

Article

Can IMU Provide an Accurate Vertical Jump Height Estimate?

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Abstract: The aim of the present study was to determine if an inertial measurement unit placed on the metatarsal part of the foot can provide valid and reliable data for an accurate estimate of vertical jump height. Thirteen female volleyball players participated in the study. All players were members of the Republic of Serbia national team. Measurement of the vertical jump height was performed for the two exemplary jumping tasks, squat jump and counter-movement jump. Vertical jump height estimation was performed using the flight time method for both devices. The presented results support a high level of concurrent validity of an inertial measurement unit in relation to a force plate for estimating vertical jump height (CMJ $t = 0.897$, $p = 379$; ICC = 0.975; SQJ $t = -0.564$, $p = 0.578$; ICC = 0.921) as well as a high level of reliability (ICC > 0.872) for inertial measurement unit results. The proposed inertial measurement unit positioning may provide an accurate vertical jump height estimate for in-field measurement of jump height as an alternative to other devices. The principal advantages include the small size of the sensor unit and possible simultaneous monitoring of multiple athletes.



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Keywords: IMU; force plate; squat jump; counter-movement jump; vertical jump

1. Introduction

The vertical jump (VJ) is a complex task that requires the coordination of multiple joints [1]. It is characterized by a rapid vertical acceleration of the body mass in the shortest possible time interval and was found to be related to common sports activities, such as sprint, acceleration and change of direction speed (CODS) [2–4]. The VJ is used in the testing of the mechanical characteristics of the lower limb muscles [5], as well as in sport praxis in order to provide an insight into athletes' training status, and thus inform future training focus [6]. The jump modalities that are most widely used in testing are the counter-movement jump (CMJ) and the squat jump (SQJ). The former utilizes the characteristics of the muscle stretch-shortening cycle (SSC) thus more closely resembling a real-world jumping task while the focus of the latter is the isolated concentric phase of muscle action [7–9].

The jump height (JH) is considered to be an alternative indirect indicator of lower limb explosive capacities [10] which is commonly used as a measure of VJ performance. Although the use of a force plate (FP) is predominant for in-depth analysis of the mechanical characteristics of the lower limb muscles, it also enables the calculation of the JH [11]. However, the use of an FP is mainly constrained to laboratory settings which certainly raises the question of ecological validity in relation to the sport-specific task demands. In addition, an FP is a barely portable, expensive piece of equipment [12] which makes it unsuitable for in-field use. Consequently, the aforementioned device is commonly used as a criterion device for validation of other equipment while the in-field estimation of VJ

performance is done using photoelectric cells, contact mats, mobile apps, and more recently, inertial measurement units (IMU) [13,14].

An inertial measurement unit is an example of a micro-electromechanical sensor system (MEMS) that typically incorporates an accelerometer, gyroscope, and magnetometer [15]. While IMU can provide kinematic and precise temporal data, when combined with a sensor fusion algorithm it can be used for tracking three-dimensional movements [16]. Due to the small size of an individual unit, IMU-based systems merely affect athletes' performance. Their low power consumption allows for a longer autonomy of the device while using a smaller battery which further reduces the overall size of the device while still allowing several hours of measurement. When these features are combined with wireless data transmission and low cost (<100\$) such systems can be effectively used for in-field measurement of performance of single or multiple athletes while the acquired data can be shared instantaneously to the coaches and athletes [17]. During the last decade, IMU-based systems have been used for the measurement and evaluation of nearly all types of sports activities [18], including VJ assessments. As different commercial and custom IMU-based systems have been validated in relation to the measurement of VJ height [19,20], different positioning of the sensor device on the athlete's body has been used. In studies by [12,14,21] sensors have been positioned on the lumbar area at the level of vertebrae L5, while a study by [17] used the positioning of the sensor on the athlete's ankles.

The majority of the equipment used for in-field VJ height assessment, such as photoelectric cells and jump mats employs the flight time (FT) calculation method for JH calculation [22]. In fact, the FT method has been shown to be valid and reliable [13,23–25] and is considered to be the most common way to estimate VJ height [26]. A study by [17] has shown that the same approach can be used for the measurement of JH using IMU. The FT method uses a basic kinematic equation to calculate jump height [27]. It is mainly dependent on accurate detection of the take-off and landing instances.

This paper proposes an implementation of a custom-made IMU placed on the distal area of the metatarsal part of the foot for VJ height estimation using the FT method. The proposed solution simplifies the detection of take-off and landing instances, due to the placement of the sensor close to the endpoint of the kinetic chain. A similar approach was adopted by [17,26] yielding good results. The present paper builds upon the finding of the aforementioned studies in terms of using a new, custom-made sensor device and a sample of specifically trained, elite female athletes. The aim of the paper was to validate the current sensor device and positioning in relation to VJ height estimation. We hypothesized that the present sensor setup will provide valid and reliable results in relation to VJ height calculation in CMJ and SQJ tasks. The paper presents a simple, cost-effective solution to the common problem of in-field VJ height estimation, which can easily be extended to simultaneous testing of multiple athletes.

2. Materials and Methods

2.1. Participants

Thirteen elite-level female volleyball players volunteered for the study. All players were active members of the Republic of Serbia national volleyball team (Age = 24.6 ± 3.2 [years]; body height = 187.8 ± 4.3 [cm]; body mass = 75.0 ± 3.87 [kg]; training experience = 13.5 ± 3.5 [years]). Prior to the testing session, all subjects were informed in detail about the measurement procedures and the possible risks and benefits of this research. The research was conducted according to the postulates of the Declaration of Helsinki and with the permission of the Ethics Committee of the University of Belgrade Faculty of Sport and Physical Education (02 No. 484-2).

2.2. Measurement Equipment

For the purposes of this research, we used an FP (AMTI, USA Inc. Watertown, MA; sampling frequency 1000 Hz) and a custom IMU-based system previously used in [16,28,29]. The IMU-based system consists of 6 degrees of freedom (DOF) LSM6DS33 3D

accelerometer/gyroscope [30] mounted on an Adafruit Feather M0 WiFi micro-controller with a built-in WiFi module [31], all powered by a LiPo battery. The overall size of the unit is 50 mm × 24 mm × 10 mm. For the purposes of this research, only accelerometer data was used. The LSM6DS33 accelerometer detection range is up to ±16 g_0 . The system sampling frequency was 200 Hz. IMU data was sent via UDP to a laptop running the main LabView application (LabView 2019, National Instruments, Austin, TX, USA) used for signal processing. Both the signal acquired from the FP and the signal acquired from IMU were filtered using a low-pass Butterworth filter (order = 5, $f_{\text{cof}} = 40$ Hz). The calculation of the jump height from IMU data was performed using the FT method [13,22,27] by Equation (1).

$$h = \frac{t_F^2 \cdot g_0}{8} \quad (1)$$

Where h is the height of the jump, t is the flight time and g_0 is gravity acceleration (9.81 ms^{-2}). The same method of jump height calculation was used for the FP data [11]. The FP ground-reaction force threshold value of zero ($\pm 5 \text{ N}$) [14] and IMU absolute acceleration threshold value of $5 g_0$ were used for detection of the start/end of the jump flight phase.

2.3. Flight Time Measurement

The methodological approach to the JH calculation is summarized in Figure 1. In the signal acquisition phase, the raw signal of acceleration is acquired for the X, Y and Z axis. The signal processing phase combines the filtering of the raw signals, followed by the calculation of the absolute acceleration and event detection. After that, in the final step, the flight time is calculated from the timestamps of the obtained events (take-off and landing) and the jump height is calculated from the determined flight time by Equation (1).

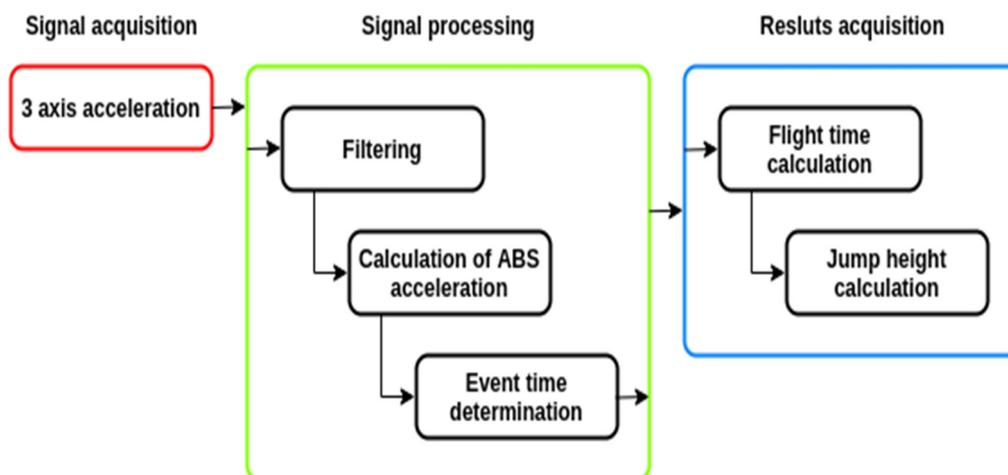


Figure 1. The methodology of JH calculation from IMU data.

The IMU accelerometer measures the 3D acceleration vector including gravity acceleration projected on the sensor axes in accordance with the sensor orientation.

The measurement of the flight time is based on the detection of take-off and landing events from the acquired absolute acceleration signal. During take-off and landing, pronounced acceleration pulses occur at the selected location of the sensor; the amplitude of both pulses exceeds gravity for the size class. When detecting take-off and landing events, we can, therefore, choose a threshold value that is much higher than the gravitational acceleration. Consequently, gravity has no significant effect on measuring the time between these two events. An example of the measured acceleration signals with the acceleration threshold marker and the time markers of the detected events is given in Figure 2.

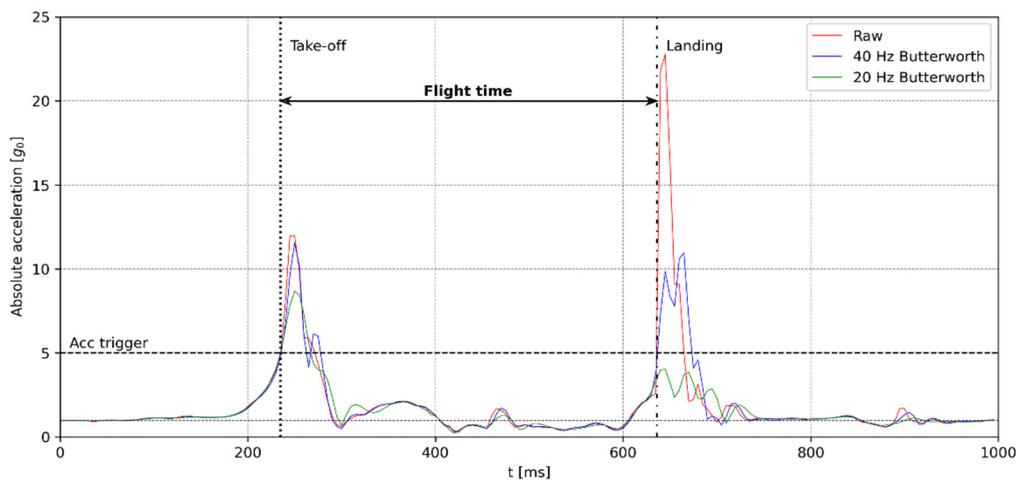


Figure 2. Flight time with the effect of different signal filters with detected events and optimal trigger.

Taking into account the sampling frequency of 200 Hz, it should be noted that the analog acceleration signal is filtered in the LMS6DS33 chip with a 100 Hz low pass anti-aliasing filterer, as defined in the manufacturer’s datasheet [30]. In addition, the acquired signal was filtered using a Butterworth low-pass filter (order = 5, $f_{\text{cof}} = 40$ Hz). A much lower filter cut-off frequency ($f_{\text{cof}} = 10$ Hz) is commonly used in the processing of signals obtained on different human movements, which is aimed towards the elimination of the signal components originating from external factors. However, for the purposes of VJ height estimation, such an approach is inappropriate in relation to the landing phase of the jump in which the athlete’s body collides with the surface thus providing an intensive jerk and high acceleration values which can exceed the sensor threshold. Figure 2 shows the detection of take-off and landing events using $5 g_0$ threshold on raw and signals filtered using 40 and 20 Hz f_{cof} (red, blue and black, respectively). Due to the signal being filtered in A/D conversion it can be noted that even raw signal can be used for event detection. However, as the external conditions of in-field measurement may vary additional filtering is implemented. Reducing acceleration signal spectra under 40 Hz introduces errors in detecting the landing event, which can be clearly seen in Figure 2.

The acceleration threshold value ($5 g_0$) used as a trigger for event detection is optimally set in terms of minimization of the flight time bias and is synchronized to the FP in terms of accurate take-off detection.

The error in calculating a vertical jump height is directly affected by flight time measurement error, according to Equation (1). Therefore, for a relatively small flight time error, we can use a linearized model to calculate the jump height error, as given by Equation (2).

$$e_h = \frac{e_t \cdot t_F \cdot g_0}{4} \quad (2)$$

Where e_h is the JH measurement error, e_t is the FT measurement error, t_F is the flight time and g_0 is gravity acceleration (9.81 ms^{-2}).

2.4. Measurement Procedure

The testing of VJ height was performed within a single testing session. The session took place between 9 and 11:30 AM in the postseason period of the yearly training cycle. Prior to the testing, all participants performed a 15 min individual warm-up supervised by the team strength and conditioning coach. Measurement of the VJ height was performed for the two exemplary jumping tasks, SQJ and CMJ [11]. The subjects started both tasks standing on the FP shoulder-width apart with their hands on their hips. For the SQJ subjects were instructed to flex their knees to a self-selected position ($90\text{--}120^\circ$ knee flexion) which was maintained for 2 s (Figure 3—left). Afterward, subjects performed a jump without

a counter-movement. For the CMJ the subjects were instructed to flex their knees to a self-selected position as quickly as possible which was followed by an immediate jump. For both jumps, it was recommended that at take-off the subjects leave the floor with the knees and ankles extended and land in a similarly extended position [13] (Figure 3—middle). The recovery period between the individual trials was set to 30 s while the pause between the jump modalities was set to a minimum of 3 min [32]. All subjects were instructed to jump for maximum height. The IMU was placed on the upper distal area of the metatarsal part of the foot of the participant, more precisely, at the level of 2nd to 3rd metatarsal bone as shown in Figure 3—right. The placement of the sensor close to the endpoint of the kinetic chain simplifies the detection of takeoff and landing instances and was previously used by [17,26].

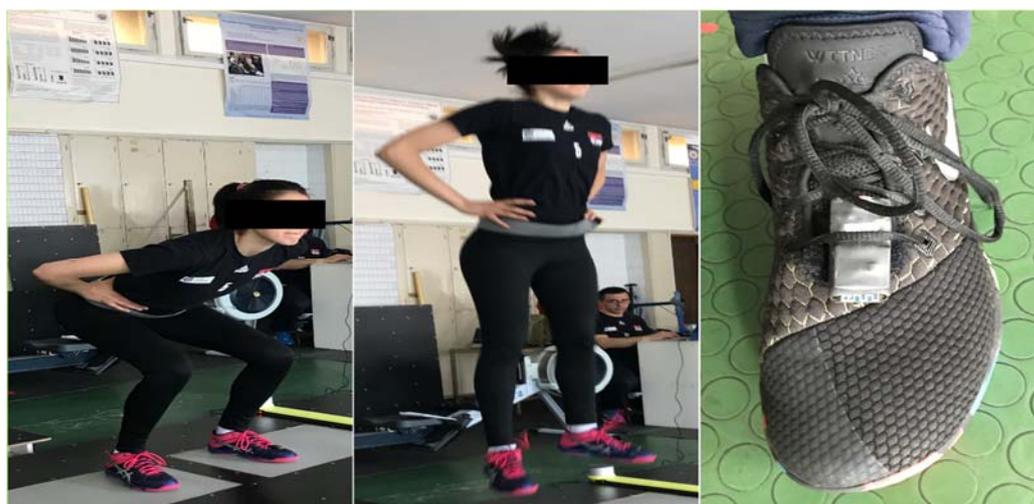


Figure 3. Squat jump—starting (left), take-off/landing position (middle), and IMU placement (right).

2.5. Variables

The variables in this research represent the VJ height estimated from the data acquired from an FP and an IMU in the specific tasks of SQJ and CMJ. For determining the validity we used the combined dataset from two trials performed on the same task. These variables are abbreviated as jumpType_device (e.g., CMJ_FP). For the reliability analysis, the dataset was split by trial and the number of the trial was added to the abbreviation. Thus, these variables are abbreviated as jumpType_device_trial (e.g., CMJ_FP_I). All variables used in this research are expressed in cm.

2.6. Statistical Analysis

For the purposes of this research, all raw data were subjected to descriptive statistical analysis in order to provide basic statistical indicators (Mean, Standard Error Mean—SEM, Standard Deviation—SD, Coefficient of Variation—cV, Minimum—Min and Maximum—Max). The assumption of normality of the distribution was tested by application of the Shapiro–Wilk test. Differences in the scores in relation to the measurement equipment were determined using a Paired sample *t*-test. Cohen’s *d* was provided for effect size, with a value of 0.2, 0.5 and 0.8 considered small, medium, and large effect, respectively [33]. Intraclass Correlation Coefficient (ICC) was used to provide a measure of inter and intra-instrument reliability. Based on the 95% confidence interval of the ICC estimate, values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively [34]. In addition, the mean coefficient of variation (McV) was provided [35]. Bland–Altman plots were used to evaluate the discrepancies of the results between the two measurement devices [36]. The level of statistical significance was defined based on the criterion $p \leq 0.05$ [37]. Statistical analyses were conducted using IBM SPSS 23 and Python3 Pandas and SciPy libraries [38,39].

3. Results

Table 1 shows the results of the descriptive statistical analysis for the CMJ and SQJ height calculated using the FT method is for both IMU and FP. Regarding the CMJ variables, i.e., CMJ_FP and CMJ_IMU, the mean jump height (Mean \pm SD) of 30.29 ± 3.41 and 30.11 ± 3.25 cm, was calculated from the FP and IMU data, respectively. The results of JH from FP data were in the range of 24.83 to 38.32 cm, with the coefficient of variation (cV) of 11.26%, while the range of JH results from IMU data was 24.60–39.14 cm, with the cV of 10.78%. In both cases, the results of the Shapiro–Wilk test were non-significant ($W = 0.957$, $p = 0.339$ for CMJ_FP; $W = 0.953$, $p = 0.276$ for CMJ_IMU), indicating a normal distribution of the results. In relation to the SQJ_FP and SQJ_IMU, the mean JH of 27.36 ± 2.67 and 27.54 ± 3.43 cm were determined, respectively. The calculated JH results are in the range of 22.15–32.65 and 19.13–33.16 cm for the respective variables. In both cases, the results were normally distributed ($W = 0.983$, $p = 0.925$ for SQJ_FP; $W = 0.972$, $p = 0.684$ for SQJ_IMU).

Table 1. Descriptive statistics and normality of the distribution of counter-movement (CMJ) and squat jump (SQJ) height, as estimated based on the flight-time (FT) determined from a force plate (FP) and an inertial measurement unit (IMU).

Descriptive Statistics									
	N	Min [cm]	Max [cm]	Mean [cm]	SEM [cm]	SD [cm]	cV [%]	W	<i>p</i>
CMJ_FP	26	24.83	38.32	30.29	0.67	3.41	11.26	0.957	0.339
CMJ_IMU	26	24.60	39.14	30.11	0.64	3.25	10.78	0.953	0.276
SQJ_FP	26	22.15	32.65	27.36	0.52	2.67	9.76	0.983	0.925
SQJ_IMU	26	19.13	33.16	27.54	0.67	3.43	12.45	0.972	0.684

Table 2 summarizes the results of the validity analysis of the VJ height measurement using an individual IMU placed on the metatarsal part of the foot versus an FP as a criterion device. Regarding the CMJ, the difference in the JH results calculated from FP and IMU data was not statistically significant ($t = 0.897$, $p = 0.379$). The Cohen's *d* of 0.176 indicates a negligible difference in the results between the two devices, which is further supported by the McV value of 1.896. The Bland–Altman analysis yielded a bias of -0.18 cm and 95% LOA of -2.26 to 1.9 cm. The determined ICC value was 0.975. In relation to the SQJ, the difference of the JH results calculated from FP and IMU data was not statistically significant ($t = -0.564$, $p = 0.578$), with a negligible effect size of 0.111. The determined McV value was low (3.556) while the ICC value was 0.921. The Bland–Altman analysis yielded a bias of 0.18 cm and 95% LOA of -3.14 to 3.5 cm.

Table 2. Concurrent validity of an inertial measurement unit (IMU) vs. a force plate (FP) for vertical jump height estimation.

Concurrent Validity IMU vs. FP		
	CMJ	SQJ
FP (95% CI) [cm]	30.29 ± 3.41 (28.98; 31.6)	27.36 ± 2.67 (26.33; 28.39)
IMU (95% CI) [cm]	30.11 ± 3.25 (28.86; 31.36)	27.54 ± 3.43 (26.22; 28.86)
<i>t</i> -test (<i>t</i> , <i>p</i> , <i>d</i>)	(0.897, 0.379, 0.176)	(-0.564 , 0.578, 0.111)
ICC (95% CI)	0.975 (0.944; 0.989)	0.921 (0.825; 0.965)
McV [%]	1.896	3.556
Bias (95% CI) [cm]	-0.18 (-0.6 ; 0.24)	0.18 (-0.49 ; 0.85)
Lower LOA (95% CI) [cm]	-2.26 (-2.99 ; -1.54)	-3.14 (-4.3 ; -1.97)
Upper LOA (95% CI) [cm]	1.9 (1.17; 2.63)	3.5 (2.34; 4.66)

Figure 4 shows the discrepancies of the estimated VJ height between an FP and an IMU for the squat jump (SQJ) as the VJ test modality.

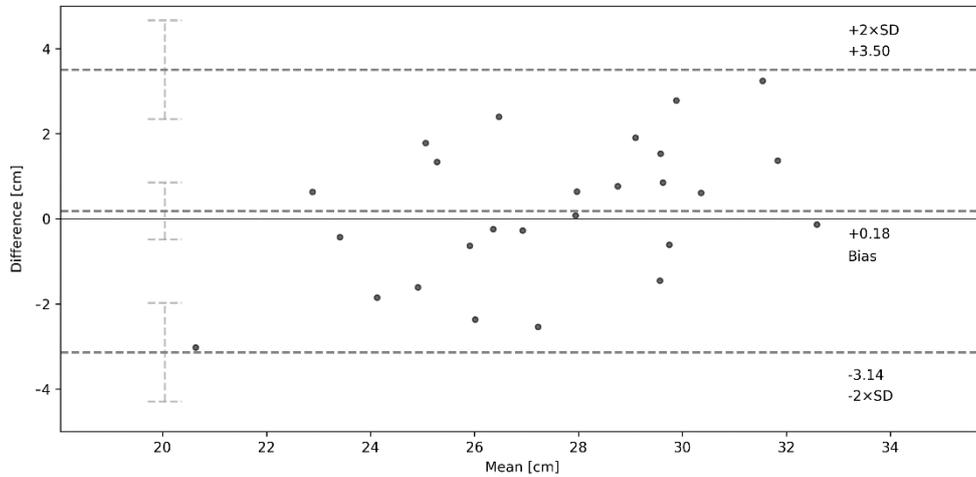


Figure 4. Force plate vs. IMU measuring SQJ height agreement (Bland-Altman plot).

Figure 5 shows the discrepancies of the estimated VJ height between an FP and an IMU for the counter-movement jump (CMJ) as the VJ test modality.

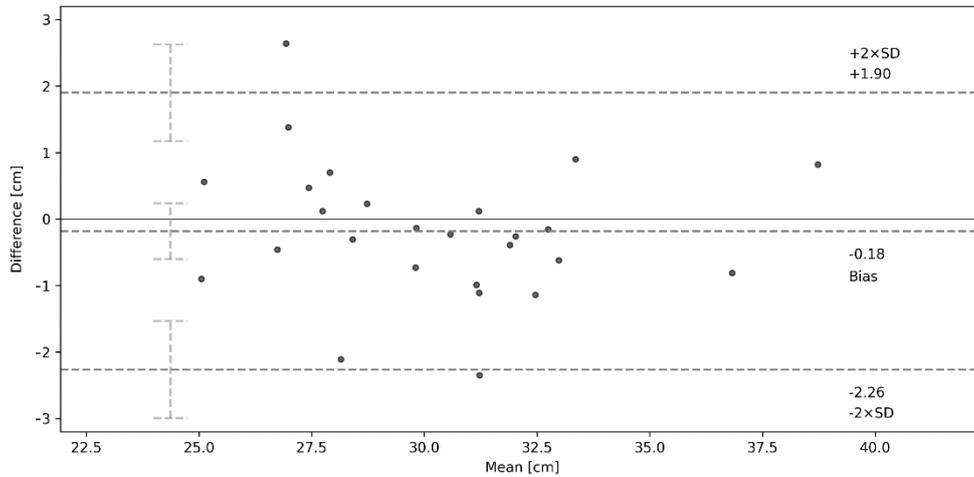


Figure 5. Force plate vs. IMU measuring CMJ height agreement (Bland-Altman plot).

Table 3 summarizes the results of the reliability analysis of the VJ height measurement using an individual IMU placed on the metatarsal part of the foot. High ICC values of 0.888 and 0.872 were determined for the CMJ and SQJ, respectively. The mean coefficient of variation of the results was 4.116 for the CMJ and 5.933 % for the SQJ.

Table 3. Test-retest reliability of an inertial measurement unit (IMU) for vertical jump height estimation.

	IMU Reliability	
	CMJ	SQJ
IMU_I (95% CI) [cm]	30.46 ± 3.7 (28.45; 32.48)	28.29 ± 3.15 (26.58; 30.01)
IMU_II (95% CI) [cm]	29.75 ± 2.82 (28.22; 31.29)	26.79 ± 3.65 (24.81; 28.77)
McV [%]	4.116	5.933
ICC (95% CI)	0.888 (0.633; 0.966)	0.872 (0.58; 0.961)

4. Discussion

This study aimed to validate the current sensor device and positioning in relation to VJ height estimation for the two most common jump modalities (CMJ and SQJ) used in testing. The results indicate an excellent level of agreement between the devices for measurement of VJ height using the FT method as well as a high level of reliability of the VJ height estimate for both jump modalities. Based on the aforementioned, it can be argued that the presented IMU-based system can be used to provide coaches a lightweight, portable alternative to photoelectric cells and contact mats for the purposes of in-field VJ height measurement as well as an alternative to the previously used IMU placement on the athletes back. Overall JH of 30.29 ± 3.41 and 27.36 ± 2.67 cm was determined for the CMJ and SQJ, respectively, using an FP. The calculated JH from IMU data was 30.11 ± 3.25 and 27.54 ± 3.43 cm for the respective jump modalities (Table 1).

Regarding the validity of IMU for measurement of VJ height, the results of a paired sample *t*-test have shown no statistically significant mean difference between the devices for both CMJ ($t = 0.897$, $p = 0.379$) and SQJ ($t = -0.564$, $p = 0.578$), with negligible effect size ($d = 0.176$ and $d = 0.111$, respectively) [30] (Table 2). The high ICC values of 0.975 and 0.921 for the respective jump modalities indicate an excellent [34,37] level of agreement between the devices for the measurement of VJ height using the FT method. This is further supported by the low McV values of 1.90% for the CMJ and 3.56% for the SQJ task. The Bland–Altman systematic bias value of -0.18 cm for CMJ and 0.18 cm for SQJ (Table 2) indicate that the difference of the calculated JH between the devices has no practical significance. The lower SQJ height results have yielded a higher value of the standard deviation of the differences, thus providing a wider LOA (-3.14 and 3.5 cm) when compared to CMJ (-2.26 and 1.9 cm, for upper and lower LOA, respectively) (Table 2). Figures 4 and 5 show the agreement of the devices for the respective jump modalities. The presented results show a somewhat better agreement when compared to the ones by [17] who determined a Bland–Altman mean bias of 0.59 cm with the 95% LOA of -0.35 ; 1.53 cm between an IMU and an FP when examining drop jumps from three different heights using an IMU placed on the athletes' ankle. A more recent study by [26] used a Polar V800 and a stride sensor to determine the JH for CMJ and SQJ tasks and compare validate them versus an FP. The results of [26] show a bias \pm random error of -0.30 ± 2.36 and -0.45 ± 1.85 cm for the SQJ and CMJ modalities, respectively. The same study determined an ICC value of 0.93 and 0.97 for the respective jump modalities. These results are in line with the ones obtained in the present study. A study by [14] has reported a Bland–Altman bias of 6 cm, with a wide LOA of -2.14 cm. Present findings suggest that JH may be accurately estimated using the proposed positioning. This may help coaches and practitioners in terms of a more rapid assessment of VJ height when working with large groups of athletes.

Regarding the test-retest reliability of IMU for VJ height estimation, a low McV of 4.12 and 5.93% was determined for the CMJ and SQJ, respectively. An ICC value of 0.888 was determined for the CMJ, while for the SQJ the value of ICC was 0.872 (Table 3). The results indicate a high level of reliability [34,37] of the VJ height estimate for both jump modalities. As a whole, the presented results support a high level of validity and reliability of an IMU for VJ height estimation using the FT method. The presented results are slightly lower when compared to the results of [26] who determined the ICC values of 0.9 for both CMJ and SJ using Polar V800 and a stride sensor. The same study has determined the McV value of 4.83% and 4.66% for the SQJ and CMJ which are in line with the ones determined in the present study. A study by [14] has determined the reliability of an IMU placed on the back of the participant. The ICC value of 0.89 and an McV of 7.1% were reported.

The presented results further contribute to the previously mentioned findings of [17], who used an IMU placed above the ankle to calculate the flight time of a drop jump (DJ) from vertical acceleration, as well as [26] who used a commercial Polar V800 and a stride sensor to estimate VJ height in SQJ and CMJ tasks using the FT method. Taken as a whole, the findings indicate that VJ height can be effectively calculated from accelerometer data only when the sensor is placed on the foot. The presented approach is an alternative to the

frequently used positioning of the sensor on the back of the participant [12,14,21] in terms of simplifying the calculation of the JH as there is no need to calculate the orientation of the sensor unit to extract the vertical acceleration component during the movement of the trunk. In addition, the present study provides the data related to the VJ height estimate in elite athletes using the proposed sensor placement which is lacking in [26].

The main limitations of the present study are related to the small size of the used sample and its high homogeneity in terms of JH. The fact that the sensor is mounted on one foot can present a general limitation in terms of FT measurement. However, this is not supported by the presented results obtained on elite athletes.

5. Conclusions

In conclusion, a simple IMU-based system can provide coaches a lightweight, portable alternative to photoelectric cells and contact mats for in-field VJ height measurement as well as an alternative to the IMU placement on the athletes back in terms of simplifying the JH calculation.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

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