## Original Article

# Comparison of two methods in the estimation of vertical jump height

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## ABSTRACT

Vertical jumps are vital aspects in many sports. Many technologies are available to determine and calculate jump height. One such portable and easy-to-use technology is an Inertial Measurement Unit (IMU) that uses accelerometers, gyroscopes, and magnetometers. The purpose of this study was to compare vertical jump heights calculated from the data captured with an IMU versus true jump height calculated using a gold standard 3-Dimensional Motion Capture system. Ten subjects completed five jumps for six different conditions including vertical counter-movement jumps and jumps involving rotations on the ground and using a trampoline. An average Pearson correlation coefficient of .87 was found between the IMU and motion capture for all conditions. Condition correlations ranged from .76 to .94. Bland-Altman analyses showed that the IMU underestimated the vertical jump height compared to the motion capture by 5.0 to 9.2 cm across all conditions. Results suggest an IMU can be used to measure jump height in a laboratory setting with a reasonable accuracy, even during vertical jumps that include rotations.
**Keywords:** Inertial measurement unit; Accelerometers; Accuracy; Sports.

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## INTRODUCTION

An essential aspect of many sports is jumping. Sports that require jumping may be classified into two different categories: those that require a straight up and down jump (e.g., volleyball, basketball or football) and those that require rotation around an axis or multiple axes while jumping (e.g., figure skating, diving, gymnastics, freestyle skiing and snowboarding). Vertical jump height is used as a measurement of lower extremity power and to track improvement during training (Balsalobre-Fernández, Glaister, & Lockey, 2015; Bui, Farinas, Fortin, Comtois, & Leone, 2015; Dias et al., 2011; Linthorne, 2001). In addition, vertical jump height is also a performance criterion integrated into scoring systems for many sports. Athletic performance can be improved by specifically training jumping ability (Bui et al., 2015; Leard et al., 2007; Requena, García, Requena, Saez-Saez de Villarreal, & Pääsuke, 2012). Many studies have examined the straight up and down jump but very few examine the rotational jump (Balsalobre-Fernández et al., 2015; Bui et al., 2015; Dias et al., 2011; Jarning, Mok, Hansen, & Bahr, 2015; Leard et al., 2007).

Methods of determining or estimating jump height in sports include 3-Dimensional (3-D) motion capture systems, force plates, 2-Dimensional (2-D) video analysis, jump mats and accelerometers. Researchers have used 3-D motion capture systems to track and calculate the displacement of the centre of mass to determine the vertical jump height (Dias et al., 2011; Magnúsdóttir, orgilsson, & Karlsson, 2014; Requena et al., 2012). Although 3-D motion capture systems are the gold standard measurement tool for physical movement (Leard et al., 2007; Ozkaya et al., 2018), they are expensive, time consuming and not portable, therefore, not practical to be used in the field (Dias et al., 2011; Nuzzo, Anning, & Scharfenberg, 2011). Force plates and jump mats have been validated and are portable. Two-dimensional video analysis is widely used by coaches, inexpensive, and can approximate jump height and degrees of rotation; however, outcome measures cannot be reported in real time and can have higher degrees of human error compared to other methods (Post et al., 2018). Inertial Measurement Units (IMU) measure acceleration and angular rotation in three dimensions (Sadi, Klukas, & Hoskinson, 2013). These devices are small, low cost, readily available and some can store data on board (Cleland et al., 2013; Lee et al., 2015; Sadi et al., 2013). Simple IMUs have been embedded into smart sport equipment and consumer products such as PIQ sports sensors (www.piq.com), action cameras, and smart phones to estimate performance variables, including jump height (Bernardina et al., 2019; Yingling et al., 2018). Algorithms have been developed to use accelerometer data to measure airtime, which can then be used to predict jump height.

The primary purpose of this study was to compare vertical jump heights as measured using a 3-D motion capture system to vertical jump height calculated using an IMU. The secondary aim of this study was to explore how vertical jumps with a rotational component affected the accuracy of the IMU jump height measurement.

## METHODS

Ten healthy subjects (five male, 5 females; age 22.9± 4.3 years; weight 71.5±17.7 kg; height 171.3±14.1 cm) were recruited to participate in this study. Subjects provided written informed consent prior to the study and procedures were explained to them verbally. This study was approved by the Conjoint Health Research Ethics Board of the University of Calgary (REB16-2027).

Two systems collected data simultaneously at 500 Hz during testing: an IMU system called the MMS (Motus Design Group, Victoria, Canada) and a 3-D motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA). The Y-axis was defined as the vertical direction for the IMU unit and the device was

positioned in the middle of the lower back between the L4-5 vertebrae secured with a neoprene belt (Figure 1). A retro-reflective motion capture marker was placed in the bottom left corner on the IMU (Figure 1). A small trampoline was used to increase jump height for one part of the protocol. One leg of the trampoline was placed in the middle of a force plate (Figure 2) in order to capture the events of take-off and landing.



Figure 1. Subject wearing the IMU system mounted on a neoprene belt. The belt was placed at the L4/L5 level and a retroreflective marker was attached to the bottom left corner.

All subjects participated in the single testing session, which included performing vertical jumps with and without rotation, both from the floor and from a small trampoline (Figure 2). Subjects were instructed to perform counter-movement jumps comfortably using their arms and limit their bounce on the trampoline when returning to the start position. Each subject was given two practice jumps per condition to become comfortable with the protocol and equipment prior to data collection.



Figure 2. The trampoline was placed in the middle of the force plate with the handle in front of the subject. Subjects began behind the trampoline and then stepped on to perform the jump.

Five counter movement jumps were completed in the following conditions from the floor and trampoline: straight jump up and down; straight jump up, 180° rotation, down; and straight jump up, 360° rotation, down. The order of jump conditions was randomized for each subject. A total of 30 trials were collected for each subject, giving a total of 300 trials for analysis.

Data collection began when the subject positioned him or herself with both feet to the side of the force plate. The IMU system was turned on by a researcher then the subject was instructed to step onto the force plate and asked to remain motionless for a few seconds to determine their standing height. The subject was then instructed to perform the required jump. The subject landed on the force plate with both feet and remained motionless until instructed to step off at which time the data collection was stopped on the IMU system. Subjects were given a five-minute rest period after three conditions were completed. The data collected from the motion capture system and the IMU were used to calculate the height of each jump performed.

Data from the IMU were downloaded and only the Y-axis data were processed. Acceleration data were processed first using a lowpass Butterworth Filter with a cut-off frequency of 5 Hz and an offset was subtracted to remove the component that represented the acceleration due to gravity. This cut-off frequency was chosen as it removed the most noise without removing true signal. An example of a typical acceleration signal showing the take-off and landing points can be seen in Figure 3. Airtime was calculated by subtracting the take-off and landing times. Take-off was the first crossing at zero and landing was the second crossing at zero of the Y accelerations signals. The equation used to determine jump height was JH= (G*AT^2) / 8 where JH is the jump height, G is acceleration due to gravity (-9.81 m•s$^{-2}$) and AT is the time spent in air (Bosco, Luhtanen, & Komi, 1983; Choukou, Laffaye, & Taiar, 2014; Linthorne, 2001; Mauch, Rist, & Kaelin, 2014; McMahon, Jones, & Comfort, 2016; Monnet, Decatoire, & Lacouture, 2014).
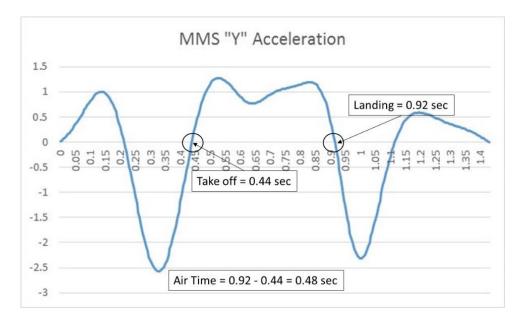


Figure 3. Typical MMS acceleration signal from a jump in the laboratory showing the Take-off and Landing times and the calculation of the Airtime.

From motion capture data and the use of a retroreflective marker, the average of 21 points before take-off when the subject was standing straight was used to determine the standing height of each subject, in other words the "zero" point of the reflective marker. The retroreflective marker was also used to determine the

maximum height jumped. From these values, jump height was calculated by subtracting the standing height from the maximal jump height achieved. Data were analysed using Pearson Correlation Coefficients and Bland-Altman plots to compare the IMU unit data to the true measurements of height from motion capture system.

## RESULTS

The highest correlation coefficient ($R^2$ = .94) was found during the straight jump from floor condition (Table 1, Figure 4). The lowest correlation coefficient ($R^2$ = .76) was found during the trampoline jump with a 180° rotation (Table 1). Bland-Altman plots were created for all conditions. The largest mean difference (-9.2 cm) was found during the trampoline straight jump condition (Table 2). Figure 5 shows a mean difference of -6.9 cm and Limits of Agreement of 1.8 cm and -15.6 cm from data combined for all conditions. A negative mean difference for all conditions indicated that calculated height from the IMU data was underestimating true jump height as measured by the video data. The largest range between the limits of agreement (19.0 cm) was found during the trampoline jump and 180° rotation condition and the smallest range (12.2 cm) was found during the trampoline straight jump condition (Table 2, Figure 6).
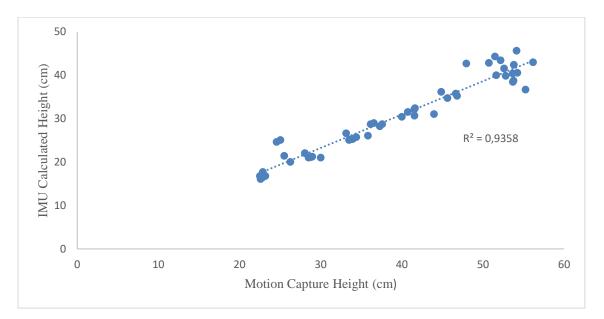


Figure 4. Scatter plot between motion capture height and predicted height from the IMU system of straight floor jumps with Pearson correlation coefficient.

Table 1. Correlation coefficients of laboratory data separated by condition.

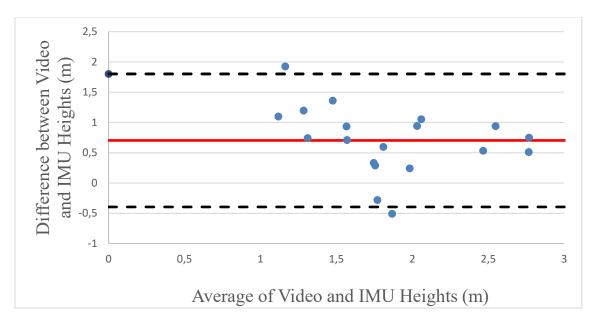| Condition | All | Floor Straight | Floor, 180° Rotation | Floor 360° Rotation | Trampoline Straight | Trampoline 180° Rotation | Trampoline 360° Rotation |
|---|---|---|---|---|---|---|---|
| $R^2$ | .87 | .94 | .88 | .80 | .92 | .76 | .87 |

Figure 5. Bland-Altman Plot with average difference between video and IMU heights for All Conditions. The dashed line represents the limits of agreement and the straight line is the average difference.

Table 2. Bland-Altman values of in-lab data separated by condition.

| Condition | All | Floor Straight | Floor 180° Rotation | Floor 360° Rotation | Trampoline Straight | Trampoline 180° Rotation | Trampoline 360° Rotation |
|---|---|---|---|---|---|---|---|
| Mean Difference (cm) | -6.9 | -8.89 | -5.0 | -5.9 | -9.2 | -5.7 | -5.7 |
| Upper LoA (cm) | 1.8 | -2.1 | 1.9 | 2.5 | -3.1 | 3.8 | 1.3 |
| Lower LoA (cm) | -15.6 | -15.7 | -11.9 | -14.2 | -15.3 | -15.2 | -12.7 |

*Note. LoA = limit of agreement.*

## DISCUSSION

The primary purpose of this study was to use IMU technology to determine how data can be used to measure jump height. It was found that in a controlled laboratory environment, the accelerometer data from the IMU system used to predict jump height was highly correlated to true jump heights as calculated using the motion capture system. The highest correlation was found with the floor straight jump condition ($R^2$ = .94). This condition was the simplest in that it had no rotation and it was hypothesized that this condition would provide the best correlations to truth. The trampoline jump with 180° rotation condition had the lowest correlation ($R^2$ = .76). The rotation could have affected the orientation of the IMU systems' vertical axis. In a study conducted by Sadi et al (2013), a stray from the axis of alignment may have influenced the readings collected by the IMU (Rantalainen, Gastin, Spangler, & Wundersitz, 2018).
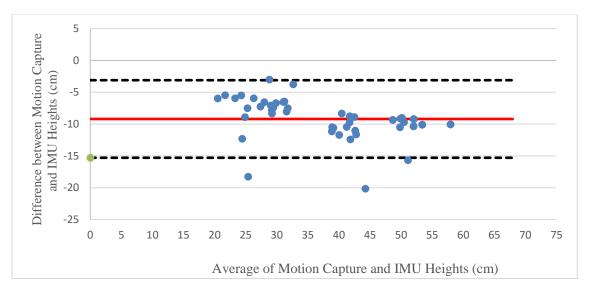
Figure 6. Bland-Altman plot of in-lab heights for trampoline straight jumps with average difference and limits of agreement.

A trend was seen in the correlations across the different conditions. In conditions with a 180° or 360° rotation, the correlation was lower than in the straight jump conditions. If the subject had leaned forwards or backwards while performing the rotation, this would create an angle from the true vertical axis and would then change the magnitude of the signal (Picerno, Camomilla, & Capranica, 2011). Dias et al (2011) also found that the movement of upper limbs influenced results. A similar trend can be seen in the Bland-Altman data plots. The trampoline jump with 180° rotation condition found the highest difference between IMU and motion capture as seen in Table 2. This could have been because of the orientation of the vertical axis. It may have also been because the trampoline created a movement artefact as the subject had to maintain their balance throughout the movement (Harding, Small, & James, 2007). There is inherent noise associated with the attachment of the IMU system or similar system (Harding et al., 2007). There is a possibility of shifting the IMU while recording that could have influenced the signal. The smallest difference was found with the trampoline straight jump condition. This could have been as it was a simple straight up and down jump where subjects were more likely to be upright maintaining an axis closer to vertical.

The underestimation found with all conditions could have been because of the sensitivity of the IMU system and its ability to detect the impact of landing and the acceleration of take-off as both measures affect airtime (Harding et al., 2007). This difference could have also been from the position of the centre of mass during take-off and landing. Picerno et al (2011) stated that the estimation of jump height depended on the position of the centre of mass during take-off and landing being the same, which rarely happened in practice. A trend was found in the data that the higher the jump the larger difference between the two methods. The highest jumps came in the straight floor and trampoline jumps and these had the two largest mean differences of -8.9 and -9.2 cm. This could have been because of an increase in the movement of upper limbs or a larger change in posture by the subject. Both methods could have had an increase in measurement error as initial heights and max heights along with take-off and landing were determined manually (Balsalobre-Fernández et al., 2015). It can be summarized that the system and analysis of the time in air using the Y-axis of the acceleration signal is a reasonable method to predict true jump height in a controlled laboratory setting.

The results of this study indicated that accelerometry can be used to predict jump heights, including jumps with simple rotations. Future research should consider more complex rotations, different approaches to analysing the IMU data and the development of an algorithm to be used by coaches and athletes. Future research could also include further testing to including more trials with more athletes, movements, and different variables such as degree of rotation. In this study, only the vertical acceleration signal was used. Landing is a variable and dependent on the athlete and type of movement being performed (Nuzzo et al., 2011). Another direction could be the use of more than one IMU to look at the combination of placements and signals in the determination of take-off and landing and accuracy of the signals (Cleland et al., 2013).

This system could be improved with more testing for accuracy, noise, and orientation. Overall, with future research, this system can be used as a beneficial tool for coaches and athletes to give objective data to help improve athletic performance.

## ACKNOWLEDGMENTS

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