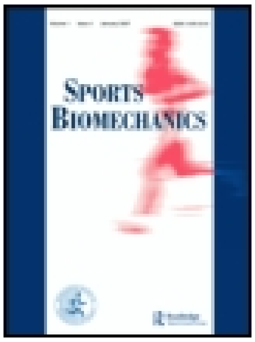

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Reliability of accelerometry to assess impact loads of jumping and landing tasks

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Abstract
Overuse injuries, resulting from repetitive subacute impact loading, are a problem in high-performance sports. Monitoring of impact loading may aid in the prevention of these injuries. The current study aimed to establish the intra-day and inter-day reliability of a tri-axial accelerometer to assess impact loading during jumping and landing tasks. Twelve participants wore an accelerometer on their upper and lower back. They performed a continuous hopping task as well as drop landings and rebound jumps from three drop heights (37.5, 57.5 and 77.5 cm), peak resultant acceleration (PRA) was calculated for all tasks. The tasks were performed twice, one week apart at the same time of day. The difference in the mean, intra-class correlation coefficient, coefficient of variation and Cohen's effect size were calculated as measures of reliability. PRA showed good intra-day reliability for the hopping task. Inter-day reliability of the PRA was moderate to good across all tasks. Reliability of PRA was slightly higher when accelerations were recorded on the lower back compared to the upper back. To assess impact loading, during continuous hopping, drop landings and rebound jumps, PRA recorded at both the upper and lower back appears to be a reliable measure.

Keywords: *Biomechanics, monitoring, sport, ground reaction force, acceleration*

Introduction

Injury is a major problem in high-performance sport. Monitoring of the physical stress athletes experience during training could provide valuable information to prevent injuries (Brink et al., 2010). The use of accelerometry has previously shown potential to assess physical loading (Beatty, McIntosh, & Frechede, 2006). However, the sample frequency of the accelerometer and the range of accelerations recorded will affect the capability of this technology to accurately record loading. A commercially available and widely used accelerometer is the tri-axial accelerometer embedded in the Minimaxx S4 GPS-unit (Catapult, Docklands, Victoria, Australia). This accelerometer has a 100 Hz sampling frequency and a 10 *g* range. Accelerations recorded with this device showed high within device and between device reliability both in laboratory settings and during Australian football matches (Boyd, Ball, & Aughey, 2011). This accelerometer has been successfully used to quantify training load in soccer (Casamichana, Castellano, Calleja-Gonzalez, San Román, & Castagna, 2013) and physiological load during competition in netball (Cormack, Smith,

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Mooney, Young, & O'Brien, 2014). Furthermore, accelerations recorded at the distal end of the tibia showed to be a reliable measure of relative mechanical load in running tasks (Moresi, O'Meara, & Graham, 2013). The widespread use of this particular accelerometer illustrates that it can be worn safely in a variety of sports settings without restricting athletes in their movement patterns.

Physiological loading is not the only type of load athletes endure as part of their training and competition. In sports incorporating jumping and landing components, athletes are also exposed to impact loading. This type of loading is suggested to be related to a range of overuse injuries in various sports. For example, patellar tendinitis (also known as jumper's knee) and lower back injuries are two of the most frequent overuse injuries in volleyball (Briner & Kacmar, 1997). High impact forces generated during jumping and landing are suggested to be factors placing athletes at risk of sustaining these injuries (Briner Jr. & Kacmar Jr., 1997). Within a population of professional dancers overuse injuries make up 40–50% of all injuries, with repetitive microtrauma, resulting from the body's inability to absorb forces, proposed to be the main cause (Macintyre & Joy, 2000). Excessive repetitive forces are furthermore suggested to be involved in causing stress fractures in figure skating (Oleson, Busconi, & Baran, 2002). In figure skating, also, knee and particularly lower back injuries make up a large part of the overuse injuries (Dubravcic-Simunjak, Pecina, Kuipers, Moran, & Haspl, 2003). Due to the stiffness of the figure skating boots, the skaters' ankle and knee range of motion are limited, often resulting in an inability to absorb impact forces upon landing. It is suggested that excessively high forces travelling up the kinetic chain are related to the high incidence of lower back overuse injuries in figure skating (Lipetz & Kruse, 2000).

The above-mentioned sports are just an example of sports and activities in which repetitive impact loading might be related to injury occurrence. It is often assumed there is a dose–response relationship between impact loading and overuse injury. Impact loading when experienced in moderation results in health benefits such as increased bone mineral density (Oleson et al., 2002), while too much impact loading can result in injury. A higher risk to incur impact-related injuries is observed for females compared to males in basketball and soccer (Powell & Barber-Foss, 2000) as well as in figure skating (Lipetz & Kruse, 2000). These observations suggest that monitoring impact loading might be important to prevent overuse injuries, particularly within female athlete populations. However, without reliable technology to record impact loading within training settings on a daily basis, it will be nearly impossible to distinguish between a healthy and a potentially harmful amount of impact loading.

Accelerometry could provide the simple wireless technology required to monitor impact loading in sports settings on a day-to-day basis. The purpose of this study was to examine the inter-day and intra-day reliability of accelerations recorded with the tri-axial accelerometer embedded in the Minimaxx S4 GPS-unit. Accelerations were recorded at both the upper and lower back during landing and jumping tasks from several heights, and during continuous hopping. Reliability was assessed for ground reaction force (GRF) and accelerations. GRF is the gold standard to assess impact loading. It was hypothesised that accelerometry will be a reliable measure to assess impact loading. The reliability of accelerometry was expected to be similar to the reliability of GRF.

Method

Participants

Twelve healthy females (age = 22.5 ± 4.0 years, height = 166.7 ± 7.9 cm, mass = 66.0 ± 10.0 kg) volunteered to participate in this study. To be included participants had to be healthy, free of injury and physically active (Australian Government; Department of Health, 2014). Participants' health, injury status and activity level were self-reported. Injury was defined as any physical pain or disability that withheld the participant from full participation (Gabbett & Jenkins, 2011). Prior to participation all participants provided written informed consent. Approval for this study was obtained from the Human Research Ethics Committee at the Australian Catholic University, Melbourne.

Data collection

All participants attended two testing sessions, one week apart, and at the same time of day. It was decided to perform the testing in two consecutive weeks, rather than two consecutive days, to prevent possible negative effects related to the participants' weekly routines with regards to physical activity and training. At the start of the first testing session, the participants' height and body mass was measured using a stadiometer (Stadi-O-Meter, Novel Products Inc, Rockton, Illinois, USA) and a uniaxial force platform (Quattro 9290AD, Kistler Group, Winterthur, Switzerland, 500 Hz), respectively. Participants then completed a warm-up consisting of 5 min of treadmill walking (Quinton Medtrack CR60, Cardiac Science Corporation, Bothell, Washington, USA) at a self-selected pace (5.2 ± 0.5 km/h), followed by a series of dynamic stretches of the legs.

On completion of the warm-up, two tri-axial accelerometers (Minimaxx S4 GPS-unit, Catapult, Docklands, Victoria, Australia, 10 *g*, 100 Hz) were placed on the participants' torso. One was located on the upper back over the second thoracic vertebra (T2), as recom-

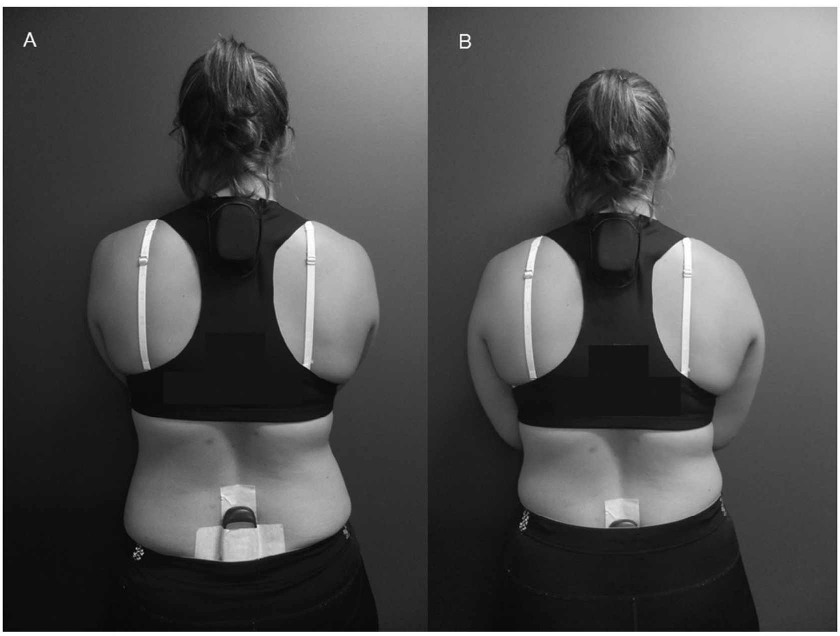

Figure 1. Placement of the accelerometers on the upper and lower back. The accelerometer on the upper back is situated at the level of the T2 and held in place by a manufacturer supplied crop top. The second accelerometer is attached using tape on the lower back, at the midpoint between the two PSIS of the pelvis (a), and further secured by pulling tight-fitting leggings over the accelerometer (b).

mended by the manufacturer, held in place using a tight-fitting crop top (Catapult Sports, Docklands, Victoria, Australia). The second accelerometer was located on the lower back, at the midpoint between the two posterior superior iliac spines (PSIS) of the pelvis (Figure 1). The accelerometer on the lower back was fixed to the skin using double-sided tape and Fixomull stretch tape (Jiaxing How Sport Medical Instrument, Jiaxing, Zhejiang, China). To further secure the accelerometer on the lower back participants all wore tight-fitting leggings or compressions pants, which were pulled over the accelerometer. To minimise possible between-weeks' differences, the same accelerometer was placed at the same position (upper or lower back) by the same researcher in both weeks. During all testing, the participants wore their own sports shoes.

Participants first performed a hopping task, comprised of ten continuous, double-legged hops. During these hops, the participants were instructed to place their hands on their hips and keep their knees straight whilst using their ankles and toes to push off. GRFs for the continuous hopping task were collected with a single-uniaxial force platform (Quattro 9290AD, Kistler Group, Winterthur, Switzerland, 500 Hz). Upon completion of the double-leg hopping task, the participants' rating of perceived exertion (RPE) was recorded using an adjusted ten-point Borg scale (Borg, 1982; Foster et al., 2001).

Following the double-legged hops all participants were asked to perform drop landings and rebound jumps from three box heights (37.5, 57.5 and 77.5 cm) onto two portable tri-axial force platforms (9286BA, Kistler Group, Winterthur, Switzerland, 1000 Hz). The force platforms were embedded in the laboratory floor with a negligible gap between them. For both the drop landing and rebound jumping tasks the participants were instructed to keep their hands on their hips and step off the box, lifting their preferred foot forward first and making sure not to jump up or lower themselves before they performed the task. The participants were instructed to land with their feet shoulder width apart, placing each foot on a separate force platform. For the rebound jumps, participants were instructed to jump up as fast and as high as they could, following the first ground contact (Young, Pryor, & Wilson, 1995). Participants were asked to perform one practice trial for each task at each drop height. If they did not feel comfortable completing the task after one practice trial, participants were encouraged to perform a second practice trial. All participants were comfortable performing the tasks after two practice trials. Three trials from each drop height were recorded (Mullineaux, Bartlett, & Bennett, 2001). The order of tasks (drop landing, rebound jump) was randomised between participants, and the box heights were block randomised (six possible orders of the three box heights). Therefore, one participant started with the drop landings and box height order of 37.5, 57.5 and 77.5 cm, whilst another started with the rebound jumps but the same box height order, and so on for the remaining ten participants. To avoid possible differences between weeks introduced by potential order effects (Sforzo & Touey, 1996), the order of the tasks and drop heights was the same in both weeks for each participant. This protocol structure was deemed valid as the aim of the study was to establish the reliability of the accelerometer, as opposed to the reliability of the task (i.e. task performance should be kept as similar as possible between weeks in order to establish reliability of the measurement device). It is acknowledged that in sports situations task order will mostly be random. In the first week of testing, participants repeated the continuous double-legged hopping task after the drop landings and rebound jumps. Upon completion of this task, participants were asked their RPE again.

Data analyses

Data from the accelerometer were first downloaded into the Sprint software supplied by the manufacturer (Catapult, Docklands, Victoria, Australia, version 5.1). The data were then imported into custom-written MATLAB software (MATLAB R2012a, Mathworks, Inc., Natick, Massachusetts, USA). The raw accelerations in the *x*-, *y*- and *z*-directions were combined into a resultant acceleration using the following equation:

$$a_r = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

where a_r is the resultant acceleration, a_x is the acceleration is the *x*-direction, a_y is the acceleration in the *y*-direction and a_z is the acceleration in the *z*-direction. All accelerations are expressed in gravitational units (*g*) (one gravitational unit is equal to the gravitational acceleration of 9.81 m/s^2). The resultant acceleration was filtered with a third-order low-pass Butterworth filter with a 20-Hz cutoff frequency. This filter was found to be the most valid out of a range of filters tested. The peak resultant acceleration (PRA) was then determined for the hopping, drop-landing and rebound-jumping tasks. For the continuous hopping task, the first and last two ground contacts were excluded. The PRA from the middle six contacts was then averaged and included in further data analysis. The PRA was identified for the drop landings, for the rebound jumps the PRA of the first ground contact was identified and incorporated in the analysis. The PRA for the three trials of each task was then averaged.

All GRF data were normalised to the participants' body weight (BW). For the hopping task, the peak vertical GRF (VGRF) was retrieved from the Quattro jump software (Kistler Group, Winterthur, Switzerland, version 1.0.9.2). For both drop-landing and rebound-jumping tasks, the combined forces (both force platforms) were filtered with a fourth-order low-pass Butterworth filter with a cutoff frequency of 100 Hz, using Bioware software (Kistler Group, Winterthur, Switzerland, version 5.03.0). The peak resultant GRF (RGRF) from the combined forces was then obtained.

GRFs for all tasks were imported into custom written algorithms in MATLAB. For the hopping task, the peak VGRF was averaged over the same six ground contacts as for the PRA. The peak RGRF was averaged over the three trials for each drop height for the landing task. For the rebound jumps, the peak RGRF during the first contact phase was averaged over the three trials for each drop height.

Statistical analyses

All average PRA, peak VGRF and peak RGRF data were collated into one spreadsheet (Microsoft Excel 2010, Microsoft, Redmond, WA, USA) for all participants. Statistical analysis was performed using SPSS for Windows software (IBM-SPSS, Armonk, NY, USA, version 20.0). The alpha level was set at .05 for all analyses. A Student's *t*-test was performed and Cohen's effect size (ES) was calculated for the RPE scores associated with the continuous double-legged hopping task. A Shapiro–Wilk test indicated that the hopping, drop-landing and rebound-jumping data were not normally distributed for both the accelerometer and force platform data. Therefore, descriptive statistics were calculated as medians and inter-quartile ranges.

Data were then log transformed prior to calculating measures of inter-day and intra-day reliability using a modified spreadsheet (Hopkins, 2000b). The measures of reliability are reported as performed on the log-transformed data. However, the medians and inter-quartile ranges reported are the original values, before the data were log transformed. One participant experienced back pain during the second testing session (the injury occurred after the first testing sessions and the participant was pain-free at the start of the second session), therefore reliability measures for the drop landings and rebound jumps from the 77.5 cm drop height were calculated for 11 participants. Intra-day reliability was also examined for the continuous double-legged hopping task. To assess reliability, both criteria of 'relative' and 'absolute' reliability measures were calculated (Atkinson & Nevill, 1998; Bradshaw, Hume, Calton, & Aisbett, 2010). These measures were: the difference in the mean (MDiff%), intra-class correlation coefficient (ICC), the typical error expressed as a coefficient of variation percentage (CV%) (Hopkins, 2000a) and the Cohen's effect size. The model of the ICC used was a two-way random single-measure ICC (2,1) (Weir, 2005). Overall reliability from all statistical measures was interpreted as 'good' when MDiff% $< 5\%$, ICC ≥ 0.80, CV% $\leq 10\%$ and ES < 0.60. Overall reliability was deemed 'moderate' when one of the above criteria was breached, if two or more criteria were not met reliability was defined as 'poor' (Joseph, Bradshaw, Kemp, & Clark, 2013).

Results

Median GRF for all tasks ranged from 3.93 BW for the rebound jumps from the 37.5 cm box to 8.35 BW for rebound jumps from the 77.5 cm box. Median PRA for the same tasks and drop heights ranged from 3.84 to 5.35 *g*, and from 4.34 to 6.50 *g* when recorded at the lower and upper back, respectively (Table I).

RPE was not significantly different between the continuous hopping before and after the jumping and landing tasks (t (11) = − 1.915, p = 0.082). Further, ES value (d = 0.237) suggests only a small change in perceived exertion when executing the hopping task the second time (Saunders, Pyne, Telford, & Hawley, 2004). Therefore, it was assumed participants were not fatigued by the drop landings and rebound jumps, which allowed calculation of measures of intra-day reliability for the hopping task (Table II). Good intra-day reliability was found for the hopping task for VGRF, PRA recorded at the upper back and PRA recorded at the lower back.

Table I. Descriptive statistics, medians (Med) and inter-quartile ranges (IQR), for GRF and PRA.

		GRF (BW)				PRA Lower Back (*g*)				PRA Upper Back (*g*)			
		Week 1		Week 2		Week 1		Week 2		Week 1		Week 2	
Task	Drop height (cm)	Med	IQR	Med	IQR	Med	IQR	Med	IQR	Med	IQR	Med	IQR
Hopping		5.12	0.92	5.14	0.68	5.05	0.95	5.06	0.76	4.97	0.98	5.00	1.60
Drop landing	37.5	4.74	1.60	4.95	1.17	4.08	0.65	4.17	0.34	4.57	0.79	4.37	0.70
	57.5	6.16	2.29	6.57	1.23	4.65	0.72	4.73	0.62	5.52	0.94	5.40	0.90
	77.5	7.91	1.71	7.97*	3.03	5.12	0.69	5.18*	1.10	6.05	0.64	6.17*	1.27
Rebound jump	37.5	3.93	1.04	4.02	1.99	3.84	0.88	3.92	0.38	4.29	0.89	4.34	1.45
	57.5	5.95	1.45	6.20	1.80	4.54	0.82	4.58	0.52	5.44	1.17	5.50	1.60
	77.5	8.35	2.80	8.10*	2.20	5.30	1.40	5.35*	0.63	6.45	0.70	6.50*	1.20

Notes: GRF is displayed in units of BW, for the hopping task the VGRF is displayed while for the drop landings and rebound jumps the RGRF is displayed, PRA is displayed in gravitational units (*g*), one gravitational unit is equal to the gravitational acceleration 9.81 m/s^2.

*Only 11 participants completed the drop landings and rebound jumps from 77.5 cm in week two.

Table II. Assessment of intra-day and inter-day reliability of GRF and PRA recorded at the lower back and upper back during continuous hopping, drop landings and rebound jumps.

Task	Drop height (cm)	Measure	MDiff %	ICC		CV%		Cohen's ES		Overall Reliability
Intra-day										
Hopping		VGRF	0.26	0.93	High	3.55	Good	0.02	Trivial	Good
		PRA Lower back	1.42	0.88	Good	4.63	Good	0.12	Trivial	Good
		PRA Upper back	4.88	0.95	High	4.87	Good	0.26	Small	Good
Inter-day										
Hopping		VGRF	1.37	0.93	High	3.92	Good	0.11	Trivial	Good
		PRA Lower back	0.40	0.92	High	3.75	Good	0.03	Trivial	Good
		PRA Upper back	2.15	0.96	High	4.95	Good	0.10	Trivial	Good
Drop landing	37.5	RGRF	0.87	0.91	High	8.56	Good	0.03	Trivial	Good
		PRA Lower back	4.52	0.41	Low	9.64	Good	0.38	Small	Moderate
		PRA Upper back	−0.23	0.89	Good	7.09	Good	−0.01	Trivial	Good
	57.5	RGRF	3.09	0.86	Good	9.88	Good	0.13	Trivial	Good
		PRA Lower back	−0.54	0.83	Good	6.35	Good	−0.04	Trivial	Good
		PRA Upper back	0.21	0.89	Good	6.59	Good	0.01	Trivial	Good
	77.5	RGRF	1.80	0.89	Good	7.25	Good	0.09	Trivial	Good
		PRA Lower back	−0.68	0.90	High	6.02	Good	−0.04	Trivial	Good
		PRA Upper back	1.84	0.79	Moderate	6.17	Good	0.16	Trivial	Moderate
Rebound jump	37.5	RGRF	−1.12	0.94	High	9.82	Good	−0.03	Trivial	Good
		PRA Lower back	2.23	0.82	Good	8.78	Good	0.12	Trivial	Good
		PRA Upper back	−2.05	0.90	High	11.90	Marginal	−0.06	Trivial	Moderate
	57.5	RGRF	−0.10	0.89	Good	9.25	Good	0.00	Trivial	Good
			1.31	0.85	Good	5.78	Good	0.10	Trivial	Good

(*Continued*)

Table II. (*Continued*)

Task	Drop height (cm)	Measure	MDiff %	ICC		CV%		Cohen's ES		Overall Reliability
		PRA Lower back								
		PRA Upper back	−0.63	0.90	High	8.81	Good	−0.03	Trivial	Good
	77.5	RGRF	0.76	0.94	High	6.39	Good	0.04	Trivial	Good
		PRA Lower back	1.24	0.90	High	5.13	Good	0.09	Trivial	Good
		PRA Upper back	−2.23	0.90	High	5.99	Good	−0.14	Trivial	Good

Notes: Overall reliability from all statistical measures was interpreted as 'good' when MDiff% < 5%, ICC ≥ 0.80, CV% ≤ 10% and ES < 0.60. Overall reliability was deemed 'moderate' when one of these criteria was breached.

The inter-day reliability of GRF and PRA to assess impact loading is displayed in Table II. GRF showed a good reliability across all tasks and all drop heights. PRA recorded at the lower back displayed a good reliability for all tasks except the drop landings from 37.5 cm, for which it showed moderate reliability. Last, the PRA recorded at the upper back exhibited a moderate reliability for drop landings from the 77.5 cm height and rebound jumps from 37.5 cm. The PRA for the upper back showed good reliability for all other tasks. Across all tasks the reliability of PRA was similar to the reliability of GRF.

Discussion and implications

Overuse injuries related to impact loading are a common issue in a wide range of sports. Despite this well-known fact, the reliability of wireless accelerometry to assess impact loads during training has only previously been established for running (Moresi et al., 2013). Therefore, in the current study, we examined the reliability of accelerometry to assess impact loading in jumping and landing tasks. PRA showed good intra-day reliability and moderate to good inter-day reliability. The reliability of the PRA recorded at the lower back was, across all tasks, slightly higher than PRA recorded at the upper back. To our knowledge, this is the first study to examine the reliability of commercially available accelerometers, such as the accelerometer embedded in the Minimaxx S4 GPS-unit employed in the current study, to assess impact loading during jumping and landing tasks.

The within-device reliability of this accelerometer, assessed in laboratory conditions by moving the accelerometer with a known acceleration, showed coefficients of variation (CV%) of 0.91–1.05% (Boyd et al., 2011). The between-device reliability was assessed during Australian football matches and showed a CV% of 1.9%. The CV% found in the current study is higher than these previously reported figures. This difference can be attributed to the fact that in the current study participants performed the tasks twice, one week apart. When participants repeat a task, there will be natural movement variability (Bartlett, Wheat, & Robins, 2007). Therefore, perfect agreement in task performance between week one and week two is not to be expected. This is also reflected in the variability observed between the GRF measures in week one and week two. In the current study, the measures of 'absolute' and 'relative' reliability are similar for GRF and PRA. GRF is the gold standard to assess impact loading, therefore finding similar reliability for PRA is promising.

In the current study, the data from both the accelerometers and the force platforms were not normally distributed. This could be due to the relatively small sample size (n = 12). It is recommended that more participants are recruited for any future studies into the reliability of accelerometers to assess impact loading. This variation could also have been due to the varied sporting backgrounds of the participants; therefore, some participants had received training in jumping and landing, while others had not. It is possible therefore that variations in jumping and landing techniques account for the distribution of the data. Furthermore, the instructions provided to the participants regarding foot placement during the drop landings and rebound jumps might have influenced task performance. This is a limitation of the study.

The use of accelerometry to assess impact loading could be of particular interest within sports, such as figure skating, where the jumps and landing techniques as performed on the ice cannot be replicated on a force platform. When tasks cannot be performed on a force platform it is impossible to assess impact loading through GRF. Similar issues arise if one were to assess impact loading in beach volleyball, where jumper's knee is a frequent overuse injury (Bahr & Reeser, 2003). Accelerometry could also be used in sports where the surface athletes land on changes regularly such as in gymnastics (Bradshaw & Hume, 2012).

While the results of this study suggest that accelerometry could potentially be used in sports settings in the future, there are some important considerations for practitioners considering the use of accelerometers. In the current study, the accelerometers were positioned on the participant's body very precisely by the same researcher before each test using bony landmarks. Experience in placing the accelerometers might influence the reliability of the data obtained from them. Another consideration is that only young healthy females were included in this study. Before the findings of the current study can be extended to other populations, such as males or populations with lower extremity injuries, future research is warranted.

If there is a dose–response relation between impact loading and overuse injuries, where too many impacts and too high impact forces will result in injury, having reliable technology to monitor impact loading might aid in the prevention of injuries. The amount of impact loading an athlete can safely endure will likely vary from person to person and might change over time. The current findings, moderate to good reliability of accelerometry to assess impact loading, suggest this measure could in the future be employed in sports settings to monitor impact loading.

Disclosure statement

The authors have no financial or personal conflicts of interest to declare.

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