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Accelerometer counts and raw acceleration output in relation to mechanical loading

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ABSTRACT

The purpose of this study was to assess the relationship of accelerometer output, in counts (ActiGraph GT1M) and as raw accelerations (ActiGraph GT3X+ and GENEA), with ground reaction force (GRF) in adults. Ten participants (age: 29.4 ± 8.2 yr, mass: 74.3 ± 9.8 kg, height: 1.76 ± 0.09 m) performed eight trials each of: slow walking, brisk walking, slow running, faster running and box drops. GRF data were collected for one step per trial (walking and running) using a force plate. Low jumps and higher jumps (one per second) were performed for 20 s each on the force plate. For box drops, participants dropped from a 35 cm box onto the force plate. Throughout, three accelerometers were worn at the hip: GT1M, GT3X+ and GENEA. A further GT3X+ and GENEA were worn on the left and right wrist, respectively. GT1M counts correlated with peak impact force (r=0.85, $p<0.05$), average resultant force (r=0.73, $p<0.05$) and peak loading rate (r=0.76, $p<0.05$). Accelerations from the GT3X+ and GENEA correlated with average resultant force and peak loading rate irrespective of whether monitors were worn at the hip or wrist ($r>0.82$, $p<0.05$, $r>0.63$ $p<0.05$, respectively). In conclusion, accelerometer count and raw acceleration output correlate positively with GRF and thus may be appropriate for the quantification of activity beneficial to bone. Wrist-worn monitors show a similar relationship with GRF as hip-worn monitors, suggesting that wrist-worn monitors may be a viable option for future studies looking at bone health.

1. Introduction

Physical inactivity is an established risk factor for osteoporosis (Bass et al., 1998). Accelerometers provide an objective, non-intrusive measure of activity and the high resolution of data acquisition makes them ideally suited for capturing the short bursts of activity beneficial to bone (Heikkinen et al., 2007). Typically, the relationship between accelerometer counts and energy expenditure is used to translate counts into biologically meaningful units (Rowlands et al., 2004). This is appropriate when examining the relationship between activity and cardio-vascular or metabolic health but is not appropriate for bone health, where counts should be calibrated against mechanical loading.

Activities eliciting a mean ground reaction force (GRF) of three body weights have positive associations with bone health (Bassey et al., 1998). Additionally, peak loading rate reflects the peak steepness of the vertical force loading curve that typically occurs during the early stages of ground contact and is a key indicator of loading underfoot (Munro et al., 1987; Lilley et al., 2011). Thus, GRF (peak and average) and peak loading rate are pertinent to bone health (Bassey and Ramsdale, 1995; Bassey et al., 1998) and are appropriate criterion variables for accelerometer calibration.

The GRF (Munro et al., 1987; Lafortune et al., 1995; van den Bogert et al., 1996; Bassey et al., 1998; Elvin et al., 2007; Lilley et al., 2011) and raw acceleration (Lafortune et al., 1995; van den Bogert et al., 1996; Mercer et al., 2003; Moe-Nilssen and Helbostad, 2004; Brandes et al., 2006; Elvin et al., 2007; Kavanagh and Menz, 2008) profiles associated with walking, running and jumping have been previously reported. However, there is little data linking the commercially available accelerometers that are used for habitual physical activity measurement to GRF. The most widely used accelerometer is the ActiGraph. ActiGraph counts reflect *peak* GRFs during walking and running in children, though not drop jumps (Janz et al., 2003), and *average* GRFs during continuous jumping and drop jumps as well as walking and running in children (Garcia et al., 2004). However, output from a commercially available accelerometer, e.g. the ActiGraph, has not been calibrated against GRFs in adults.

Output from most accelerometers (e.g. the ActiGraph GT1M, RT3, Actical) is in proprietary counts, hindering between model comparisons (Kavanagh and Menz, 2008). Briefly, to obtain a count, the

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voltage signal from the accelerometer is first digitized by an analog-to-digital converter. Differing analytical approaches can then be applied, but, most commonly, the signal is rectified and integrated over a user-defined epoch of between 1 s and 60 s (Chen and Bassett, 2005). This summation of activity counts over epochs leads to smoothing of data which may mask the peaks of acceleration that are particularly beneficial to bone (Heikkinen et al., 2007).

Recent developments in commercial accelerometry, i.e. the development of a new accelerometer, the GENEA (Esliger et al., 2011) (manufactured and distributed as the GeneActiv, by ActivInsights Ltd.), and release of the latest version of the ActiGraph accelerometer (GT3X+), both of which measure acceleration at a frequency of 100 Hz in three dimensions, provide scope to determine temporal aspects of dynamic loading. As raw acceleration data is provided, the output from each of these monitors should be comparable facilitating comparisons between data regardless of the monitor used.

Most accelerometers are designed to be worn at the hip and are not waterproof. The GENEA and GT3X+ are waterproof and can be worn at the wrist. These qualities largely negate the need to remove the monitor and participants find the monitor more acceptable for assessment of habitual activity (van Hees et al., 2011). However, greater inter-individual variability in arm movement relative to torso movement means it is likely that the wrist location will provide a less valid assessment of activity. For any given study the chosen wear location should reflect consideration of validity, but also of feasibility and participant compliance to the measurement protocol. To enable researchers to do this it is necessary that the performance of these accelerometers is assessed and compared at both the wrist and the standard hip wear locations.

In this study, we hypothesized (a) that there would be a positive relationship between accelerometer output (vertical ActiGraph GT1M counts, raw acceleration data from the GENEA and the GT3X+) and GRF in adults and (b) the raw acceleration data from the GENEA and the GT3X+ accelerometers would be comparable. The GENEA and GT3X+ were worn at the wrist and the hip to provide a comparison of accelerometer performance at each wear location.

2. Methods

2.1. Procedure

Ten participants (males (N=5): age: 26.4 ± 4.0 yr, mass: 78.2 ± 12.6 kg, height: 1.82 ± 0.10 m; females (N=5) age: 32.4 ± 10.5 yr; mass: 70.3 ± 6.4 kg; height: 1.70 ± 0.04 m) were recruited from the University population. The Institutional ethics committee granted approval and all participants gave written informed consent.

After familiarization, each participant performed a series of activities designed to cover a range of GRFs: slow walking, brisk walking, slow running, faster running, low jumps, higher jumps and box drops. Eight trials of each of the walking and running activities were performed over a straight distance of 40 m with GRF data collected for one step per trial. A force plate set flush within the floor (960 Hz, Advanced Mechanical Technology Inc., Massachusetts) was used to collect GRF data. Time to complete 40 m was recorded for each trial. Speed gates were positioned either side of the force plate to ensure speed remained consistent and trials were discarded and recollected if participants' self selected speed for running/walking was outside ±5% of their preferred speed determined during familiarization, or the participant failed to correctly contact the force plate. Low jumps (2–5 cm) and higher jumps (10–15 cm) were performed continuously (one per second) for 20 s on the force plate. A metronome was used to regulate jumping rate. Finally participants dropped from a 35 cm high box onto the force plate eight times. Participants were instructed to land two-footed and then remain stationary on the force plate for five seconds. No restrictions were placed on arm movement throughout all activities.

Throughout testing, an ActiGraph GT1M, GT3X+ and GENEA accelerometer were worn at the waist (on an elastic belt with the GT1M and GT3X+ accelerometers adjacent and the GENEA taped to the GT1M, positioned over the right hip, Fig. 1). A second GT3X+ was worn on the left wrist and a second GENEA on the right wrist.

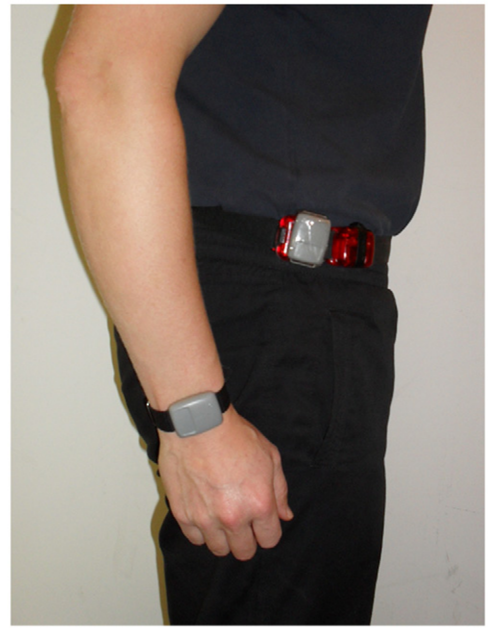

Fig. 1. Accelerometer locations at the waist and right wrist: GT1M and GT3X+ accelerometers adjacent and the GENEA taped to the GT1M, positioned over the right hip; GENEA on right wrist.

The ActiGraph GT1M (version 3, ActiGraph, Pensacola, USA) and GENEA accelerometers have been described in detail elsewhere (Esliger et al., 2011). ActiLife5 analysis software (version 5.0.48) was used to initialize the GT1M and GT3X+ and upload the data. The GT1M was set to collect data in the vertical axis with a 1 s epoch and the GT3X+ to collect triaxial data at a sampling frequency of 100 Hz. GENEA software (version 1.602) was used to initialize the GENEAs at a sampling frequency of 80 Hz and to upload data.

2.2. Data analysis

Force plate output variables were peak impact force, average resultant force (throughout the step) and peak loading rate. Forces were expressed as body weights (output force/mass (kg) × acceleration due to gravity (9.81 m/s^2)). Proprietary count data (counts per second) were extracted from the GT1M files and peak acceleration (g) and peak slope (g.s^{-1}) were extracted from the raw acceleration files for the GT3X+ and the GENEA monitors. Data for both vertical acceleration and resultant acceleration were extracted for the GT3X+ and the GENEA worn at the hip, but only data for resultant acceleration were extracted for the GT3X+ and GENEA worn at the wrist. For the monitors worn at the hip the majority of loading through the body would be in line with the vertical vector, but no such assumption can be made for the monitors worn at the wrist.

A series of repeated measures ANOVAs were run to assess whether the GRF dependent variables and the GT1M output differentiated by activity. A series of fully repeated measures ANOVAs (monitor × activity) were run to assess whether the raw output from the GT3X+ and the GENEA differed by activity and/or monitor for each of the dependent variables. Finally, two fully repeated measures ANOVAs (location × activity, one for the GENEA and one for the GT3X+) were run to assess whether the resultant peak g differed by hip or wrist location across activities. Where sphericity was violated, the Greenhouse–Geisser correction factor was applied. Post-hoc analyses were carried out using pairwise comparisons with alpha (0.05) adjusted using the Bonferroni correction.

Correlations were used to assess relationships between accelerometer output variables and force plate output variables. Correlations were carried out across all activities for each individual separately. The mean of the individual correlations (calculated using Fisher's zr transformation) is reported.

Alpha was set at 0.05 and PASW Statistics 18.0 (SPSS Inc., Chicago, IL) was used for all analyses.

3. Results

All GRF output variables showed a main effect for activity type ($p < 0.001$), with forces generally increasing with locomotion speed and with jump height (Fig. 2). Peak impact force was significantly higher for low jumps, high jumps and box drops than for walking and