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Application of a tri-axial accelerometer to estimate jump frequency in volleyball

JON M. JARNING[1,2], KAM-MING MOK[2], BJØRGE H. HANSEN[3], & ROALD BAHR[2]

[1]*Faculty of Medicine and Dentistry, University of Bergen, Bergen, Norway,* [2]*Oslo Sports Trauma Research Center, Norwegian School of Sport Sciences, Oslo, Norway, and* [3]*Department of Sports Medicine, Norwegian School of Sport Sciences, Oslo, Norway*

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Abstract
Patellar tendinopathy is prevalent among athletes, and most likely associated with a high jumping load. If methods for estimating jump frequency were available, this could potentially assist in understanding and preventing this condition. The objective of this study was to explore the possibility of using peak vertical acceleration (PVA) or peak resultant acceleration (PRA) measured by an accelerometer to estimate jump frequency. Twelve male elite volleyball players (22.5 ± 1.6 yrs) performed a training protocol consisting of seven typical motion patterns, including jumping and non-jumping movements. Accelerometer data from the trial were obtained using a tri-axial accelerometer. In addition, we collected video data from the trial. Jump-float serving and spike jumping could not be distinguished from non-jumping movements using differences in PVA or PRA. Furthermore, there were substantial inter-participant differences in both the PVA and the PRA within and across movement types ($p < 0.05$). These findings suggest that neither PVA nor PRA measured by a tri-axial accelerometer is an applicable method for estimating jump frequency in volleyball. A method for acquiring real-time estimates of jump frequency remains to be verified. However, there are several alternative approaches, and further investigations are needed.

Keywords: *Jumper's knee, jump counting, jump load, overuse injury, injury prevention*

Introduction

Patellar tendinopathy, also known as jumper's knee (Ferretti, Ippolito, Mariani, & Puddu, 1983), is one of the most frequent overuse injuries among athletes, with an overall prevalence ranging from 8.5% to 14.2% in large epidemiological studies (Lian, Engebretsen, & Bahr, 2005; Zwerver, Bredeweg, & van den Akker-Scheek, 2011). The condition is even more prevalent in sports characterised by high demands on leg extensor speed and power, such as volleyball and basketball, where it has a prevalence of 45% and 32%, respectively (Ferretti, Papandrea, & Conteduca, 1990; Lian et al., 2005; Zwerver et al., 2011). The risk factors suggested include male sex, younger age, high training volume, high jumping load, high

Correspondence: Roald Bahr, Oslo Sports Trauma Research Center, Department of Sports Medicine, Norwegian School of Sport Sciences, Oslo, Norway, Email: roald.bahr@nih.no

performance in jump tests, and hard playing surfaces (Briner & Kacmar, 1997; Ferretti, 1986; Lian, Engebretsen, Ovrebo, & Bahr, 1996; Lian, Refsnes, Engebretsen, & Bahr, 2003; Visnes & Bahr, 2013; Zwerver et al., 2011).

Prognosis is poor (Kettunen, Kvist, Alanen, & Kujala, 2002), and treatment strategy and effectiveness is debated (Cook & Khan, 2001; Larsson, Käll, & Nilsson-Helander, 2012; Visnes & Bahr, 2007). This highlights the importance of preventing the initial development of patellar tendinopathy, an approach that will most likely have to include restrictions in training volume (Visnes & Bahr, 2013), and possibly also in jump frequency (Bahr & Bahr, 2014). The current method for measuring training exposure and jump frequency is manual video analysis. This approach is time-consuming; to obtain accurate jump counts for 12 volleyball players from a 2-h training session might take up to 12 h. Clearly, this is not feasible. If a more effective method were available, the jump count data could be used to investigate the association between patellar tendinopathy and jump frequency. If such an association exists, the method could also potentially assist in determining at what level of jump frequency the risk for developing the condition increases. It may even be possible to monitor players in real time and interfere if jump frequency reaches levels associated with an increased risk of injury.

One possible approach is using body-mounted electronic accelerometers. These devices have in recent years been used extensively for the measurement of physical activity in large epidemiological studies (Bento, Cortinhas, Leitao, & Mota, 2012; Hansen, Kolle, Dyrstad, Holme, & Anderssen, 2012). In addition, it has been shown that they can classify different categories of physical activity with high accuracy, including walking, running, and jumping (Long, Yin, & Aarts, 2009; Mannini & Sabatini, 2011; Ruch, Rumo, & Mäder, 2011; Trost, Wong, Pfeiffer, & Zheng, 2012). Using an accelerometer, it is possible to determine peak vertical acceleration (PVA) and peak resultant acceleration (PRA) for a specific movement, and we hypothesised that the jumping movements presented either greater PVA or greater PRA than non-jumping movements in volleyball. If this difference in either PVA or PRA were sufficiently large, it would be possible to separate a jump from a non-jumping movement using a peak acceleration (PVA or PRA) threshold value. Every movement presenting peak acceleration above the threshold value could be registered as a jump, and consequently one would be able to obtain a jump count estimate for a given time period. Such estimations could be validated through comparison with true jump counts obtained from video analysis. In this exploratory study, we wanted to investigate the possibility of using PVA or PRA in the aforementioned manner to estimate jump frequency.

Methods

Participants

The participants in this study were 12 male elite volleyball players (age 22.5 ± 1.6 years old, height 195 ± 7 cm, weight 88 ± 8 kg) recruited from the Norwegian men's national team participating in the World Cup Qualifiers in May 2013. The number of team members restricted sample size. Informed consent was obtained from all participants.

Procedures

The trial was a predetermined training protocol consisting of seven high-intensity exercises specifically related to key volleyball skills (Table I). Four of the exercises included jumping movements, while the three others consisted of non-jumping activities. All exercises were

Table I. Exercise protocol consisting of seven exercises, performed by 12 male elite volleyball players equipped with a triaxial accelerometer.

Exercise performed	Number of subjects performing exercise	Number of repetitions per subject	Duration of exercise (min:s)
Non-jumping movements			
4.5-m side-to-side shuffle steps	12	Not specified	0:30
9-m shuttle run	12	5	1:33
9-m sprint ending with floor dive	12	5	2:24
Jumping movements			
Jump-float serve	12	5	1:37
Block jumping	12	35	5:56
Jump serve	12	5	2:25
Spike jumping	9[a]	5	3:11

[a] Three subjects were not included in the data collection from spike jumping, as they performed other functions than spiking during this exercise.

performed with maximal or close to maximal effort. After each exercise, the participants were instructed to stand completely still or move minimally for approximately 30 s, so that the data from different exercises would be easier to separate in the data analysis. The total duration of the trial was approximately 25 min. It was conducted in a standard hardwood floor sports arena, and apart from the accelerometer devices, the participants wore their own sports equipment. Before the data collection started, the participants had performed a typical 15-min warm-up routine as instructed by the team coach.

Data acquisition

Video data from the trial were collected using two digital video cameras, placed and directed so that all movements of the participants within the sports arena would be recorded. Acceleration data were obtained using the ActiGraph GT3X+ (ActiGraph™ Inc., Pensacola, FL, USA). The GT3X+ is an activity monitor containing an ADXL335 accelerometer (Analog Devices, Norwood, MA, USA), which is a tri-axial capacitive MEMS sensor with a full scale range of ±6 g (John & Freedson, 2012). It does not contain a magnetometer or a gyroscope. ActiLife 6 analysis software (version 6.8.0) was used to initiate the GT3X+ to collect data at a sampling frequency of 100 Hz, and to output the pre-filtered raw acceleration signal in units of g. Each participant was equipped with an accelerometer attached to an adjustable cotton fabric belt. The belt was strapped around the waist at the level of the anterior superior iliac spine, and the accelerometer was positioned in the midline of the lumbosacral region with a specific vertical orientation.

Data analyses

To determine the exact number of jumps for a participant, a jump count for each exercise was obtained through visual video analysis. Each jump was classified as a block jump, a spike jump, a jump-float serve, or a jump serve. The acceleration data were extracted from the raw files of the GT3X+ through the ActiLife 6 analysis software described above. Using customised Matlab scripts (MathWorks, Natick, MA, USA), PVA and PRA for each jump was identified by the maximal value of acceleration in the point where the slope (g/s) is zero. The data outputs were further confirmed by visual inspection of the graphs. Examples

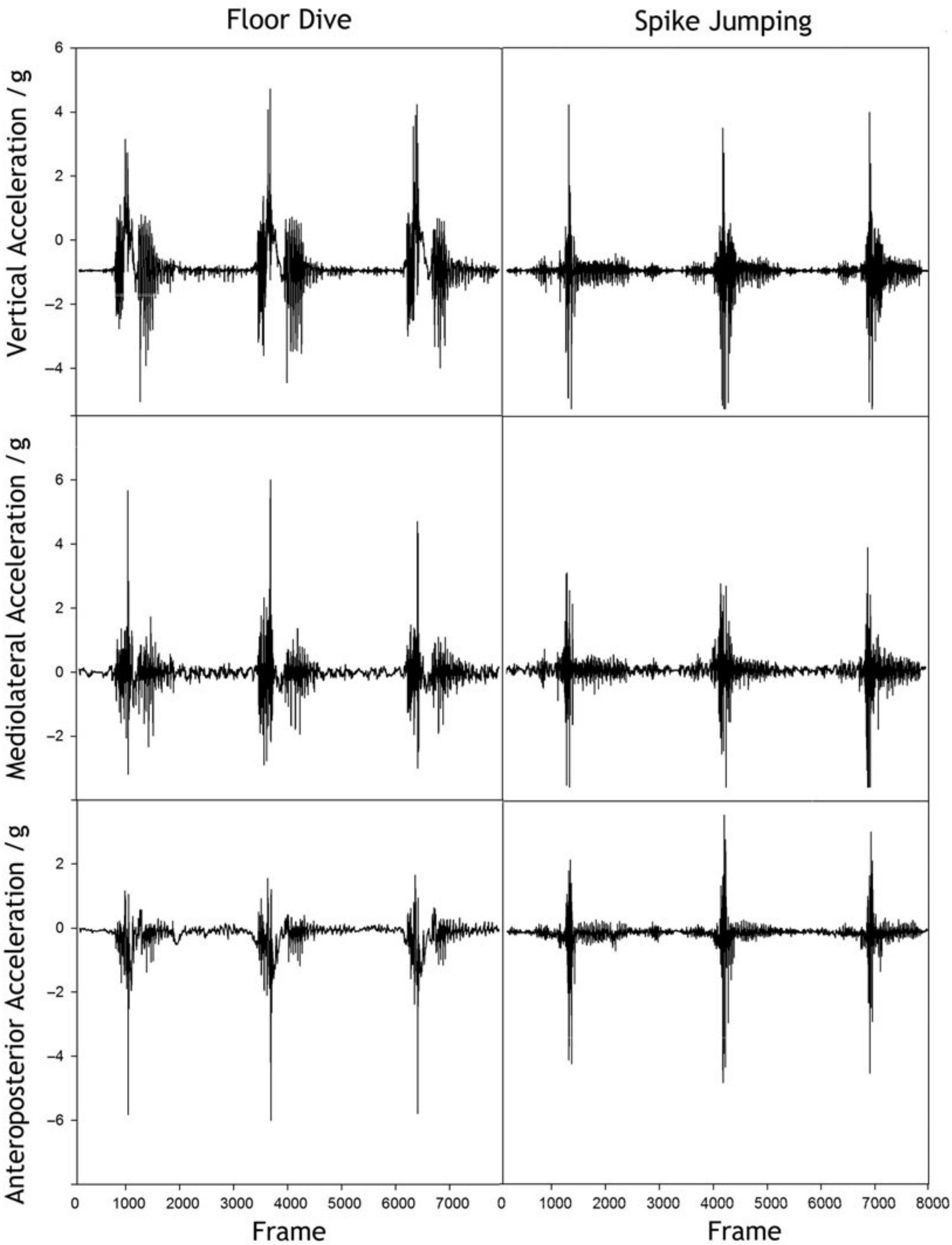

Figure 1. Acceleration in floor dive and spike jump for one randomly selected individual. Acceleration along the vertical, mediolateral and anteroposterior axes are presented in separate boxes.

of three-dimensional acceleration pattern for floor dive and spike jumping are shown in Figure 1.

Statistical analyses

Statistical analyses were performed using SPSS v.21 (SPSS Inc., Chicago, IL, USA). A one-way analysis of variance (ANOVA) *F*-test was used as the omnibus test to compare the peak vertical acceleration (g) for seven specific movement patterns, and when a significant *F*-value was found, Bonferroni's post-hoc tests were applied. Furthermore, a two-way ANOVA was performed for both participant and movement as factors in the PVA. The level of significance was set at $p < 0.05$.

Results

Peak vertical acceleration

PVA varied both between the jumping movements and between the non-jumping movements (Figure 2, Table VI). Spike jumping had the highest mean PVA (4.62 ± 1.21 g), while side-to-side shuffle steps had the lowest (1.52 ± 0.54 g). Notably, floor dive presented a mean PVA of 4.09 ± 1.01 g, even though it primarily is a movement in the

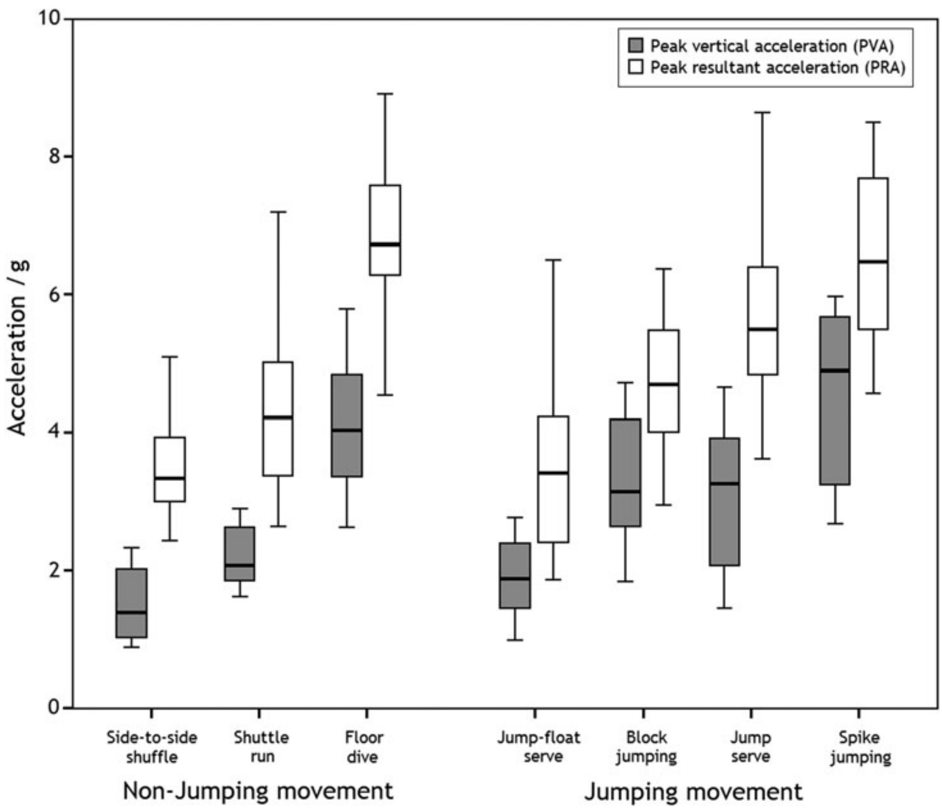

Figure 2. Box-plot showing median (and interquartile range) peak vertical acceleration for non-jumping and jumping volleyball specific movements.

Table II. Comparison of peak vertical acceleration (g) between jumping and non-jumping movements (one-way ANOVA with post-hoc Bonferroni correction).

	Jumping movements			
	Jump-float serve	Block jumping	Jump serve	Spike jumping
Non-jumping movements				
Side-to-side shuffle	$p = 0.422$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Shuttle run (Sprint)	$p = 0.999$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Floor dive	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.303$

horizontal plane. In approximately 15% of the spike jumps, vertical acceleration reached the 6 g ceiling. As F-values were significant ($F = 65.3$, $p < 0.05$), the Bonferroni post-hoc tests were applied. The statistical analysis revealed that two of the jumping movements could not be separated from the non-jumping movements (Table II). Specifically, the PVA of jumps performed when jump-float serving did not differ significantly from the PVA of side-to-side shuffle steps or shuttle running ($p = 0.422$ and 0.999, respectively), and PVA of jumps performed when spiking was not significantly different from PVA of floor diving ($p = 0.303$).

A two-way ANOVA showed that movement type and participant number each had a significant main effect ($p < 0.05$) on the variance of PVA (Table III). In addition, there was a significant interaction between movement type and participant as factors affecting PVA ($p < 0.05$). Considering the Eta^2, the model consisting of movement and participant can explain up to 63% of the variability in PVA. Moreover, the movement explained the majority of the variability.

Choosing a threshold for PVA provided an estimated jump count for all participants, which is illustrated for three individuals in Figure 3. Note that the true jump counts for the individuals do not share the same threshold. Since it became clear from the results that a PVA (or PRA) threshold approach would not provide an accurate jump count estimation, a manually obtained jump count for comparison was not performed for all 12 participants.

Peak resultant acceleration

PRA presented variations between the movement types similar to those observed in PVA (Figure 2, Table VI). PRA of floor diving (6.84 ± 1.04 g) displayed the highest mean PRA, while jump-float serve had the lowest mean PRA (3.44 ± 1.09 g). F-values were significant ($F = 94.9$, $p < 0.05$), and Bonferroni post-hoc tests were applied. When comparing PRA between jumping and non-jumping movements, the PRA of jump-float serving did not differ

Table III. Two-way ANOVA summary for movement type and subject as factors in the peak vertical acceleration of a movement.

Factor	df	SS	MS	Eta^2	F-value	P-value
Movement (M)	6	410	68.4	0.35	292	<0.05
Subject (S)	11	173	15.7	0.14	67.4	<0.05
M × S	63	169	2.69	0.14	11.5	<0.05

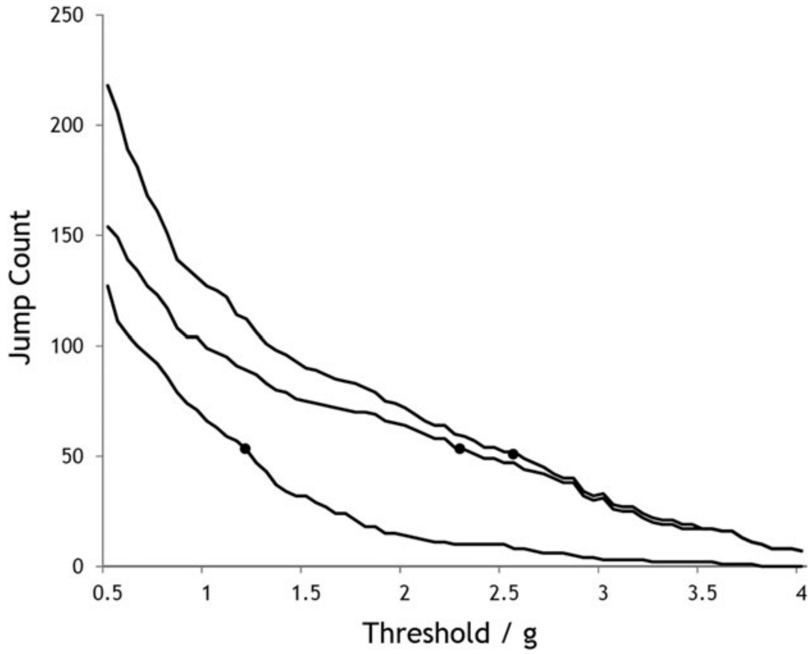

Figure 3. Relationship between PVA thresholds and estimated jump count for three randomly selected individuals. Dots illustrate the true jump count obtained by video analysis.

Table IV. Comparison of peak resultant acceleration (g) between jumping and non-jumping movements (one-way ANOVA with post-hoc Bonferroni correction).

	Jumping movements			
	Jump-float serve	Block jumping	Jump serve	Spike jumping
Non-jumping movements				
Side-to-side shuffle	$p = 0.999$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Shuttle run (sprint)	$p < 0.001$	$p = 0.434$	$p < 0.001$	$p < 0.001$
Floor dive	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.999$

significantly from the PRA of side-to-side shuffle steps ($p = 0.999$), PRA of block jumping did not differ significantly from the PRA of shuttle run ($p = 0.434$), and spike jumping could not be separated from floor dive ($p = 0.999$) (Table IV). As for PVA, there was a significant interaction between movement type and participant ($p < 0.05$) as factors affecting PRA (Table V). Movement and participant can explain up to 70% of the variability in PRA

Table V. Two-way ANOVA summary for movement type and subject as factors in the peak resultant acceleration of a movement.

Factor	df	SS	MS	Eta^2	*F*-value	*p*-value
Movement (M)	6	636	106	0.43	251	<0.05
Subject (S)	11	119	10.9	0.08	25.7	<0.05
M × S	63	284	4.51	0.19	10.7	<0.05

Table VI. Mean and standard deviation of the peak vertical acceleration (PVA) and peak resultant acceleration for seven different movement types, mean ± SD.

Movements	Peak vertical acceleration (g)	Peak resultant acceleration (g)
Side-to-side shuffle	1.52 ± 0.54	3.50 ± 0.71
Shuttle run (sprint)	2.14 ± 0.47	4.25 ± 1.20
Floor dive	4.09 ± 1.01	6.84 ± 1.04
Jump-float serve	1.95 ± 0.62	3.44 ± 1.09
Block jumping	3.08 ± 1.13	4.59 ± 1.09
Jump serve	3.19 ± 1.04	5.60 ± 0.94
Spike jumping	4.62 ± 1.21	6.54 ± 1.13

(Table V), and the movement explained the majority of the variability. Again, manually obtained jump counts for comparison were not performed for all 12 participants.

Discussion and implications

The objective of this study was to investigate the possibility of using PVA or PRA measured by an accelerometer to estimate jump frequency. As the statistical analyses show, neither PVA nor PRA differed significantly between jumping movements and non-jumping movements. The fact that jump-float serving could not be differentiated from sprinting or side-to-side shuffle steps using PVA is most likely due to true similarities in PVA for these movements. These results are supported by findings in a previously performed biomechanical study on PVA and ground reaction force, where jogging and running could not be separated from jumping using differences in PVA (Rowlands & Stiles, 2012). The fact that variance of PRA follows a similar pattern to that of PVA (Figure 2) is consistent with findings in the same study.

However, we were surprised to see that floor diving and spike jumping could not be differentiated using PVA. The explanation is most likely the alteration in vertical orientation of the accelerometer during a floor dive, which causes acceleration in the horizontal plane to appear as vertical in the accelerometer data.

In addition, we observed substantial inter-individual differences in PVA and PRA for each of the specific movements, indicating that individual threshold values would be needed in order to count jumps. These would need to be obtained through a preliminary trial and subsequent analyses, and therefore the approach would be less practical and more time-consuming. Furthermore, the finding that spike jumping presents the largest variability in the PVA is particularly interesting, as this likely contributes to prevent the differentiation of this movement from the other movements. One could speculate that this variation in PVA during spike jumping is related to variation in jumping height, but further studies are required in order to confirm this association. We also observed a significant interaction between movement and participant as factors in both the PVA and PRA. This demonstrates that the magnitude of PVA and PRA for jumping movements relative to the PVA and PRA for non-jumping movements varies between the individuals. Once again this implies that individual threshold settings would be required to estimate jump frequency.

Unfortunately, these results strongly imply that the methodology explored is not applicable for estimating jump frequency accurately. Since jumping and non-jumping movements did not significantly differ from each other in PVA or PRA, a threshold value that separates jumps from other movements could not be determined. As mentioned in the result section, a comparison of the estimated jump count obtained by PVA/PRA threshold and the manual jump count was therefore not performed for all 12 participants. However, a manual jump count was obtained for three individuals for illustration (Figure 3). As expected, an effort to determine a PVA threshold value would provide very different jump count estimations for the three individuals included in Figure 3, even though they performed approximately the same number of jumps.

As stated, this study is exploratory, and therefore an established but relatively basic approach was investigated. However, there are several alternative approaches that are potentially suitable for estimating jump frequency. The data analysis could be performed differently, for example using pattern recognition (Mannini & Sabatini, 2010; Zhang, Wang, Xu, & Liu, 2006) or waveform analysis (Lugade, Fortune, Morrow, & Kaufman, 2014; Marsland et al., 2012). Use of different attachment methods or multiple accelerometers are also possible alternatives. Furthermore, more sophisticated inertial sensing systems could prove helpful. For example, devices containing both an accelerometer and a gyroscope (Xia, Yu, & Kong, 2014; Zeng & Zhao, 2011) provide additional information that could make it possible to differentiate a jump from other movements.

Real-time estimation of jump frequency will make it possible to investigate the association between jump exposure and the development of patellar tendinopathy through prospective studies on large populations of athletes at risk. This would allow us to examine if there is a threshold value for total jump counts, jump frequency or for a rate of increase beyond which the risk of injury increases substantially. Baseball is an example of a sport where pitch counts have been introduced to prevent shoulder and elbow problems among young and adolescent players. Real-time jump counts would make it possible to monitor players, and interfere before jump exposure exceeds a level associated with increased risk of the condition. An accurate method to estimate jump counts would also be valuable in rehabilitation and return to sport in players with established patellar tendinopathy.

There are mainly two potential limitations regarding the methods used in this study. First, the accelerometers used had a sampling range of 6 g, and it is possible that this range limited the ability to capture maximal vertical acceleration, particularly in the spike jumps. Consequently, the mean PVA for spike jumping may be underestimated. However, results showed that only a limited portion of the spike jumps (15%) presented with a PVA of 6 g or more, and we therefore believe that the sampling range does not significantly affect the results in this study. Second, even though the device was tightly fastened using an elastic cotton fabric belt, the relative movement between the participant's body and the accelerometer device is a potential limitation to consider.

In conclusion, our results imply that the methodology tested, using PVA or PRA measured by a standard tri-axial accelerometer, is not applicable for estimating jump frequency. Further investigations are needed in order to find an applicable and reliable method.

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