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Considerable variability in tibial acceleration slope (AS) values, and different interpretations of injury risk based on these values, have been reported. Acceleration slope variability may be due in part to variations in the quantification methods used. Therefore, the purpose of this study was to quantify differences in tibial AS values determined using end points at various percentage ranges between impact and peak tibial acceleration, as a function of either amplitude or time. Tibial accelerations were recorded from 20 participants (21.8 ± 2.9 years, 1.7 m ± 0.1 m, 75.1 kg ± 17.0 kg) during 24 unshod heel impacts using a human pendulum apparatus. Nine ranges were tested from 5–95% (widest range) to 45–55% (narrowest range) at 5% increments. $AS_{Amplitude}$ values increased consistently from the widest to narrowest ranges, whereas the AS_{Time} values remained essentially the same. The magnitudes of $AS_{Amplitude}$ values were significantly higher and more sensitive to changes in percentage range than AS_{Time} values derived from the same impact data. This study shows that tibial AS magnitudes are highly dependent on the method used to calculate them. Researchers are encouraged to carefully consider the method they use to calculate AS so that equivalent comparisons and assessments of injury risk across studies can be made.

Keywords: tibial acceleration, heel impacts, loading rate

To assess the injury risk associated with activities involving impacts to the lower extremities, the time profiles of either the impact force or segment accelerations should be taken into consideration to provide information on shock wave transmissibility (Hennig et al., 1993; Nigg et al., 1995; Williams et al., 2001). Loading rates of vertical ground reaction forces (Bahlsen, 1989; Bauman, 1997; Lafortune & Lake, 1995; Munro et al., 1987; Nigg & Liu, 1999; Williams et al., 2001), and acceleration slopes (AS) (Flynn et al., 2004; Holmes & Andrews, 2006) or transient rates (Lafortune & Lake, 1995; Lafortune et al., 1996) measured by surface accelerometers, are quantities that have been used to assess impact forces or segment accelerations caused by heel-ground contact.

In terms of injury risk, greater tibial acceleration and loading rates, as measured by the slope of the acceleration waveform, have been reported by Davis et al. (2004) and Milner et al. (2008) for females diagnosed with tibial stress fractures. Increases in loading rate may result in a stiffened pathway, along which the shock wave will travel (Greenwald et al., 1998), and may therefore result in an increased risk of injury such as fracture (Hansen, et al., 2008; Milner et al., 2008).

Comparison between studies reporting acceleration slope values is made difficult because, although a number of authors have calculated acceleration slope by using the linear portion of the acceleration waveform (Flynn et al., 2004; Holmes & Andrews, 2006; Lafortune & Lake, 1995; Lafortune et al., 1996), their calculations have relied on using different slope end points. Slope end point ranges have been reported from 10– 90% (Lafortune & Lake, 1995) to 30–70% (Flynn et al., 2004; Holmes & Andrews, 2006; Lafortune et al., 1996) of either time to peak tibial acceleration (PA) (Flynn et al., 2004), or PA amplitude (Holmes & Andrews, 2006; Lafortune & Lake, 1995; Lafortune et al., 1996). The effect of using different percentage ranges of either time or amplitude on the calculation of acceleration slope values has not been documented to date and could have implications for assessing injury risk. Therefore, the purpose of this study was to quantify differences in tibial acceleration slope magnitudes determined using end points at various percentage ranges between the time of impact and peak tibial acceleration, as a function of either amplitude or time.

Methods

Tibial acceleration waveforms from 10 male and 10 female healthy, right leg dominant participants (21.8 ± 2.9 years, 1.7 m ± 0.1 m, 75.1 kg ± 17.0 kg) with no previous injuries to the lower extremities, were collected and analyzed using custom LabVIEW software (v. 8.2, National Instruments, Austin, TX, USA). A custom-made triaxial accelerometer (MMA1213D, Freescale Semiconductor, Inc, Ottawa ON, Canada; range, ±50 *g*; mass, approximately 2.1 g) was attached to the skin with double-sided tape just medial to the tibial tuberosity on the dominant leg, but only the acceleration along the long axis of the

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leg was analyzed in this study. The accelerometer was preloaded with a strap, using a force of approximately 45 N perpendicular to the tibia (Andrews & Dowling, 2000; Flynn et al., 2004; Holmes & Andrews, 2006). Subjects completed 24 unshod heel impacts onto a vertical force platform when lying supine on a human pendulum apparatus. The pendulum was pulled back and then released from a distance that resulted in impact forces of between 1.8 and 2.8 × body weight and velocities of between 1.0 and 1.15 m/s^2 for all conditions (procedure more fully described in Flynn et al., 2004 and Holmes & Andrews, 2006). Data were sampled at 4096 Hz and A/D converted (12-bit PCI 6023E card, National Instruments) starting at release and continuing until after impact (total time of approximately 2 s).

Acceleration slope was calculated between two end points described by percentages, as a function of the PA amplitude ($AS_{Amplitude}$) or the time to PA (AS_{Time}) (Figure 1). Nine percentage ranges were tested from 5–95% to 45–55%, at 5% increments. Therefore, data from the 24 impacts were analyzed at nine percentage ranges, rendering a total of 216 AS values per subject. These AS values were then collapsed across the 24 conditions for each subject. A 2 × 9 repeated-measures ANOVA was conducted to examine any significant differences between the two methods ($AS_{Amplitude}$ or AS_{Time}), or the nine percentage ranges. Alpha (α) was set at 0.05, and Tukey HSD post hoc tests were completed on significant main effects and interactions. Within-subject coefficients of variation (CV) for both AS_{Time} and $AS_{Amplitude}$ were calculated to assess the variability of these measures for each subject across the 24 trials.

Results

Main effects based on AS method and percentage range were incorporated into a higher order interaction ($p < .001$), which is clearly shown by the divergence of the two curves in Figure 2. Mean $AS_{Amplitude}$ values (2121 g/s ± 463 g/s) were significantly greater for all ranges than AS_{Time} values (1374 g/s ± 375 g/s). The $AS_{Amplitude}$ magnitudes increased consistently across all ranges, but were not significantly different at the narrowest ranges, from 35–65% to 45–55%, whereas all AS_{Time} magnitudes narrower than 5–95% were statistically the same (Table 1, Figure 2).

Within-subject CVs were fairly high in general, ranging from 13 to 67%, and 7 to 80% for AS_{Time} and $AS_{Amplitude}$, respectively (Table 2). Across all percent ranges, a moderate correlation (r = .69) was found between the average AS_{Time} and $AS_{Amplitude}$ values of each subject (range between r = .55 and r = .99). Comparable variability in AS_{Time} and $AS_{Amplitude}$ values has been previously noted using the same methodology (Holmes & Andrews, 2006).

Table 1 Mean (± *SD*) acceleration slope values calculated as a function of time (AS_{Time}) and amplitude ($AS_{Amplitude}$), across all percentage ranges studied

Percentage Range	AS_{Time} (g/s)	$AS_{Amplitude}$ (g/s)
5–95%	1212 (285)	1736 (370)
10–90%	1350 (292)	1904 (407)
15–85%	1391 (326)	2013 (435)
20–80%	1422 (354)	2103 (453)
25–75%	1396 (420)	2175 (469)
30–70%	1346 (442)	2237 (487)
35–65%	1399 (407)	2280 (502)
40–60%	1418 (414)	2311 (514)
45–55%	1432 (435)	2336 (528)

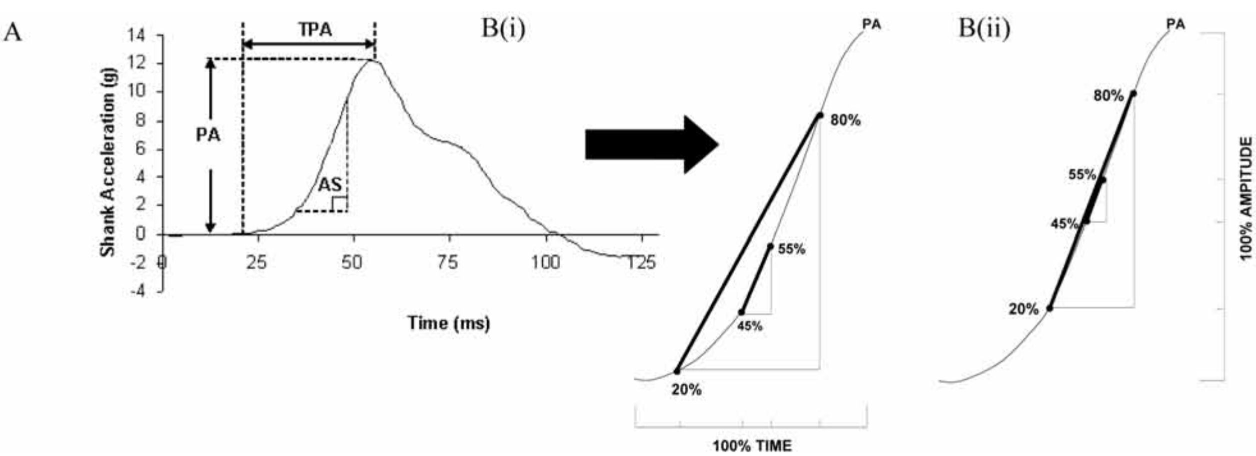

Figure 1 — A) Tibial acceleration waveform with peak tibial acceleration (PA), time to peak tibial acceleration (TPA), and acceleration slope (AS) highlighted. B) Sample ranges for acceleration slope (AS) calculations as a function of (i) time and (ii) amplitude.

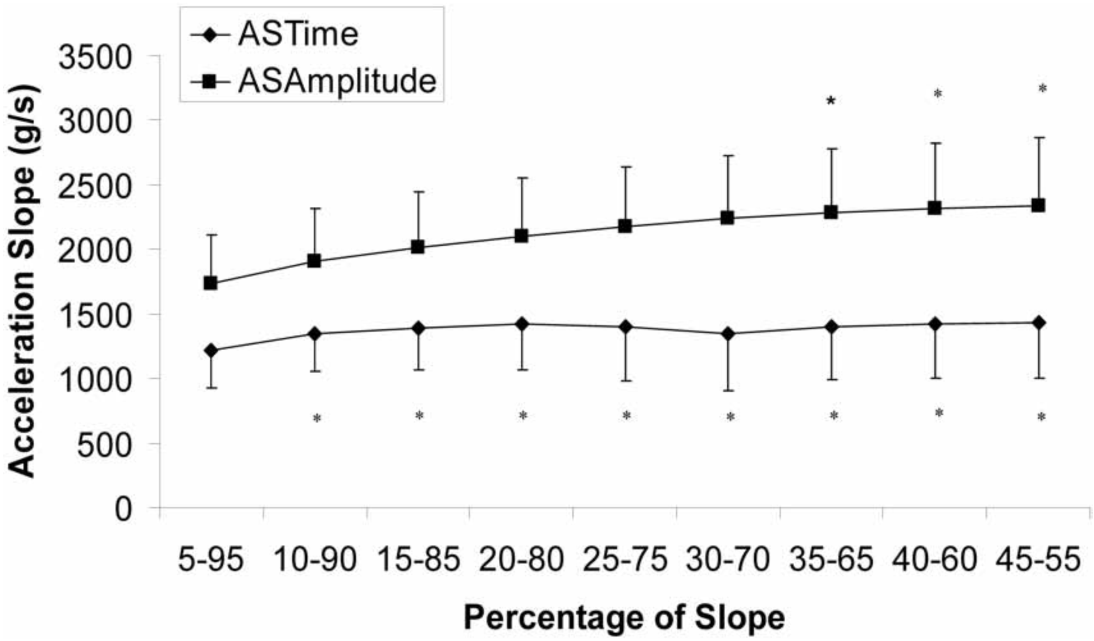

Figure 2 — Acceleration slope (AS) calculated as a function of amplitude ($AS_{Amplitude}$) or time (AS_{Time}). *Statistically the same.

Table 2 Mean acceleration slope (AS) values and within-subject coefficients of variation (CV) calculated as a function of time (AS_{Time}) and amplitude ($AS_{Amplitude}$), based on the 24 trials completed at nine percentage ranges by each subject

Subject	Mean AS_{Time} (g/s)	CV AS_{Time} (%)	Mean $AS_{Amplitude}$ (g/s)	CV $AS_{Amplitude}$ (%)
1	1378	21	2897	12
2	1611	28	2110	24
3	1637	17	3210	13
4	1285	13	1890	11
5	957	67	1429	80
6	1584	28	2083	26
7	2188	27	3125	24
8	1122	22	1519	17
9	552	48	1938	23
10	1460	17	1679	19
11	1867	23	2269	23
12	1641	31	3250	7
13	872	27	1018	22
14	1489	25	2840	11
15	1073	39	1754	43
16	1244	21	1577	16
17	1470	37	2605	26
18	1019	33	1540	28
19	1985	25	2366	20
20	1040	30	1328	35

Discussion

When characterizing tibial acceleration waveforms, a decision must be made regarding what portion of the waveform most appropriately describes the acceleration slope. Most authors have assessed the linear portion of the acceleration waveform, yet inconsistencies in methods of quantifying slope have been reported (Holmes & Andrews, 2006; Flynn et al., 2004; Lafortune & Lake, 1995; Lafortune et al., 1996). The current study has shown that $AS_{Amplitude}$ values were significantly higher and more sensitive to changes in percentage range than AS_{Time} values derived from the same impact data. Despite the differences between the approaches, the acceleration slope values calculated by both methods ($AS_{Amplitude}$ and AS_{Time}) fell within the range of those previously reported in the literature (Table 3).

The purpose of this study was to quantify differences in tibial acceleration slope magnitudes determined using end points at various percentage ranges between impact and peak tibial acceleration, as a function of either amplitude or time. Different percentage ranges of 10–90% (Lafortune & Lake, 1995) and 30–70% (Flynn et al., 2004; Holmes & Andrews, 2006; & Lafortune et al., 1996) of the acceleration waveform have been previously used in the literature. For the type of data reported here, using a percentage range that is narrower than 10–90% and 35–65% for AS_{Time} and $AS_{Amplitude}$, respectively, would be appropriate, since values were statistically similar beyond these ranges. These data have important implications, as percentage ranges wider than 35–65% have been used for assessing $AS_{Amplitude}$ (Holmes & Andrews, 2006; Lafortune & Lake, 1995; Lafortune et al., 1996). It is possible that the most linear portion of the acceleration slope may not be as accurately represented at these wider ranges. For example, as depicted schematically in Figure 1, the characteristic nonlinear toe region right after impact likely had some influence on slope values at the wider ranges using both approaches. It may be that less of the nonlinear toe region was captured using the amplitude approach in general, given that the midpoints between impact and time to peak acceleration are slightly different when assessing the slope based on time or amplitude (Figure 1). This might also help to explain the higher mean values for $AS_{Amplitude}$ than AS_{Time} in general (Figure 2). It should be noted though that the linearity of the regions for each percentage range was not quantified directly in this study. Slight variability in the automatic detection of the time of impact using software, such as that used in this study, may also play a role in the magnitude and variability of the slope values determined using both approaches. Time of impact, and therefore AS magnitudes, can be adversely affected by the variability in the waveform shape between impacts, as well as signal processing and the sensitivity of the equipment.

It is not the intention of the authors of the current study to promote the use of acceleration slope data as the determining factor in assessing tibial response. Research has suggested that the time profiles of either the impact force or segment accelerations must be taken into consideration to properly understand the injury risk due to impacts (e.g., Hennig et al., 1993; Nigg et al., 1995; Williams et al., 2001). Acceleration slope data have also been used by previous authors to assess impact-induced shock waves (Flynn et al., 2004; Holmes & Andrews, 2006; Lafortune & Lake, 1995; Lafortune et al., 1996). For these reasons, an investigation into the method employed (amplitude or time) and the percentage range was warranted.

In conclusion, $AS_{Amplitude}$ magnitudes were significantly higher, and more sensitive to changes in percentage range than AS_{Time} values. Researchers should be aware of the differences that can exist in acceleration slope values, based on the method they use to calculate them, and are encouraged to be precise in their description of the method they used so direct comparisons between studies can be made.

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Table 3 Comparison of the mean (± *SD*) acceleration slope values across studies in the literature that used similar methodologies

Reference	Slope Method Used	Acceleration Slope (g/s)
Current Study	Amplitude	2121 (463)
Current Study	Time	1374 (375)
Holmes & Andrews (2006)	Amplitude	1563 (614)
Flynn et al. (2004)	Time	2742 (1426)
Lafortune & Lake (1995)	Amplitude	671 (220)
Lafortune et al. (1996)	Amplitude	1150 (930)

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