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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 cardiovascular 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 $\pm 5\%$ 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) $\times$ 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 $\times$ 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 $\times$ 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

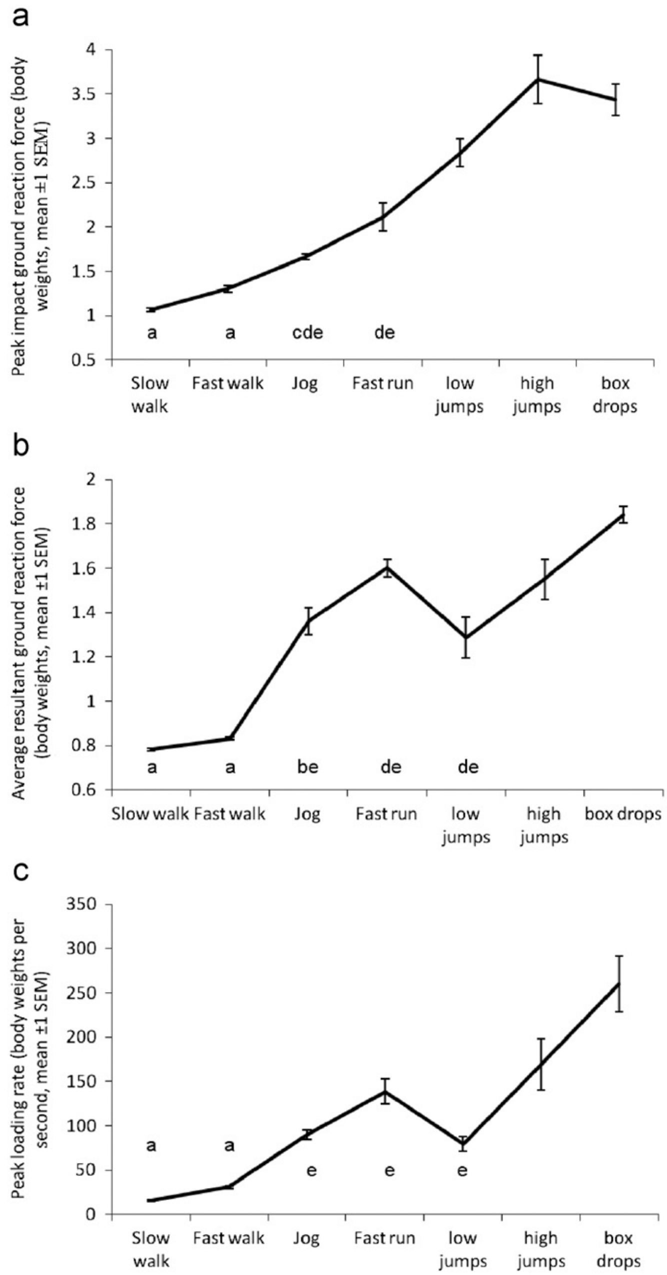

Fig. 2. Ground reaction force variables by activity: peak impact force (top panel, a); average resultant force (middle panel, b); peak loading rate (bottom panel, c). Significant differences ($p<0.05$) across activity: a = different from all other activities, b = different from fast run, c = different from low jumps, d = different from high jumps, e = different from box drops.

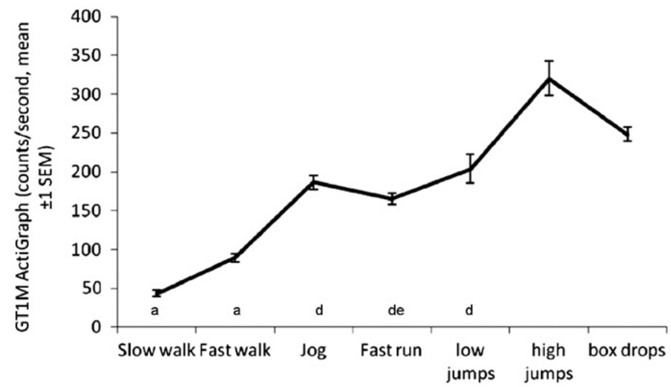

Fig. 3. ActiGraph GT1M output (proprietary counts/second) by activity. Significant differences ($p<0.05$) across activity: a = different from all other activities, b = different from fast run, c = different from low jumps, d = different from high jumps, e = different from box drops.

running and for high jumps and box drops than for all locomotor tasks (Fig. 2a); however, average resultant force and peak loading rate for low and high jumps were not significantly different from those for jogging and fast running (Fig. 2b and c).

A main effect for GT1M counts showed a similar pattern to average resultant force ($p<0.001$, Fig. 3). However, counts plateaued for the fast run and declined for box drops, thus counts for box drops were not significantly different from counts for low jumps and high jumps. GT1M counts correlated positively and significantly with peak impact force [mean $r=0.85$ ($p<0.05$; $zr=1.27\pm0.45$, mean $\pm$ SD)], and peak loading rate [mean $r=0.76$ ($p<0.05$; $zr=1.00\pm0.47$, mean $\pm$ SD)]. The correlation between GT1M counts and average resultant force was positive and borderline significant [mean $r=0.73$ ($p=0.06$; $zr=0.94\pm0.39$, mean $\pm$ SD)].

Results for raw acceleration measures from the GT3X+ and the GENEA are shown in Fig. 4. Irrespective of raw acceleration outcome measure there was a main effect for activity ($p<0.001$, Fig. 4a–f). The pattern of response across activities was very similar to that for average resultant force. However, output for low and high jumps tended to be lower or not different from those for jogging and running.

Main effects for monitor showed the raw acceleration output from the GENEA at the hip was higher than the corresponding output for the GT3X+ for the peak g (resultant), the slope of the resultant acceleration and the peak g (vertical) ($p<0.004$, Fig. 4a–c). Post-hoc analysis of significant interactions for peak g (resultant acceleration, $p=0.002$ and vertical acceleration, $p=0.011$) indicated that the resultant peak acceleration from the GENEA was higher than that from the GT3X+ for all activities except walking, but the vertical peak acceleration from the GENEA was only higher than that from the GT3X+ for low jumps. No interaction was evident for the slope of the resultant acceleration. No differences between monitors were evident for the slope of the vertical acceleration at the hip ($p=0.485$, Fig. 4d) or for the monitors worn at the wrist (resultant acceleration: peak g $p=0.174$; slope $p=0.929$, Fig. 4e and f).

Significant location $\times$ activity interactions were evident for the resultant g for both the GENEA and the GT3X+ ($p<0.001$ and $p=0.01$, respectively, Fig. 5a and b). Post-hoc analysis revealed that the output from the hip was higher than that for the wrist for brisk walking and all jumping activities for both monitors and for slow running for the GENEA only ($p<0.05$). Conversely, for fast running the GT3X+ wrist output was higher than the GT3X+ hip output ($p<0.05$).

Output from the GT3X+ and the GENEA correlated positively with average resultant force and peak loading rate from the force plate, irrespective of whether the monitors were worn at the hip or wrist (mean $r>0.82$, $p<0.05$ and mean $r>0.63$, $p<0.05$, respectively, Table 1). Correlations with peak impact force were weaker (wrist: mean $r=0.58$–0.59; hip: mean $r=0.73$–0.74), and not significant.

4. Discussion

Accelerometers appear to be ideally suited for the capture of short bursts of activity beneficial to bone (Freedson et al., 2005; Janz et al., 2010). To provide outcomes relevant to bone,

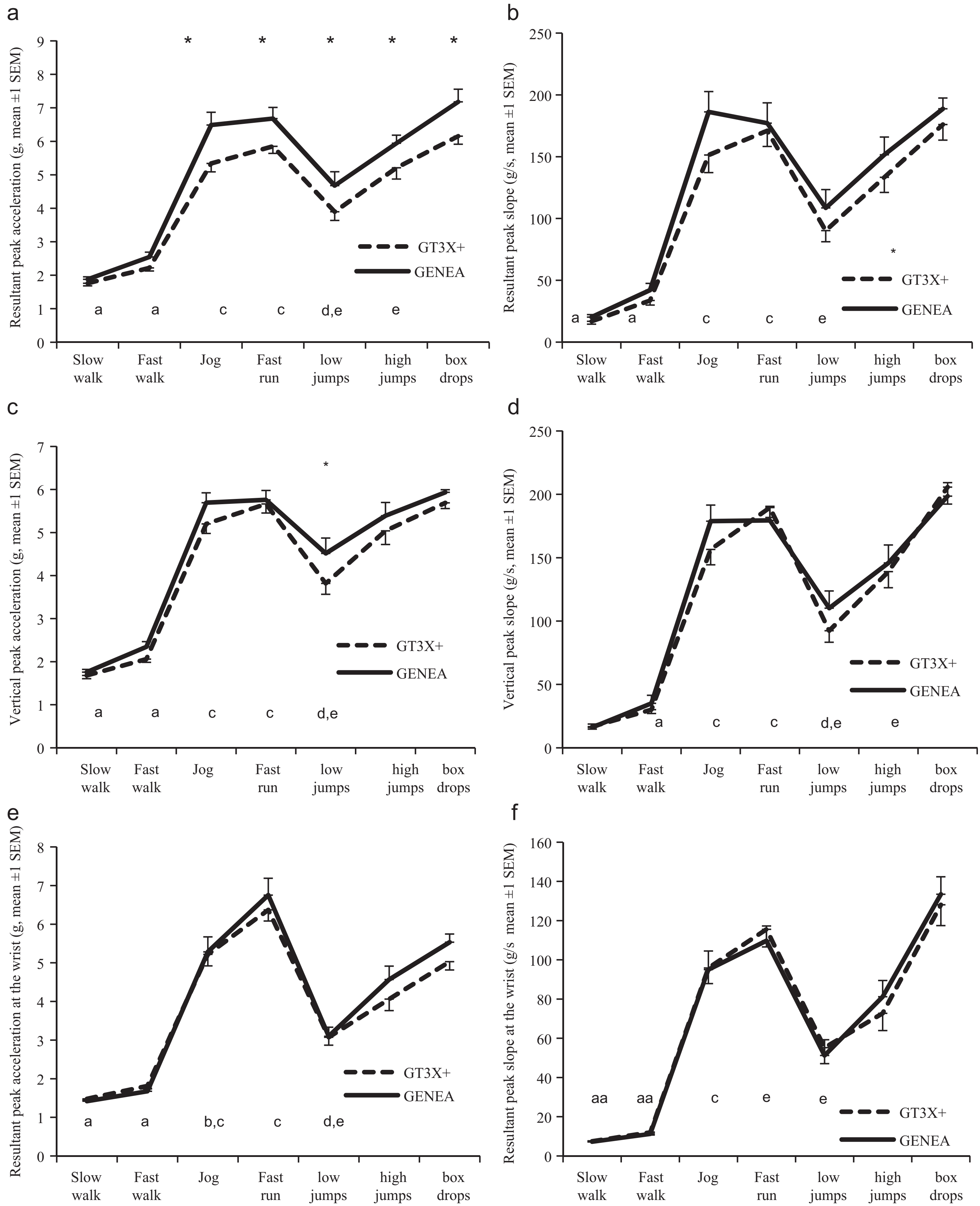

Fig. 4. Raw acceleration output (ActiGraph GT3X+ and GENEA) by activity: resultant peak acceleration and resultant peak slope from the monitors worn at the waist (top panel, a and b, respectively); vertical acceleration and vertical peak slope from the monitors worn at the waist (middle panel, c and d, respectively); resultant acceleration and resultant peak slope from the monitors worn at the wrist (bottom panel, e and f, respectively). Significant differences ($p < 0.05$) across activity: a = different from all other activities, aa = different from all other activities, except those also marked aa, b = different from fast run, c = different from low jumps, d = different from high jumps, e = different from box drops. * = GENEA output significantly higher ($p < 0.05$) than GT3X+ output (interactions (a) and (c), main effect (b).

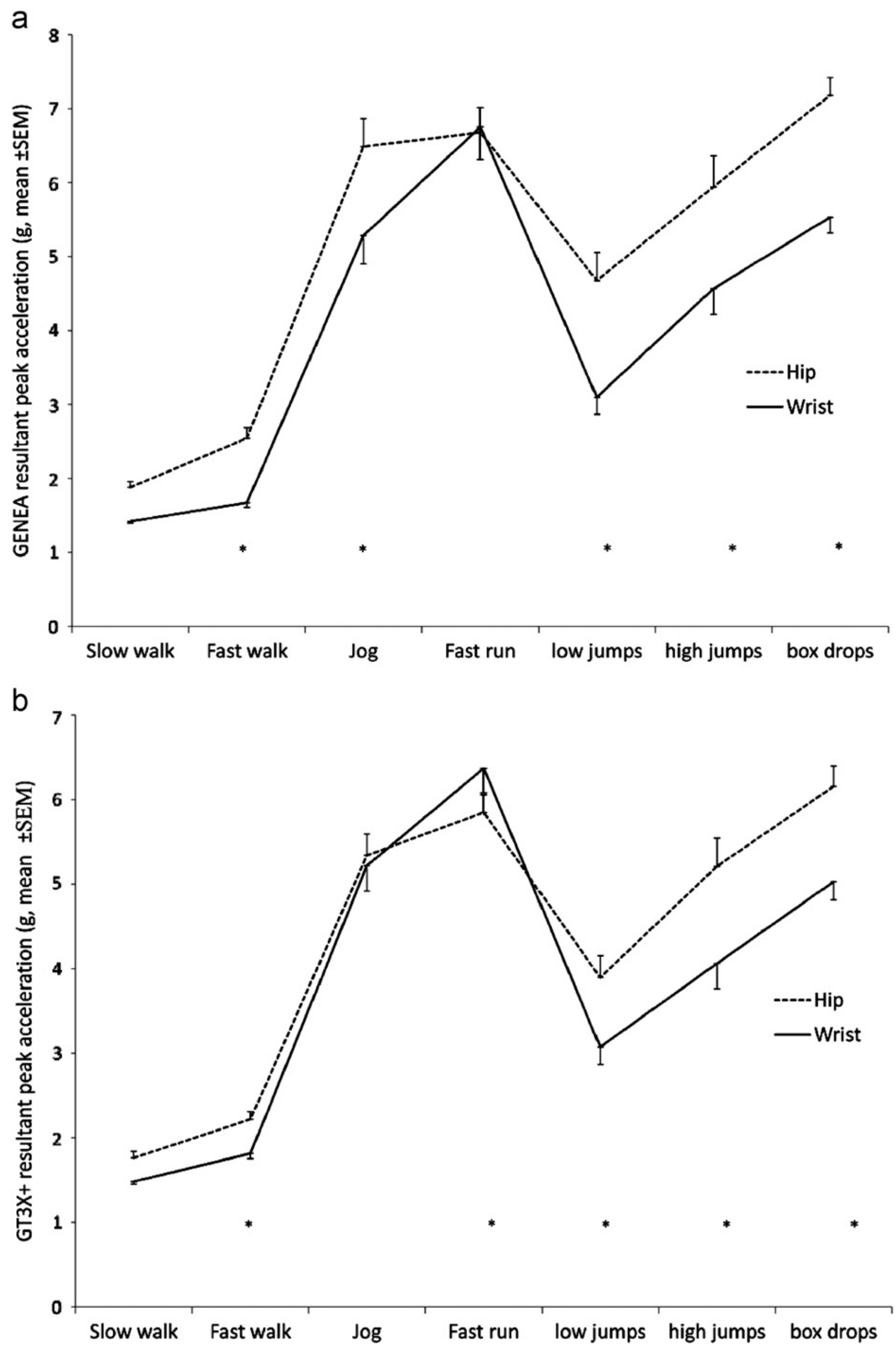

Fig. 5. Raw acceleration output (resultant peak *g*) for the GENEA (top panel), (a) and the ActiGraph GT3X+ (bottom panel), (b) location (wrist/hip) and activity. *Significant difference between locations ($p<0.05$).

Table 1
Relationships between ground reaction force output variables (peak impact force, average resultant force and peak loading rate) and raw acceleration output (GT3X+ and GENEA), *r* (*zr* (mean ± SD)).

	Hip (vertical axis)		Hip (resultant)		Wrist (resultant)	
	GT3X+	GENEA	GT3X+	GENEA	GT3X+	GENEA
Peak acceleration						
Peak impact force	0.73 (0.93 ± 0.50)	0.74 (0.95 ± 0.52)	0.73 (0.94 ± 0.50)	0.73 (0.93 ± 0.58)	0.59 (0.68 ± 0.56)	0.58 (0.67 ± 0.48)
Average resultant	0.85* (1.25 ± 0.40)	0.82* (1.17 ± 0.31)	0.87* (1.33 ± 0.52)	0.85* (1.25 ± 0.44)	0.82* (1.17 ± 0.67)	0.87* (1.32 ± 0.78)
Peak slope						
Peak loading rate	0.76* (1.00 ± 0.40)	0.70* (0.86 ± 0.28)	0.70* (0.86 ± 0.29)	0.63* (0.75 ± 0.23)	0.79* (1.08 ± 0.53)	0.81* (1.13 ± 0.52)

* $p<0.05$.

calibration against measures of GRF is necessary. This study provides the first such validation study of commercially available accelerometers in adults.

ActiGraph GT1M output had a strong relationship with GRF and followed a similar pattern across activities as average resultant force and peak loading rate. This is consistent with previous research with children (Janz et al., 2003; Garcia et al., 2004). Activities eliciting a mean GRF of three body weights have positive associations with bone health (Bassey et al., 1998); a peak GRF of three body weights related to an ActiGraph output of 274 ± 57 counts/s ($16{,}465 \pm 3391$ counts/min) in the current study. ActiGraph output greater than 15,000 counts/min is classed as spurious data (Esliger et al., 2005). However, this is based on data collected in one minute epochs. Counts elicited by high jumping were consistently higher than 274 counts/s (16,000 counts/min); thus classification of spurious data is epoch-dependent and recommendations based on one minute epoch data cannot be assumed to be valid for use with one second epoch data.

Recent availability of raw acceleration data from commercially available accelerometers should lead to comparability of monitors across manufacturers. Results from this study indicate that data from accelerometers from two manufacturers is comparable and, further, that the output from both waist-worn and wrist-worn accelerometers are positively related to average resultant GRF and peak loading rate. Validity of the accelerometer worn at the wrist is important as compliance is a major problem when collecting activity data using accelerometry; for example in the National Health and Nutrition Examination Survey in the US (2003–2004), only 26% of the sample had seven valid days of accelerometer wear (Troiano et al., 2008). Relative to a standard waist-worn monitor, a wrist-worn monitor is more acceptable to participants (van Hees et al., 2011).

There was a tendency for output from the GENEA to be higher than the GT3X+ at the hip for higher intensity activities, although no differences between monitors were evident at the wrist. Maximum output for each axis on each accelerometer was listed as 6*g*. The vertical axis frequently reached the maximum output of both monitors, indicating the range is insufficient for accelerometers worn at the hip. However, while the GT3X+ did peak at 6*g* the GENEA peaked at 6.021*g*. It is possible that discrepancy in maximum output contributed to the higher output from the GENEA. In contrast, output rarely reached the maximum for the wrist data, where no differences between monitors were evident. The output range for the GeneActiv is larger at $\pm 8g$. However, recently Ahola et al. (2010) reported acceleration levels of up to 11*g* from an accelerometer worn on the hip by 35–40 yr old women during normal daily activity. Thus it appears that the extended range of $\pm 8g$ is still insufficient for a hip-worn monitor.

In general, accelerations showed the same pattern of response irrespective of whether the monitor was worn at the wrist or the hip. However, there was a tendency for higher accelerations at the hip except fast running. Due to the attenuation of shock as it travels up the body, accelerations monitored at inferior body segments are typically found to yield higher magnitudes compared to those monitored at superior segments during running (Mercer et al., 2003; Kavanagh and Menz, 2008). This concurs with our findings for the tendency for higher accelerations at the hip compared to the wrist during activities other than fast running.

During fast running, accelerations were higher at the wrist than the hip. This may be explained from studies of arm swing. During walking and low speed running arm swing is a passive mechanical response to the forces exerted on the torso by leg swing (Pontzer et al., 2009). However, during faster running arm swing relies less on passive origins and more on active shoulder muscle activity (Elftman, 1939) to contribute to running pace. This mechanically active arm activity may result in higher accelerations at the wrist relative to the hip during fast running. Thus, it is important to note that the effect of location on monitor is not consistent across activities (Godfrey et al., 2008).

In common with most accelerometer validation studies (e.g. Eston et al., 1998; Janz et al., 2003; Swartz et al., 2000), this study consisted of a series of structured activities. This is a limitation as activities tend to be sporadic and unstructured during daily life. In the current study, relationships with GRF were similar for both epoch and raw acceleration data. However, raw acceleration data may more accurately capture the sporadic nature of habitual physical activity and thus be more reflective of GRF in daily life than epoch data.

Indeed, Vainionpää et al. (2006) reported that fewer than 100 vertical accelerations $g > 3.9g$ per day recorded by an accelerometer worn at the hip were associated with increased bone mineral density in premenopausal women. It would not be possible to capture this information using epoch data. These accelerations equate to values of 4.9*g* in the current study, as Vainionpää et al. subtracted 1*g* from values to account for the acceleration of gravity. This threshold is approximated or exceeded by the mean values for jogging, fast running, high jumps and box jumps in the current study.

In conclusion, accelerometer output correlates positively with GRF. Raw acceleration data provided by the GT3X+ and the GENEA are comparable and also compare well with published acceleration values for different activities. Importantly, monitors worn at the wrist show a similar relationship with GRF as monitors worn at the hip. However, the nature of activities included in this calibration meant that arm movements generally paralleled lower body movements. Future studies should investigate whether the validity at the wrist remains when activities with greater inconsistency between upper and lower body movements are included (e.g. sweeping).

Conflict of interest statement

No external funding was received for this research. None of the authors have a conflict of interest with ActivInsights or ActiGraph, the manufacturers of the technologies on which this article is based.

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