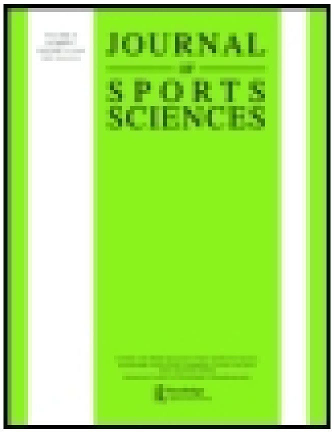

Click for updates

Journal of Sports Sciences
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rjsp20

Vertical jumping biomechanical evaluation through the use of an inertial sensor-based technology

I. Setuain[ab], J. Martinikorena[c], M. Gonzalez-Izal[a], A. Martinez-Ramirez[c], M. Gómez[c], J. Alfaro-Adrián[bd] & M. Izquierdo[a]

[a] Department of Health Sciences, Public University of Navarra, Tudela, Spain
[b] Clinical Research Department, TDN, Orthopaedic Surgery and Advanced Rehabilitation Centre, Pamplona, Spain
[c] Department of Mathematics, Public University of Navarra, Tudela, Spain
[d] TDN/San Miguel Clinic, Pamplona, Spain

Published online: 10 Aug 2015.

JOURNAL OF SPORTS SCIENCES, 2015
http://dx.doi.org/10.1080/02640414.2015.1075057

Routledge
Taylor & Francis Group

Vertical jumping biomechanical evaluation through the use of an inertial sensor-based technology

I. Setuain[1,2], J. Martinikorena[3], M. Gonzalez-Izal[1], A. Martinez-Ramirez[3], M. Gómez[3], J. Alfaro-Adrián[2,4] and M. Izquierdo[1]

[1]Department of Health Sciences, Public University of Navarra, Tudela, Spain; [2]Clinical Research Department, TDN, Orthopaedic Surgery and Advanced Rehabilitation Centre, Pamplona, Spain; [3]Department of Mathematics, Public University of Navarra, Tudela, Spain; [4]TDN/San Miguel Clinic, Pamplona, Spain

ABSTRACT
Progress in micro-electromechanical systems has turned inertial sensor units (IUs) into a suitable tool for vertical jumping evaluation. In total, 9 men and 8 women were recruited for this study. Three types of vertical jumping tests were evaluated in order to determine if the data provided by an IU placed at the lumbar spine could reliably assess jumping biomechanics and to examine the validity of the IU compared with force plate platform recordings. Robust correlation levels of the IU-based jumping biomechanical evaluation with respect to the force plate across the entire analysed jumping battery were found. In this sense, significant and extremely large correlations were found when raw data of both IU and force plate-derived normalised force–time curves were compared. Furthermore, significant and mainly moderate correlation levels were also found between both instruments when isolated resultant forces' peak values of predefined jumping phases of each manoeuvre were analysed. However, Bland and Altman graphical representation demonstrated a systematic error in the distribution of the data points within the mean ±1.96 SD intervals. Using IUs, several biomechanical variables such as the resultant force–time curve patterns of the three different vertical jumps analysed were reliably measured.

ARTICLE HISTORY
Accepted 16 July 2015

KEYWORDS
Vertical jump; inertial unit; validation; biomechanics

Introduction

Vertical jumping performance is considered a key component of many training routines in numerous sport disciplines and conditioning programmes (Gorostiaga et al., 2010; Izquierdo, Aguado, Gonzalez, Lopez, & Häkkinen, 1999; Ramírez-Campillo et al., 2014). For instance, it has a direct influence on several explosive activities such as jumping and sprinting (Bobbert, Huijing, & Van Ingen Schenau, 1987). Moreover, in the last 30 years, other athletic tasks such as vertical drop jumps have also been studied and implemented by athletic coaches to maximise the performance of explosive activities (Markovic, 2007). In the field of sports biomechanics, vertical jumping manoeuvres have been widely studied. The main goal of these studies has been to clarify several concerns related to adaptations of the human body to exercise and to describe basic movement patterns (Devita & Skelly, 1992; Markovic, 2007). To do so, direct mechanics-based procedures have been utilised to estimate the centre of mass (CM) displacement and to detail the biomechanics of jumping (Bobbert et al., 1987; Devita & Skelly, 1992).

However, many other methods and instrumentations have recently been developed to evaluate vertical jumps (Requena, Garcia, Requena, De Villarreal, & Paasuke, 2012). Briefly, some such as optical cells and contact mats have been developed to assess jumping performance in terms of the jumping time (JT) duration (Bosco, Luhtanen, & Komi, 1983; Glatthorn et al., 2011). Others, through the description of force and/or vertical velocity by time curves, have estimated the CM movement in human beings (Cormie, McBride, & McCaulley, 2009; Linthorne, 2001).

To describe the direct or inverse mechanics-based biomechanics of vertical jumping manoeuvres, force plates have become the gold standard during the last decades (Hatze, 1998). As such, numerous research articles related to vertical jumping-related biomechanics focused on both performance enhancement (Gorostiaga et al., 2010; Gorostiaga, Granados, Ibañez, González-Badillo, & Izquierdo, 2006; Marques & Izquierdo, 2014) and injury prevention and rehabilitation (Hewett et al., 2005; Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005; Oberländer, Brüggemann, Höher, & Karamanidis, 2013) have been published. In the latest study, Myer et al. (Myer et al., 2011) recommended the utilisation of unilateral functional jump tests after anterior cruciate ligament reconstructions to examine the deficits between extremities among collegiate recreational athletes.

However, the equipment needed to perform the abovementioned studies requires a considerable financial investment and implies the necessity for highly skilled technicians familiarised with such laboratory-derived procedures. Recently, the latest advances in micro-electromechanical systems (MEMS) have turned inertial sensor units (IUs) into a suitable tool for sports motion analysis related to both performance-related (Bonnet, Mazza, Fraisse, & Cappozzo, 2013;

CONTACT: M. Izquierdo mikel.izquierdo@gmail.com Universidad Pública de Navarra, Av. de Tarazona s/n, 31500 Tudela, Navarra, Spain.

Requena et al., 2012) and injury rehabilitation and prevention-related fields (Eitzen, Moksnes, Snyder-Mackler, Engebretsen, & Risberg, 2010; Patterson & Delahunt, 2013). Briefly, IU systems provide the linear acceleration and angular displacement orientation values in a sensor-fixed Cartesian reference frame (*XYZ*). In this way, IUs offer the possibility of landing outside of a predefined place as opposed to traditional ground-located force plates. This fact enables a more functional and unplanned movement analysis at the training field itself (Dowling, Favre, & Andriacchi, 2011).

In this context, the purposes of the present study were (1) to determine if the data provided by an IU placed at the lumbar spine could reliably assess jumping biomechanics and (2) to examine the validity of the IU compared with force plate recordings. The study hypothesis posited that the force by time curves obtained from the IU during the execution of a vertical jump task would become valid and reliable in terms of correlation robustness and absolute coefficient of variation, respectively, as compared with the force plate (as the gold standard) recordings. This assumption is based on previous research reporting acceptable levels of concordance between IUs and force plates for isolated biomechanical analysed variables of the analysed force by time curve (Choukou, Laffaye, & Taiar, 2014; Requena et al., 2012).

Methods

Experimental approach

A validation study design was carried out. The experiment was carried out at a biomechanics laboratory. The participants performed a vertical jump test battery that included a 50-cm vertical bilateral drop jump (VBDJ), 20-cm vertical unilateral drop jump (VUDJ) and vertical unilateral countermovement jump (VUCMJ) (Figure 1A–C).

Participants

The participants were physically active young participants. There were 9 men (mean ± SD; age: 29.33 ± 4.80 years; weight:

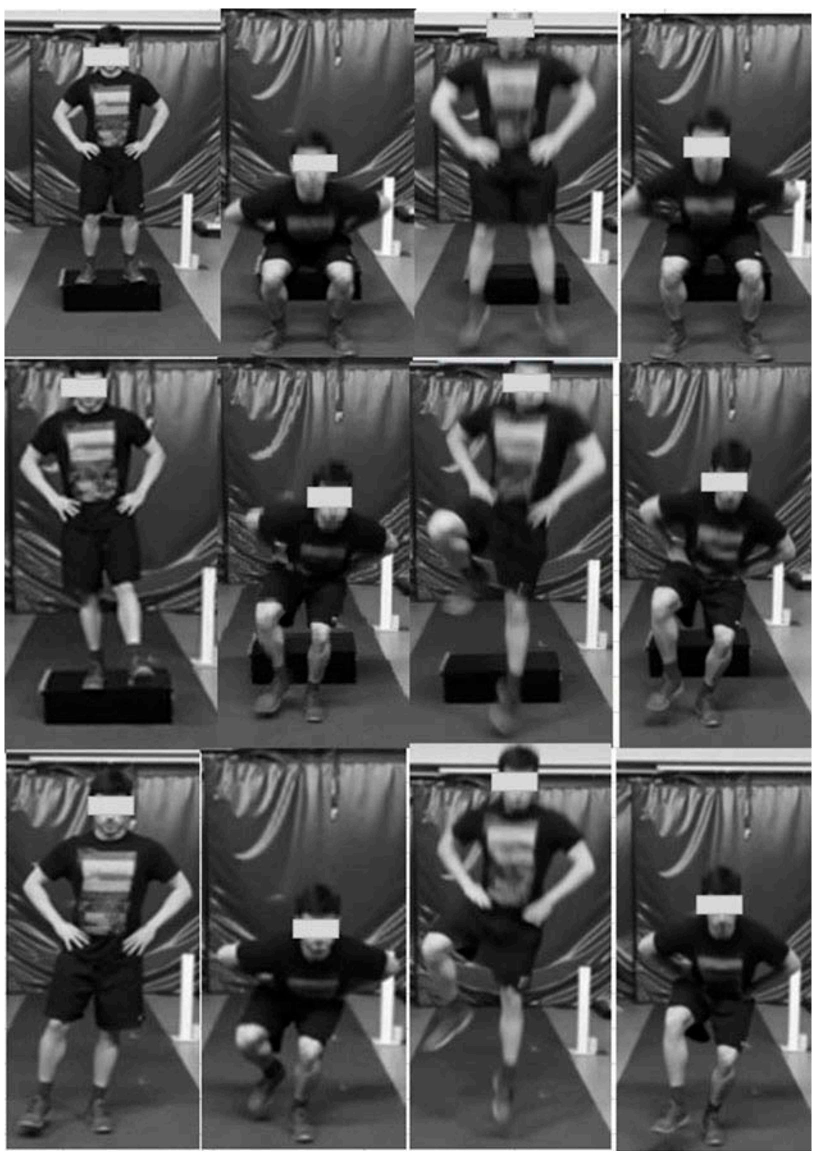

Figure 1. VBDJ explicative illustration (A). VUDJ explicative illustration (B). VUCMJ explicative illustration (C).

74.84 ± 10.38 kg; height: 172.53 ± 5.86 cm) and 8 women (age: 27.50 ± 4.75 years; weight: 57.92 ± 5.40 kg; height: 164.03 ± 3.61 cm). The inclusion criteria for participation in the present study were that the participants performed regular strength and or endurance training a minimum of two times a week at least during the last year. Furthermore, none of the participants were suffering from any articular or muscle pain in the lower legs at the moment of the experimental evaluation. Potential participants with a previous background of any severe injury affecting the lower leg lasting more than six weeks for complete recovery were excluded from the study.

The experimental protocol was approved by the ethics committee of the Public University of Navarra according to the ethical principles of the Declaration of Helsinki. All participants gave their consent to the experiment after having been informed of the aims and the risks of the testing procedures.

Procedures

The testing procedure comprised the execution of three vertical jump manoeuvres: the VBDJ, the VUDJ and the VUCMJ (Figure 1A–C). Each examination was composed of five repetitions of each of the three vertical jumps mentioned above. The participants performed 5 min of resistance-free stationary cycling as a warm up to start activity and reduce chondral and soft tissue viscosity. Participants were asked to define which leg they would employ to jump as high as possible in order to jump with their dominant leg. None of the participants were involved in any jumping-based activity.

The resting period was 30 s between two consecutive jump trials within a set and 1 min between each of the three vertical jump manoeuvres examined. To avoid possible injury risks associated with the intensity of the jumping tasks, the order of execution was fixed; the jumps were performed from easiest to most complex execution requirements. A detailed explanation of the selected jumping manoeuvres has been described elsewhere (Setuain, Millor, Gorostiaga, Alfaro, & Izquierdo, 2015). For the entire jump repetitions performed, the participant was instructed to perform a maximal effort task immediately following an acoustic signal.

The participants were equipped with an IU (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V. Enschede, the Netherlands). The IU was attached over the L4–L5 region of the participant's lumbar spine, which is considered to be the CM of the human body (Linthorne, 2001) (Figure 2). A technical explanation describing the IU-derived analysed variables has been previously provided (Millor, Lecumberri, Gómez, Martínez-Ramírez, & Izquierdo, 2013) and it is detailed below (see the section "Kinematic data").

The trials were simultaneously recorded by the IU at a sampling rate of 100 Hz and the force plate (AMTI net force v.2.4.0 2006 Advanced Mechanical technology. Inc., USA, IU-based jumping biomechanical evaluation) at a sampling rate of 1000 Hz.

In order to reduce the error due to the integration process, the highest sampling rate for data recording was selected for both instruments (Choukou et al., 2014). Therefore, both devices were calibrated on the highest possible value: 1000 Hz for the force platform and 100 Hz for the IU. Before each trial, the participants were asked to assume a vertical posture as well as to keep their hands over their waists during the three jumps to avoid upper body interference caused by arm swinging (Lees, Vanrenterghem, & De Clercq, 2004).

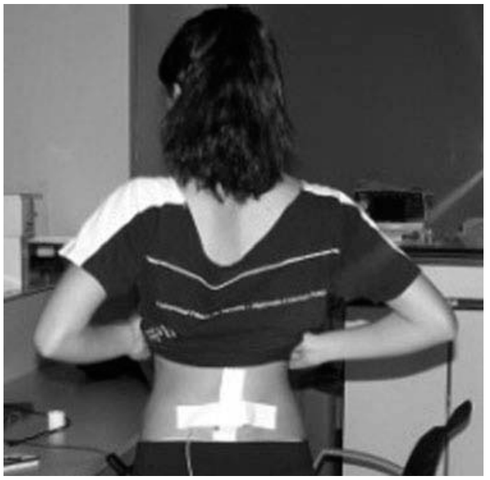

Figure 2. IU collocation explicative illustration.

Direct mechanics-based procedures were utilised to estimate the CM displacement and to detail the biomechanics of jumping. In this manner, direct mechanics procedure is based on the description of the participant as a mechanical system and the estimation of movement and actuation of forces through the CM displacement (Hatze, 1998). Based on this approach, was the positioning of the IU at the lumbar spine level where the human's centre of gravity is considered to be located (Linthorne, 2001) and hence were the vertical velocity by time descriptive curves depicted.

Kinematic data

The IU provides the linear acceleration and rate of turn in a sensor-fixed Cartesian reference frame (*XYZ*). The MTx sensor combines nine individual MEMS sensors to provide drift-free three-dimensional (3D) orientation, as well as kinematic data: 3D acceleration, 3D rate of turn (rate gyro) and 3D magnetometry.

Before the beginning of the test, while the participant was standing on the ground with her back in an upright position, the sensor-fixed reference frame was aligned to an Earth-fixed global reference frame (*XYZ*), for which the *Z*-axis was vertical and pointing upwards, the *X*-axis was in the medio-lateral direction and the *Y*-axis was in the antero-posterior direction. The same reset procedure was performed with the force plate according to the manufacturer's instructions.

Each jump was assessed in different phases for a more comprehensive biomechanical analysis. This required the definition of different events that were determined using vertical accelerations provided by the IU and vertical forces obtained from the force plate. Once the different events of the jumping tasks were identified, the different phases could be defined. Finally, the peak acceleration (expressed in $m \cdot s^{-2}$) and peak ground reaction force (expressed in N) variables were considered for each of the analysed jumping tasks. For every cycle, the (*Z*-) acceleration signal from the

IU and the (*Z*-) force signal for the force plate were used to distinguish the peaks from the transition phases of each jump (i.e. participant moving upwards – positive *Z*-acceleration or force at the propulsive phase; participant moving downwards – negative *Z*-acceleration or force at the landing phase). All of the information was combined to define the boundaries between the different relevant phases; the initial attenuation (IA), propulsive (P) and final attenuation (FA) phases were defined for the drop jumps (bilateral and unilateral), and the propulsive (P) and FA phases were determined for the countermovement jump (Figure 3A and B).

The attenuation phase (A) of the jump was determined as the fraction of the jump in which the participant was negatively accelerating relative to the instant prior to the initial contact (or active impulse exertion) and to the management of the impact against the ground (negative followed by positive vertical-axis accelerations or forces, corresponding to the vertical-axis decomposition of the ground reaction force, simultaneously recorded by both the inertial unit and the force plate). There were two absorption phases described for the drop jumps: (1) the IA phase (T1–T2 events) and (2) the FA phase (T4–T5 events). Alternatively, for VUCMJ FA phase was described (T5–T6 events) (Figure 3A and B).

The propulsive phase (P) of the jump was defined as the fraction of the jump in which the participant exerted a positive force, or an active concentric action against the ground (positive vertical-axis accelerations or forces simultaneously recorded by both the inertial unit and the force plate). The JT of the jump was determined as the fraction of the jump in which the participant was not exerting any force against the ground (no positive vertical-axis accelerations or forces recorded by neither the inertial unit nor the force plate) (Figure 3A and B). It corresponds to T2–T3 events for the drop jumps and T3–T4 events for the VUCMJ.

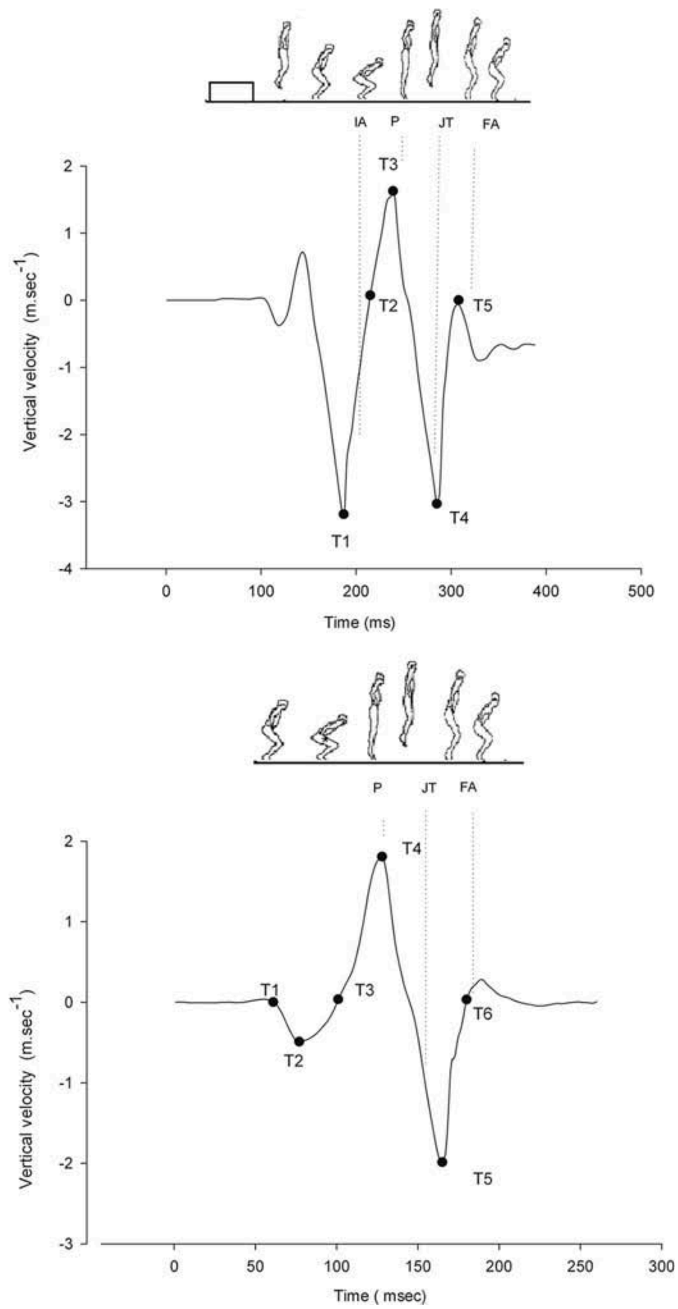

Figure 3. *Z* vertical axis force descriptive curves. Vertical bilateral drop jump explicative illustration (A). Vertical unilateral counter movement jump explicative illustration (B). IA, initial attenuation; P, propulsive phase; JT, jumping time; FA, final attenuation.

Data processing and statistical analysis

Peak maximal vertical accelerations (obtained in $m \cdot s^{-2}$) and forces (N) occurring at the propulsive and FA phases of the studied jumping tasks were recorded. To analyse the reliability and agreement between the force plate and the IU recordings in the same magnitude, the acceleration values were transformed into N by using the following formulae based on the Newton's third law:

$$F = ma,$$

where *F* is the force (N), *m* is the mass of participant (kg) and *a* is the peak acceleration (resultant) at each jump phase analysed ($m \cdot s^{-2}$).

Subsequently, the *X*- and *Y*-axis values corresponding to the vertical (*Z*-) peak predefined times were obtained for each analysed phase in order to calculate the resultant forces (RFs). This calculation was performed by using the root-mean-square quadratic equation of the 3D peak forces registered:

$$\mathrm{RF}(N) = \sqrt{[\text{peak}\,(X-)\,\text{axis force}^2\,(N) + \text{peak}\,(Y-)\,\text{axis force}^2\,(N) + \text{peak}\,(Z-)\,\text{axis force}^2\,(N)]}.$$

Finally, graphical representations of the vertical force (*Z*-force) provided by the force plate and calculated from the IU data, respectively, were performed. In order to avoid jumping height-related variability and sampling frequency-related deviations in the data acquired from the IU and the force plate, the *Z*-force curve representations were normalised to the mean and time. Additionally, root-mean-square quadratic errors and correlation coefficients were calculated for each of the obtained point pairs to assess the concordance between sensor- and force plate-derived data acquisition.

All of the descriptive statistics were utilised to assess the normality assumption of all of the studied variables. The

Kolmogorov–Smirnov test revealed no abnormal data patterns ($P > 0.05$).

The reliability of the IU with respect to the force plate was assessed with Pearson's correlation coefficient (r) and 95% confidence intervals (95% CI). Correlations between global force–time curves (raw data) and isolated previously defined IA and FA peak ground reaction RF values obtained from both devices were analysed for the VBDJ, VUDJ and VUCMJ. Correlations were separately carried out across all activities for each individual (intra-participant, intra-task and repetition). The correlation coefficients (r) were interpreted in accordance with the scale of magnitude proposed by Hopkins (Hopkins, Marshall, Batterham, & Hanin, 2009): $r \leq 0.1$, trivial; $r > 0.1–0.3$, small; $r > 0.3–0.5$, moderate; $r > 0.5–0.7$, large; $r > 0.7–0.9$, very large; and $r > 0.9–1$, extremely large.

Coefficients of variation (CV %) were also calculated in order to measure the dispersion of the scores for each participant and jump task performed for both the IU and the force plate. Furthermore, paired sample T-test were used for mean comparisons across the CVs obtained from both instrumentations. The level of significance was set at $P < 0.05$. SPSS® statistical software (V. 20.0, Chicago, IL, USA) was used for the above-mentioned statistical calculations.

Bland and Altman graphical representations were performed to increase the understanding of the data with respect to the agreement and the existence of a standard bias between the values obtained from the force plate and IU sensor.

Results

IU demonstrated to exhibit a robust correlation level with respect to the force plate across the entire analysed jumping battery; the VBDJ, VUDJ and VUCMJ (Figure 4A–C). In this sense, significant ($P < 0.001$) and extremely large correlations were found when raw data of both IU and force plate-derived normalised force–time curves were compared. Furthermore, significant ($P < 0.001$) and moderate to very large correlation levels were also found between both instruments when isolated RFs' peak values of defined IA and FA phases' of each manoeuvre were analysed (Table I).

Both IU and force plate-recorded force–time curves reported acceptable levels of variability (Figure 5A and B). Furthermore, the mean CV displayed by each participant across the entire jumping task performed reported by IU and force plate ranged from 10 to 19 and from 4% to 14%, respectively (Table I).

Lastly, Bland and Altman graphical representation were used in order to display the agreement of both IU and force plate for measuring resultant ground reaction force (RGRF)

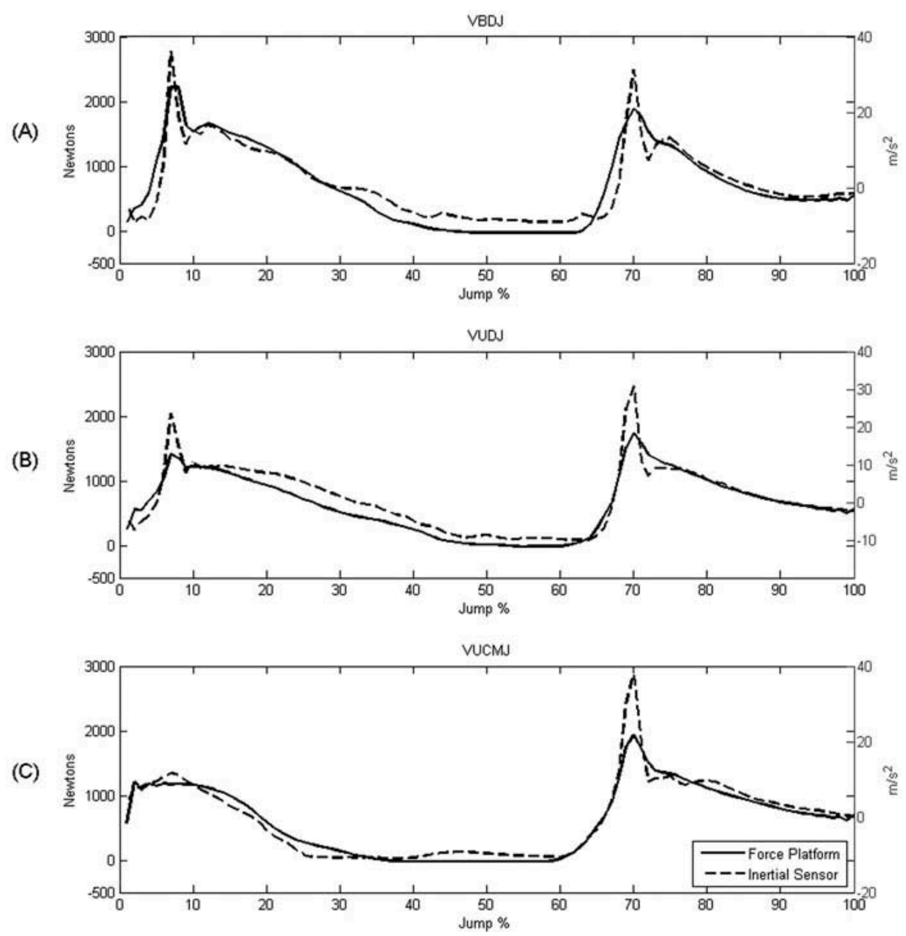

Figure 4. Z vertical force by time IU and force plate curves. Vertical bilateral drop jump (A). Vertical unilateral drop jump (B). Vertical unilateral counter movement jump (C).

Table I. IU and force plate-related data correlation and variability report.

				VBDJ	VUDJ	VUCMJ
IU-force plate Pearson's correlation product		Raw data (whole curve)	*r*-value (95%CI)	0.93(0.81–0.97)	0.93 (0.810.97)	0.96 (0.89–0.99)
			P-value	<0.001*	<0.001*	<0.001*
		IA pre-defined instant	*r*-value (95%CI)	0.48 (−0.01–0.78)	0.44 (−0.015–0.76)	0.48 (−0.01–0.78)
			P-value	<0.001*	<0.005*	<0.001*
		FA pre-defined instant	*r*-value (95%CI)	0.52 (0.05–0.80)	0.62 (0.20–0.85)	0.71 (0.35–0.89)
			P-value	<0.001*	<0.001*	<0.001*
Coefficient of variation	IA phase	IU	mean range (max–min)	10.74	19.74	12.81
				1.43–25.48	3.84–39.25	3.97–32.09
		Force plate	mean range (max–min)	14.25	10.10	4.71
				6.73–26.02	3.85–33.15	1.58–8.61
	FA phase	IU	mean range (max–min)	16.04	17.05	10.45
				3.15–40.9	2.76–33.50	4.29–29.91
		Force plate	mean range (max–min)	12.14	13.14	10.84
				2.89–25.75	6.40–34.21	2.55–42.93

Note: *Denotes statistical significance $P < 0.005$.

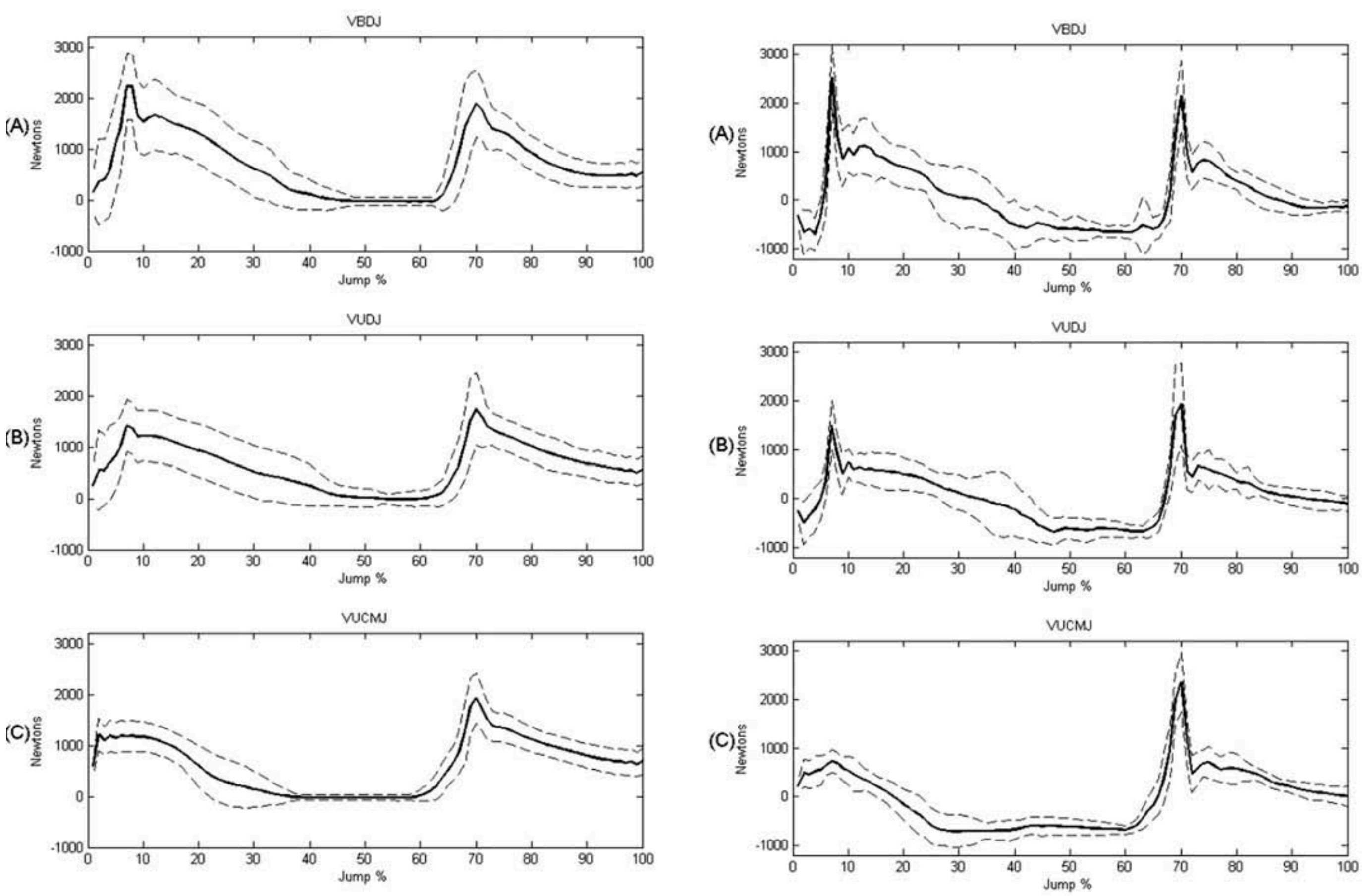

Figure 5. *Z* vertical force by time force plate curves. Mean (solid line) and SD (dotted line) (left). *Z* vertical force by time IU curves. Mean (solid line) and SD (dotted lined) (right).

across the IA and FA phases of each jump analysed. They showed that the vast majority of points were enclosed within the mean ±1.96 SD. The mean difference (estimated bias) was calculated and plotted in the representations. The significant ($P < 0.05$) correlations encountered in the mean of between pairs differences (*Y*-axis) and the mean of the measured data from both IU and force plate (*X*-axis) revealed a non-random distribution of the data points within the confidence intervals which indicates the existence of a systematic bias. Thus, the assumption that no relation existed between the measurement differences (errors) and their mean could not be accepted. It was demonstrated, in consequence, that greater the force, greater the disagreement between IU and force plate recordings (Figure 6A–C).

Discussion

The aims of this validation study were (1) to determine if the data provided by an IU placed at the lumbar spine could reliably assess jumping biomechanics and (2) to examine the

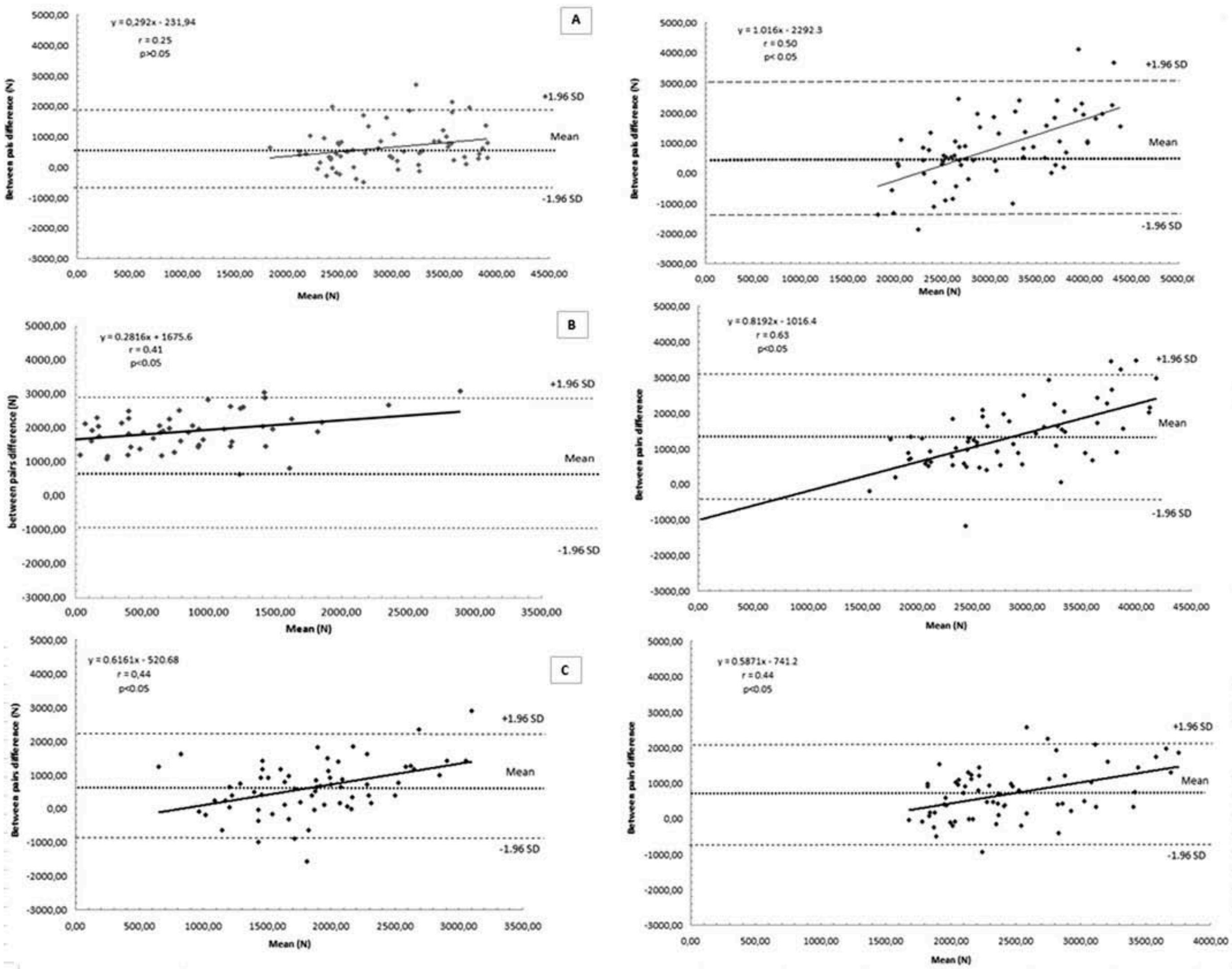

Figure 6. Bland and Altman representations comparing the differences between IU and force plate registered data. See text for details. The dotted horizontal lines represent the mean bias between the measurements made from each instrumentation. The dashed horizontal lines represent the 95% limits of agreement between the two variables. The solid lines correspond to the regression lines. Vertical bilateral drop jump; IA left; FA right (A). Vertical unilateral drop jump; IA left; FA right (B). Vertical unilateral counter movement jump; IA left; FA right (C).

validity of these data compared to force plate platform recordings.

The primary finding of this study corroborated the study hypothesis. Thus, a robust level of agreement was found between the force curve patterns obtained from IU data and those provided by a force plate for the direct mechanics-based vertical jumping biomechanical evaluation. Accordingly, both instruments demonstrated significant ($P < 0.01$) and extremely large correlation levels across the analysed resultant patterns of the whole force–time curves. Furthermore, significant ($P < 0.01$) and mainly moderate correlation levels were also found between both instruments upon analysing the isolated peak values of the acting RFs of the initial and FA phases of each jumping task. However, a considerable systematic bias was found between both instrument recordings when the magnitude of the acting forces increased. Greater the force magnitude, greater the disagreement between IU and force plate recordings. This novel IU systems' utilisation-derived methodology could aid athletic trainers and or team physicians; to directly measure both jumping performance and athlete's estimated CM biomechanical behaviour of several vertical jumping manoeuvres in a feasible and economic manner.

The accuracy of a new assessment tool is usually studied by comparing the new device and its methodology with the current gold standard (Requena et al., 2012). Force plate instruments have become the gold standard for jumping-related biomechanical research during the last decades (Hatze, 1998). As such, numerous research articles have been published related to the biomechanical evaluation of vertical jumps by utilising a force platform for both performance enhancement (Gorostiaga et al., 2010, 2006; Marques & Izquierdo, 2014) and injury prevention and rehabilitation concerns (Hewett et al., 2005; Noyes et al., 2005; Oberländer et al., 2013). Briefly, as previously stated by Hatze (Hatze, 1998), two different methodologies for the biomechanical evaluation of vertical jumps have been described: the direct or inverse dynamics methods. The present research utilised the direct dynamic method approach based on a point mass body model: the CM, estimated at the L4–L5 spine level to estimate the actuating forces generated when executing the analysed vertical jumping tasks (Kibele, 1998; Linthorne, 2001).

The utilisation of several IU devices to assess different biomechanical variables of vertical jumping has been widely reported in the literature, demonstrating its internal validity and agreement with the gold standard (Bonnet et al., 2013; Requena et al., 2012; Rowlands & Stiles, 2012). Furthermore, using a similar methodology with respect to placing the IU at the mid lumbar spine level of the body, previous studies have also found significant correlations between the biomechanical parameters of jumping measured by IUs and force plates (Choukou et al., 2014; Requena et al., 2012; Rowlands & Stiles, 2012). In this sense, Choukou et al. (2014) demonstrated high interclass reliability of an accelerometric system placed at the lumbar spine level for several jumping performance parameters, as well as good agreement with respect to the force platform in measuring vertical jumping-related biomechanical variables. The jump height, contact time, leg stiffness and reactivity indices were assessed and shown to positively correlated to the gold standard. Furthermore, Rowlands and Stiles (2012) reported significant moderate-to-large correlations between the IU and the force plate recordings for the average RF and peak loading rate during different functional activities, including walking and vertical jumping manoeuvres. All of these previous studies agree with the findings of the present investigation. Even positioned at the trunk level, inertial sensor devices cannot replace the higher precision 3D motion analysis trough inverse dynamics technology-based models, but regarding previous (Bonnet et al., 2013; Choukou et al., 2014; Dowling et al., 2011; Rowlands & Stiles, 2012) and the present research, they could feasibly record CM-supporting 3D axis forces as well as measure jump phases' duration of several vertical jumping tasks performed at the training court itself.

In the present study, we analysed the entire resultant force–time curve obtained from each instrument. Previous research highlighted the importance of plotting all of the raw data of a numerical analysed variable in an attempt to identify a pattern or behaviour described by the primary outcome of the study (Bland & Altman, 1986). By doing so, further information regarding variability is provided because a point-by-point direct comparison offers further comprehension of the analysed data trends than isolated standard deviation or standard error calculations from the mean values (Bland & Altman, 1986). Furthermore, previous studies have also used raw data to identify direct correlations between two different instruments and to analyse their agreement in other research fields (Zheng et al., 2013). Nevertheless, to ensure the consistency of the reported signals from both instrumentations, correlations between the predefined initial and FA peak ground reaction RF values obtained from both instruments were also calculated and successfully correlated. Bland and Altman analysis was also performed to check out for potential systematic bias in the measurements and the level of agreement determination between both instrumentations.

Significant differences with respect to the CV values from both the force plate and the IU were observed when isolated IA and FA points from the force by time curve were analysed. Furthermore, a considerable mean bias as well a systematic error between the measurements from both instrumentations was detected through the Bland and Altman scatter plots. Greater the force magnitude measured, greater the disagreement between IU and force plate recordings (Figure 6A–C). This fact should make the clinician interpret the results of the present investigation with caution. In the authors' opinion, the encountered differences between IU and force plate recording would arise from a sensor location-related issue. In this context, the traditionally accepted assumption that the vertical translational motion of the CM of the body represents the total body motion when assessing jumping biomechanics by using a force platform through direct mechanics procedures could be controversial (Hatze, 1998; Kibele, 1998; Linthorne, 2001). This potential controversy is justified by the assumptions that all body segments execute rotational and translational motions relative to the CM and that the CM itself also executes non-vertical motions in the sagittal and lateral directions. This implies that an additional amount of forces acting at the trunk level could not be registered when analysing jumping biomechanics through a direct method based on force plate recordings. In the authors' opinion, the placement of the IU at the L4–L5 lumbar spine level, which is considered to be the CM in human beings (Kibele, 1998; Linthorne, 2001), could allow for more comprehensive monitoring of the CM's mechanical behaviour during the execution of vertical jumping tasks.

Potential limitations from the present research could arise from technical differences between the alignments of the 3 orthogonal axes of the IU and force plate instruments. Thus, alignment problems could arise because of the positioning of the IU at the lumbar spine level. This fact could provide confusing data compared with those obtained from the force plate due to intrinsic movement of the trunk while executing the analysed jumping tasks with respect to the force plate recordings, taken at ground level. To mitigate this problem, the accelerations registered by the IU were expressed with respect to an aligned Earth-fixed global reference frame (*XYZ*). Afterwards, the obtained accelerometric values were transformed into force values and were finally expressed as the RF of both instruments to coincide with the highest level of concordance between the registered measurements.

The present study provides further evidence about the suitability of the IUs to measure jumping biomechanical parameters. Using IUs, several biomechanical variables such as the resultant force–time curve patterns as well as the peak resultant acting forces during the initial and FA phases of the three different vertical jumps analysed could be directly measured. However, some considerations are warranted when attempting to compare isolated IA, P and

FA data points between IU and force plate devices. Having assessed its validity and reliability, the purposed IU technology-based methodology could provide athletic trainers, sport clinicians and scientists with a portable and cost-effective tool for the direct mechanics-based biomechanical evaluation of vertical jumping.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

M. Izquierdo http://orcid.org/0000-0002-1506-4272

References

Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet*, *327*, 307–310.

Bobbert, M. F., Huijing, P. A., & Van Ingen Schenau, G. J. (1987). Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Medicine and Science in Sports and Exercise*, *19*, 332–338.

Bonnet, V., Mazza, C., Fraisse, P., & Cappozzo, A. (2013). Real-time estimate of body kinematics during a planar squat task using a single inertial measurement unit. *IEEE Transactions on Biomedical Engineering*, *60*, 1920–1926.

Bosco, C., Luhtanen, P., & Komi, P. V. (1983). A simple method for measurement of mechanical power in jumping. *European Journal of Applied Physiology and Occupational Physiology*, *50*, 273–282.

Choukou, M. A., Laffaye, G., & Taiar, R. (2014). Reliability and validity of an accele-rometric system for assessing vertical jumping performance. *Biology of Sport*, *31*, 55–62.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: Impact of training. *Journal of Strength and Conditioning Research*, *23*, 177–186.

Devita, P., & Skelly, W. A. (1992). Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine & Science in Sports & Exercise*, *24*, 108–115.

Dowling, A. V., Favre, J., & Andriacchi, T. P. (2011). A wearable system to assess risk for anterior cruciate ligament injury during jump landing: Measurements of temporal events, jump height, and sagittal plane kinematics. *Journal of Biomechanical Engineering*, *133*, 071008.

Eitzen, I., Moksnes, H., Snyder-Mackler, L., Engebretsen, L., & Risberg, M. A. (2010). Functional tests should be accentuated more in the decision for ACL reconstruction. *Knee Surgery Sports Traumatology Arthroscopy*, *18*, 1517–1525.

Glatthorn, J. F., Gouge, S., Nussbaumer, S., Stauffacher, S., Impellizzeri, F. M., & Maffiuletti, N. A. (2011). Validity and reliability of Optojump photoelectric cells for estimating vertical jump height. *Journal of Strength and Conditioning Research*, *25*, 556–560.

Gorostiaga, E. M., Asiáin, X., Izquierdo, M., Postigo, A., Aguado, R., Alonso, J. M., & Ibáñez, J. (2010). Vertical jump performance and blood ammonia and lactate levels during typical training sessions in elite 400-m runners. *Journal of Strength and Conditioning Research*, *24*, 1138–1149.

Gorostiaga, E. M., Granados, C., Ibañez, J., González-Badillo, J. J., & Izquierdo, M. (2006). Effects of an entire season on physical fitness changes in elite male handball players. *Medicine & Science in Sports & Exercise*, *38*, 357–366.

Hatze, H. (1998). Validity and reliability of methods for testing vertical jumping performance. *Journal of Applied Biomechanics*, *14*, 127–140.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt Jr., R. S., Colosimo, A. J., & McLean, S. G., et al. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *American . Journal of Sports Medicine*, *33*, 492–501.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*, 3–13.

Izquierdo, M., Aguado, X., Gonzalez, R., Lopez, J. L., & Häkkinen, K. (1999). Maximal and explosive force production capacity and balance performance in men of different ages. *European Journal of Applied Physiology*, *79*, 260–267.

Kibele, A. (1998). Possibilities and limitations in the biomechanical analysis of countermovement jumps: A methodological study. *Journal of Applied Biomechanics*, *14*, 105–117.

Lees, A., Vanrenterghem, J., & De Clercq, D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics*, *37*, 1929–1940.

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physics*, *69*, 1198–1204.

Markovic, G. (2007). Does plyometric training improve vertical jump height? A meta-analytical review. *British Journal of Sports Medicine*, *41*, 349–355.

Marques, M. C., & Izquierdo, M. (2014). Kinetic and kinematic associations between vertical jump performance and 10-m sprint time. *Journal of Strength and Conditioning Research*, *28*, 2366–2371.

Millor, N., Lecumberri, P., Gómez, M., Martínez-Ramírez, A., & Izquierdo, M. (2013). An evaluation of the 30-s chair stand test in older adults: Frailty detection based on kinematic parameters from a single inertial unit. *Journal of NeuroEngineering and Rehabilitation*, *10*, 86.

Myer, G. D., Schmitt, L. C., Brent, J. L., Ford, K. R., Barber Foss, K. D., Scherer, B. J., … Hewett, T. E. (2011). Utilization of modified NFL combine testing to identify functional deficits in athletes following ACL reconstruction. *Journal of Orthopaedic & Sports Physical Therapy*, *41*, 377–387.

Noyes, F. R., Barber-Westin, S. D., Fleckenstein, C., Walsh, C., & West, J. (2005). The drop-jump screening test: Difference in lower limb control by gender and effect of neuromuscular training in female athletes. *American Journal of Sports Medicine*, *33*, 197–207.

Oberländer, K. D., Brüggemann, G.-P., Höher, J., & Karamanidis, K. (2013). Altered landing mechanics in ACL-reconstructed patients. *Medicine & Science in Sports & Exercise*, *45*, 506–513.

Patterson, M. R., & Delahunt, E. (2013). A diagonal landing task to assess dynamic postural stability in ACL reconstructed females. *The Knee*, *20*, 532–536.

Ramírez-Campillo, R., Meylan, C., Álvarez, C., Henríquez-Olguín, C., Martínez, C., Cañas-Jamett, R., … Izquierdo, M. (2014). Effects of in-season low-volume high-intensity plyometric training on explosive actions and endurance of young soccer players. *Journal of Strength and Conditioning Research*, *28*, 1335–1342.

Requena, B., Garcia, I., Requena, F., De Villarreal, E. S. S., & Paasuke, M. (2012). Reliability and validity of a wireless microelectromechanicals based system (keimove) for measuring vertical jumping performance. *Journal of Sports Science Andmedicine*, *11*, 115–122.

Rowlands, A. V., & Stiles, V. H. (2012). Accelerometer counts and raw acceleration output in relation to mechanical loading. *Journal of Biomechanics*, *45*, 448–454.

Setuain, I., Millor, N., Gorostiaga, E. M., Alfaro, J., & Izquierdo, M. (2015). Jumping performance differences among elite professional handball players with or without previous ACL reconstruction. *Journal of Sports Medicine and Physical Fitness*. Advance online publication. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/25828195.

Zheng, Y.-B., Zhang, Z.-M., Liang, Y.-Z., Zhan, D.-J., Huang, J.-H., Yun, Y.-H., & Xie, H.-L. (2013). Application of fast Fourier transform cross-correlation and mass spectrometry data for accurate alignment of chromatograms. *Journal of Chromatography A*, *1286*, 175–182.