW/s and 5.69 ± 3.05 BW/s in VALR and VLIR respectively. Similarly, the inter-subject variances in the measurement at lateral malleoli were 5.24 ± 2.85 BW/s and 6.67 ± 2.83 BW/s in VALR and VLIR respectively.

Conclusions: PA measured at lateral malleoli has stronger correlation with VALR or VILR than the measurement at distal tibia. Caution is advised when using PA to conduct inter-subject comparisons of vertical loading rates during running.

1. Introduction

High vertical loading rates (VLRs) have been reported as a biomechanical risk factor for running injuries, such as stress fracture and plantar fasciitis [1–3]. However, measurements of VLRs outside laboratory are limited by the requirement of a force plate. With advances in sensor technology, wireless accelerometers provide a possible way to measure running kinetics in an outdoor running environment. Some studies reported positive correlations between VLRs and peak acceleration (PA) measured by accelerometers attached at different body sites in adults during level ground walking and running [4–6] and it has been suggested that the PA measured at the lateral malleoli may better predict VLRs than the measurement at proximal tibia and thigh [4].

However, the association between VLRs and the PA at the anteromedial part of the distal tibia has not been assessed. This site provides a flat surface for sensor attachment and PA measured at this site has been associated to the development of tibia stress fracture [1,4]. In addition, outdoor running environment includes running at different speed and inclination surfaces. It has been noted that VLRs change with different running conditions [7]. Thus, whether the association between VLRs and PA can be maintained during running in different conditions should be taken into consideration. More importantly, previous studies only addressed intra-subject correlation between PA and VLRs. Inter-subject variance may affect the results especially in some randomized

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control trials which compared PA between subjects [8] but it is yet examined. Therefore, this study sought to establish the intra- and inter-subject relationship between VLRs and PA measured at the lateral malleoli and the distal tibia in different running conditions.

2. Methods

2.1. Subjects and procedures

Ten healthy adults (8 males and 2 females; age = 23.6 ± 3.8 years; height = 1.73 ± 0.08 m; mass = 66.1 ± 12.7 kg) free from any active lower-extremity injuries were recruited. All the subjects signed an informed consent form and the experiment was approved by the concerning institutional review board.

Four lightweight accelerometers (Model 7523A5, 0–400 Hz frequency range, 50 g range, Dytran Instruments, CA, USA) were securely taped on both sides of the lateral malleoli and anteromedial aspect of the distal tibias (Fig. 1). All the subjects conducted nine randomized running conditions on an instrumented treadmill (AMTI, Watertown, MA, USA), with differences in speed (usual speed; +15% of usual speed; and −15% of usual speed) and inclination surfaces (flat; 10% inclined; and 10% declined). Each running trial lasted for 2 min with 1 min rest to avoid fatigue. Customized LabVIEW codes (version 8.6, National Instruments, Austin, TX, USA) were used to capture the vertical ground reaction force and acceleration data.

2.2. Data analysis

Ground reaction force and acceleration data were recorded at 1000 Hz, filtered at 50 Hz with a fourth order Butterworth lowpass filter [9]. Average (VALR) and instantaneous vertical loading rate (VILR) were obtained by the method previously described [1], and normalized by body mass. Landing PA was defined as the maximum positive acceleration that occurred during the early stance phase of running [1]. VALR, VILR, and landing PA at different body sites were identified in 40 consecutive steps in each running trial.

2.3. Statistical analysis

All the data were processed using SPSS.21® statistics software of package (Chicago, IL, USA). Global alpha was set at 0.05. Intra-subject correlations between VALR, VILR, and PA measured at different body sites were analyzed using Pearson's *r*. Paired-*t* tests were used to compare the Pearson's *r* between distal tibia and lateral malleoli among the 10 subjects.

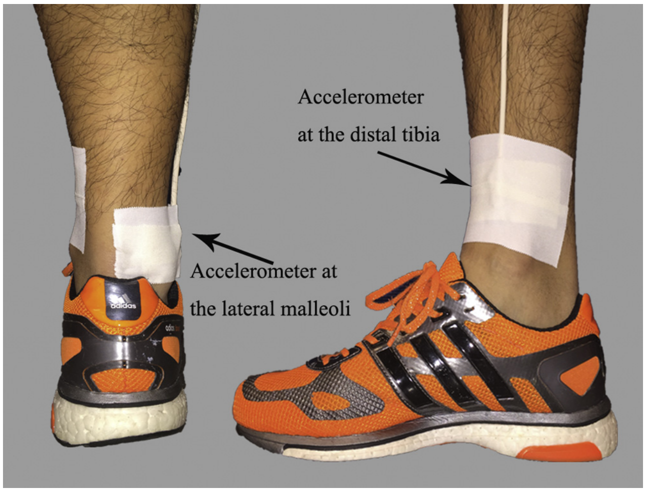

Fig. 1. Accelerometers taped to the subject's lateral malleoli and the anteromedial aspect distal tibia.

Bland and Altman's method [10] was used to examine the inter-subject variance in the association between PA and VLRs. Multiple regressions were performed and subject was treated as a categorical factor using dummy variables to assess the variation brought by each subjects on prediction of VLRs, expressing as the unstandardized coefficient (B). Any subject with significant ($p < 0.05$) B was considered to have a significant variance with the pooled regression curves. Paired-*t* tests were used to compare the B values between distal tibia and lateral malleoli among the 10 subjects.

3. Results

The intra-subject correlations between PA and VLRs in all the nine running conditions were shown in Table 1. PA at the lateral malleoi and the distal tibia demonstrated a moderate to excellent positive correlation with VALR and VILR ($r = 0.486–0.950$, $p < 0.001$). The PA measured at the lateral malleoli showed stronger association compared to that at the distal tibia (both $p = 0.04$).

The inter-subject analysis between PA and VLRs were shown in Fig. 2a–d, with each subject represented by a colored line, and the pooled regression curve was shown as a line with dots at both ends. Five out of 10 subjects had significant variance in the correlation between PA measured at the distal tibia (Fig. 2a and b,

Table 1
Mean and SD values for each subject and intra-subject correlation coefficients (*r*) between PA and VLRs.

Subject	Measured value (mean (SD))				Correlation coefficient (*r*)			
	Landing PA at distal tibia (g)	Landing PA at lateral malleoli (g)	VALR (BW/s)	VILR (BW/s)	Landing PA at distal tibia		Landing PA at lateral malleoli	
					VALR	VILR	VALR	VILR
1	13.71 (2.29)	13.10 (2.42)	88.37 (19.31)	131.30 (27.62)	0.546**	0.584**	0.617**	0.647**
2	10.15 (2.22)	10.05 (2.18)	79.82 (25.87)	123.89 (41.12)	0.793**	0.779**	0.950**	0.948**
3	7.99 (1.88)	7.26 (1.36)	42.82 (12.91)	67.98 (15.86)	0.778**	0.771**	0.878**	0.887**
4	7.62 (2.19)	6.97 (1.68)	52.15 (20.01)	83.38 (28.11)	0.913**	0.898**	0.863**	0.879**
5	6.08 (1.08)	5.31 (1.07)	30.19 (9.15)	45.63 (13.56)	0.580**	0.583**	0.736**	0.682**
6	13.06 (2.85)	11.33 (2.36)	68.04 (18.85)	106.86 (25.28)	0.495**	0.528**	0.595**	0.633**
7	7.12 (1.74)	6.37 (0.84)	30.78 (9.03)	46.06 (14.24)	0.556**	0.577**	0.561**	0.608**
8	8.75 (1.87)	7.62 (1.28)	70.28 (17.17)	100.46 (24.43)	0.802**	0.807**	0.926**	0.934**
9	7.27 (1.81)	7.25 (1.44)	41.17 (15.81)	65.84 (24.93)	0.638**	0.737**	0.688**	0.815**
10	6.28 (1.47)	5.71 (1.01)	30.82 (3.96)	43.36 (7.72)	0.486**	0.547**	0.699**	0.862**

[*] $p < 0.05$.
[**] $p < 0.001$.