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Short communication

Measurement of peak impact loads differ between accelerometers – Effects of system operating range and sampling rate

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ABSTRACT

A wide variety of accelerometer systems, with differing sensor characteristics, are used to detect impact loading during physical activities. The study examined the effects of system characteristics on measured peak impact loading during a variety of activities by comparing outputs from three separate accelerometer systems, and by assessing the influence of simulated reductions in operating range and sampling rate. Twelve healthy young adults performed seven tasks (vertical jump, box drop, heel drop, and bilateral single leg and lateral jumps) while simultaneously wearing three tri-axial accelerometers including a criterion standard laboratory-grade unit (Endevco 7267A) and two systems primarily used for activity-monitoring (ActiGraph GT3X+, GCDC X6-2mini). Peak acceleration (*gmax*) was compared across accelerometers, and errors resulting from down-sampling (from 640 to 100 Hz) and range-limiting (to ±6 g) the criterion standard output were characterized. The Actigraph activity-monitoring accelerometer underestimated *gmax* by an average of 30.2%; underestimation by the X6-2mini was not significant. Underestimation error was greater for tasks with greater impact magnitudes. *gmax* was underestimated when the criterion standard signal was down-sampled (by an average of 11%), range limited (by 11%), and by combined down-sampling and range-limiting (by 18%). These effects explained 89% of the variance in *gmax* error for the Actigraph system. This study illustrates that both the type and intensity of activity should be considered when selecting an accelerometer for characterizing impact events. In addition, caution may be warranted when comparing impact magnitudes from studies that use different accelerometers, and when comparing accelerometer outputs to osteogenic impact thresholds proposed in literature.

1. Introduction

Exercises involving impact loading are critical for initiating osteogenic activity in bone. The loading magnitude of exercise is critical because bone adaptations are suggested to be threshold-driven (Bassey and Ramsdale, 1995; Heinonen et al., 1996; Kemmler et al., 2004). Accelerometers are commonly used to estimate impact loading; however, there is substantial variation in device characteristics reported in the literature, and the influence of these characteristics on measures of peak impact is unclear (e.g. operating ranges from ±6 to ±40 g, sampling rates from 40 to 2000 Hz, Table 1). If sensor characteristics do influence measures of peak acceleration, identifying mechanistic pathways that explain these differences could assist researchers/clinicians in selecting the most appropriate sensor specifications for their applications.

There are distinct mechanisms by which insufficient sampling rate and operating range could influence measures of peak signal magnitude. A low sampling rate decreases the probability that the peak magnitude of a transient signal spike (e.g. jump landing) will occur at the same instant the signal is sampled. When a sensor's operating range is exceeded, the measured values saturate at upper limit of the operation range. Errors associated with insufficient sampling rate are primarily sensitive to signal frequency, while those associated with operation range are sensitive to signal magnitude. As the two errors are derived from different

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Table 1
A sample of accelerometer devices (and associated operating ranges and sampling rates) reported in the literature for characterizing impact loading during exercise and activities of daily living.

Device	Study reference	Operating range (g)	Sampling rate (Hz)
Actigraph	Esliger et al. (2011), Garcia et al. (2004), Meyer et al. (2015), Rowlands and Stiles (2012) and Stiles et al. (2013)	±6	100
BioTrainer	Garcia et al. (2004) and Neugebauer et al. (2012)[a]	±40	40
GENEActiv	Esliger et al. (2011), Meyer et al. (2015), Rowlands and Stiles (2012) and Stiles et al. (2013)	±8	100
MEMS accelerometer	Morrow et al. (2014)[a]	±16	100
Custom Accelerometer	Heikkinen et al. (2007), Jämsä et al. (2006), Vainionpää et al. (2006) and Vihriälä et al. (2003)		400
Custom Accelerometer	Liikavainio et al. (2007)[a]	±10	2000

[a] Study only reported impacts associated with walking and/or running tasks, activities which were not examined in the current study.

mechanisms, the combination of insufficient sampling rate and operating range could introduce more error than either factor alone. However, the influences of these two factors on peak impact loading measured by accelerometers have never been reported in the literature.

Accordingly, the objectives of this study were to examine how system characteristics, such as operating range and sampling rate, influence the measurement of peak impact loads by commercial activity-monitoring systems as compared to a laboratory-grade criterion standard accelerometer. We hypothesized that: (1) the criterion standard accelerometer would measure higher peak accelerations across all tasks; (2) the activity-monitoring accelerometers would demonstrate more pronounced underestimation error for tasks with higher impact magnitudes; (3) post hoc decreases in sampling rate and operating range in the criterion standard accelerometer data would decrease measures of peak acceleration; and (4) the underestimation errors from the activity-monitoring accelerometers would be associated with the effects of post hoc decreases in sampling rate and operating range. Rather than focussing on the output from any particular sensor, the overall goal of the study was to provide evidence of the importance of considering accelerometer system characteristics (in concert with acceleration magnitudes from activities-of-interest) in the design and interpretation of studies characterizing impact events.

2. Methods

2.1. Participants

Twelve participants were included in the study (5 males, 7 females; mean (SD) age = 24.1 (2.6) years; height = 171.3 (8.1) cm; mass = 66.8 (11.5) kg), which was approved by the University of Waterloo's Office of Research Ethics. All participants completed the Physical Activity Readiness Questionnaire (PAR-Q) (Thomas et al., 1992) and had no contra-indications to exercise.

2.2. Instrumentation

Participants were instrumented with three accelerometers. Our criterion standard accelerometer was a laboratory-grade tri-axial unit (Model 7267A, Endevco Corporation, San Juan Capistrano, CA, USA) with a wired connection to an external amplifier (Model 1012, Endevco Corporation, San Juan Capistrano, CA, USA). While its maximum operating range was ±1500 g, a ±260 g range was used to improve amplitude resolution. The signal was directed through a 16-bit analog-to-digital converter, and 1st Principles software (Northern Digital Inc., Waterloo, ON) sampled the signal at 640 Hz (nearly double the rate of the highest activity-monitoring accelerometer described below).

Two tri-axial accelerometers commonly used for activity monitoring were also tested: ActiGraph GT3X+ (ActiGraph LLC, Pensacola, FL) and X6-2mini (Gulf Coast Data Concepts, Waveland, MS). Most importantly for the objective of this study, these devices were selected as they employed a lower operating range than our criterion standard accelerometer, and utilized different sampling rates. Furthermore, both were commercially-available devices which had been used for research purposes (Dobkin et al., 2011; Esliger et al., 2011; Meyer et al., 2015; Rowlands and Stiles, 2012; Stiles et al., 2013; Tung et al., 2014). The Actigraph device employed an operating range of ±6 g and a sampling rate of 100 Hz. The X6-2mini used the same operating range (±6 g), but a higher sampling rate (360 Hz). All three accelerometers were affixed to one-another using double-sided tape, secured to the participant's left anterior superior iliac crest (ASIS) using a flexible belt, then further secured with a second elastic belt to ensure unified movement. The ASIS was selected as the hip is a common accelerometer site for similar applications (e.g. Jämsä et al., 2006; Meyer et al., 2015; Rowlands and Stiles, 2012; Stiles et al., 2013; Vainionpää et al., 2006), and it aligned with manufacturers' recommendations.

2.3. Protocol

Based on previous literature (e.g. Jämsä et al., 2006), seven tasks were selected to provide a range of impact magnitudes including: vertical jump (including counter-movement), bilateral single leg jumps, bilateral lateral jumps, box drop (height 32 cm), and heel drop. Three trials of each task were performed, with rests of ten-seconds between each trial and 30 s between tasks. Data from the criterion standard accelerometer were saved directly onto a desktop computer, while data from the other devices were downloaded to the computer after each participant completed the protocol.

2.4. Data processing

All signals were analyzed using custom MATLAB routines (R13, Mathworks Inc., Natick, MA). Data corresponding to the vertical plane at the start position were analyzed. All data were first high-pass filtered (3rd order Butterworth, cutoff = 0.25 Hz) to remove offsets due to gravity (Veltink et al., 1996). For each trial, peak vertical acceleration (*gmax*) from each device was identified automatically and confirmed by visual inspection. For each device, *gmax* from the three trials for each task were averaged. In addition, % error for the Actigraph and X6-2mini devices was calculated as:

$$error = ((gmax_{comparator} - gmax_{crit\_standard})/gmax_{crit\_standard}) * 100\%$$

To explicitly examine the effects of sampling rate and operating range, custom MATLAB routines were used to down-sample the criterion standard signal from 640 Hz to 100 Hz, and data points >6 g were set to 6 g (equivalent to the Actigraph's sampling rate and operating range). gmax from each trial was identified using the methods described above for: (i) down-sampled data; (ii) range-limited data; and (iii) combined down-sampled and range-limited data. gmax percent error for each of these conditions was calculated as outlined above.

2.5. Statistical analysis

A repeated measures analysis of variance (ANOVA) was used to assess the influence of accelerometer and task on *gmax* (Hypothesis 1). We assessed whether *gmax* underestimation errors increased for tasks with higher impact magnitudes (Hypothesis 2) by performing Pearson product-moment correlations between task-averaged *gmax* from the criterion standard accelerometer and error for the two activity-monitoring accelerometers. A repeated measures ANOVA assessed the influence of criterion standard post-processing (range-limiting, down-sampling, combined) and task on *gmax* (Hypothesis 3). Finally, we performed a Pearson product-moment correlation between task-averaged underestimation errors from the Actigraph data vs. the combined down-sampled and range-limited data from the criterion standard accelerometer (Hypothesis 4). For the