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Designing and implementation of IMU-based wearable real-time jump meter for vertical jump height measurement

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Abstract

The vertical jump height has been widely used in sports-related studies to track athletes' development. Although many systems can measure vertical jump height, there are still problems with measuring it in real-time during sports activity. Therefore, the use of inertial measurement unit (IMU)-based systems in this area is increasing. In this study, a low-cost, small, wireless, and wearable jump meter has been designed to address the real-time measurement problem. The developed system has a high accuracy for vertical jump measurements and provides some extra parameters for performance evaluation. Fourteen volleyball players' measurements were taken simultaneously with the designed system and a jump mat to evaluate the developed system's performance (n = 350). The obtained results show that the system is highly correlated with jump mat ($r^2 = 0.92$), and it also has a mean bias of −0.06 cm (95% limits of agreement −3.4 cm to 3.3 cm; $p < 0.001$).

Keywords

Embedded systems, IMU (inertial measurement unit), jump, performance monitoring, sensors, wearable systems

Introduction

Vertical jump height (VJH) is a parameter that should be measured to evaluate and improve the performance of athletes in many sport branches, such as athletics, basketball, and volleyball (Ziv and Lidor, 2010a, 2010b). This parameter can be used with some other parameters to track the development and performance, develop individual training, and determine the athletes' training load. The VJH is also essential for evaluating the leg muscles' strength, plyometric training effectiveness, and jumping technique improvement (Fatouros et al., 2000).

Vertical jump performance is evaluated by measuring the VJH with systems such as jump mat (Whitmer et al., 2015), vertec (Nuzzo et al., 2011), laser-operated systems (Musayev, 2006), and motion capture systems (Rojas-Lertxundi et al., 2017). However, these systems are not fully compatible to be used in real-time during the training or competition. Therefore, they are not very practical for the performance evaluation of the athletes. Due to these reasons and the increasing use of wearable technologies, Internet of things (IoT)-based wearable systems find a place in the VJH measurement as an alternative to the systems mentioned above as they are practical (Senanayake and Naim, 2019).

Inertial measurement unit (IMU) sensors are used to measure the VJH based on the change of acceleration values during the vertical jump. IMU-based systems are frequently used in studies as they have advantages such as having a small form factor and wearable, low-cost compared to other systems, portable, and easy to apply in the field. In addition to VJH measurement, there are studies in the literature, IoT technologies are used to track different sports branches (Huifeng et al., 2020; Kim and Kim, 2020; Mencarini et al., 2019; Wang and Gao, 2021).

There are many comparative studies in the literature about measuring VJH. Buckthorpe et al. measured VJH with belt mat, contact mat, portable, and laboratory force plates. When the results were evaluated to laboratory force plates, it was found that belt mat and portable force plate, with a mean difference of −0.1 and −0.8, were suitable for VJH measurement (Buckthorpe et al., 2012). Nuzzo et al. measured countermovement jump (CMJ) height with Vertec, Myotest, and Just-Jump systems comparatively, and they obtained the best results in terms of reliability with Myotest. According to obtained results about intrasession reliability for Myotest, intraclass correlation coefficient, standard error of measurement, and coefficient of variation are 0.95, 1.5 cm, and 3.3% in males, and 0.91, 1.4 cm, and 4.5% in females, respectively (Nuzzo et al., 2011). Bui et al. used a contact mat, optical system, and Sargent jump system to measure and compare the results. They stated that the contact mat, optical system methods gave similar results, but the Sargent jump gave different results, about 5 cm on average (Bui et al., 2015). Nogueira et al. (2020) compared vertical impulse and laser sensor

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instrument tests, and they found a difference of about 5.84 cm on average between methods and r = 0.8 as the correlation. Apart from these, there are different studies in which VJH is measured with similar systems (Garcia-Lopez et al., 2005; Leard et al., 2007; Samozino et al., 2008).

Grainger et al. compared IMU with a 3D motion capture system in measuring VJH. They measured vertical CMJ and jump both on the ground and with a trampoline. The highest correlation was obtained as a result of the jump on the ground. In this study, they found difference from 5 to 9.2 cm between two systems (Grainger et al., 2020). Rantalainen et al. measured jump height with IMU and jump mat, and they compared their results. As a result of the study, they obtained −0.1 cm mean bias and a high correlation in the measurements of both systems. Thus, they concluded that the IMUs could provide a valid assessment of jump height measurements (Rantalainen et al., 2020).

Wang et al. using an IMU sensor above the toe and under the heel, measured VJH and compared their results with optical marker–based motion capture. According to their results, they showed the usability of IMU in maximum jump height estimation. When the results are evaluated, IMU measurements were highly correlated with other systems: r = 0.98 and r = 0.99 for toe and heel, respectively (Wang et al., 2018). Nielsen et al. performed this measurement with IMU and compared the results with a force plate and motion capture system. They used some numerical methods such as numerical double integration (NDI), flight time (FT), and take-off velocity (TOV) to calculate the height, and so they showed that the IMU predicted height measurement successfully (Nielsen et al., 2019). Apart from these, there are studies performed with IMU for VJH measurement in the literature (Heredia-Jimenez and Orantes-Gonzalez, 2020; Schmidt et al., 2014; Umek and Kos, 2020).

Since IMU-based systems are so successful and practical, some commercial products such as WIMU, Optojump, and VERT use IMUs to measure VJH. These systems are used in many studies to perform high-accuracy measurements in athletes (Borges et al., 2017; Hanley and Tucker, 2019; Mahmoud et al., 2015; Pino-Ortega et al., 2018; Skazalski et al., 2018).

There are different estimation methods for VJH in the literature. Chiu and Daehlin performed a study using a force platform and compared the numerical methods used to estimate VJH. This study evaluated five methods: FT, TOV, TOV plus the center of mass (COM), and two different methods related to COM. They compared the results of these methods in detail (Chiu and Dæhlin, 2020).

There are also mobile applications for VJH measurement, and they are frequently used in this measurement as they are easily accessible. One of these applications is My Jump 2 (Sharp et al., 2019). Bogataj et al. used this app in primary school children (Bogataj et al., 2020b) and recreationally active adults (Bogataj et al., 2020a) to measure VJH and evaluate the validity, reliability, and usefulness of this application. In this study, measurements were made with Optojump simultaneously for comparison. They stated that this app was suitable for jump measurements and useful for evaluators. Many different recent studies using such applications are included in the literature (Balsalobre-Fernández et al., 2018; Brooks et al., 2018; Coswig et al., 2019; Cruvinel-Cabral et al., 2018; Haynes et al., 2019; Stanton et al., 2017).

These mentioned VJH measurement systems have some difficulties such as alignment in laser-operated system, evaluation differences in vertec, high cost and data size in motion capture system. IMU systems and mobile applications, on the contrary, have difficulties such as simultaneous transfer of data to the computer and providing few parameters for evaluation.

In this study, a jump meter based on IMU and microcontroller, a wearable, small form factor, low-cost is designed as the real-time measurement is difficult in athletes in the fields such as volleyball and basketball. The VJH can be measured with the developed system, and data are sent to a computer with Bluetooth during a match or a training session. Therefore, the developed system has an advantage compared to the other systems, which cannot make measurements during the match in real-time. The VJH for CMJ was measured in 14 volleyball players with the jump mat to control the developed system simultaneously. With the designed system, the VJH of the athletes was measured wirelessly with high accuracy and precision. The designed system can also calculate initial speed, force, work, and power parameters to evaluate athletes' jumping performance. Thanks to these parameters, the training's efficiency can be understood, and so the athletes' development can be assessed more accurately in detail. Unlike the existing jump meters, the designed system can operate with a computer in real-time wirelessly. Thus, the athletes' performances can be analyzed more easily than the existing jump meters. To summarize, the system has contributions such as being low-cost, measuring different parameters of jumping during the match or training independent of location in real-time, and being wireless communication with the computer for detailed analysis.

Materials and methods

Hardware

In this study, M5Stick, which has MPU9250, 1.3" Led Screen, 80 mAh battery, and ESP32, is used to design a jump meter, Figure 1(a). M5Stick provides some advantages by providing this hardware in a small (48.2 × 25.5 × 13.7 mm) and light (65 gr) package. The powerful CPU of ESP32 can easily handle data acquisition and processing tasks, and the collected data can be wirelessly transferred using the built-in Bluetooth or Wi-Fi of the ESP32 (EspressifSystems, 2016).

Bluetooth communication is used to transfer the data to the PC. I2 C protocol using SDA and SCL pins is used for the communication of the MPU9250. The block diagram of the system is shown in Figure 1(b).

Measurement setup

The jump meter is attached with a clip to the shorts, as shown in Figure 2.

Before measuring the VJH, the system is calibrated on a flat surface, where the acceleration values are zero, then using them as an offset to increase the system's accuracy. The

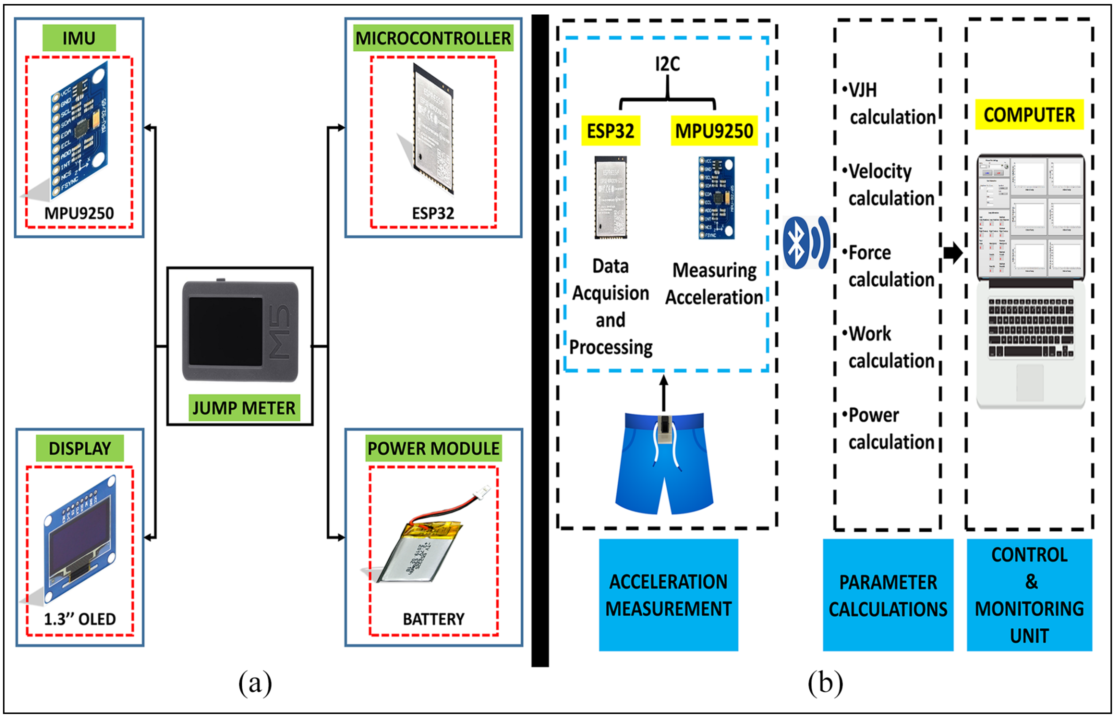

Figure 1. (a) The internal structure of the system. (b) Block diagram of the system.

Figure 2. Jump meter—short connection. The red square shows the jump meter.

system is calibrated at the startup once, and then the system is attached to the athlete. The flow chart of the system is shown in Figure 3.

The VJH is measured to acceleration's changing with the designed system attached to the athletes' short. Besides, the system can operate high sampling rate frequency. So, the system can sensitively detect changes in acceleration signal. Therefore, successive jumps can be measured with high speed.

In this study, the VJH was measured in 14 volleyball players, and a total of 350 vertical jumps were measured with the designed system and jump mat simultaneously. In these measurements, the athletes made CMJ in training. The reason this was chosen is a most common jump into sports branches, and often used as benchmark measure (Wang et al., 2018). This jump movement is shown in Figure 4.

In this figure, h_s and h_{po} are taped and they are entered into the graphical user interface (GUI) before the VJH measurement.

Measurement of acceleration and parameter calculations

Acceleration can be measured with the designed jump meter in three axes. However, since the VJH measurement is performed with the system, only the acceleration values in the x-axis (a_x) are measured depending on the sensor's placement. Since the acceleration data during the flight is not used, the take-off and take-on data are used; only the x-axis is measured to find the most accurate VJH. Therefore, movements in the other axes should not be taken into account. The x-axis corresponds to longitudinal axis. In this way, VJH can be measured with the change in acceleration. The acceleration values for five consecutive vertical jumps are shown in Figure 5.

As seen in Figure 5, there are two distinct peaks in each jump. While the first peak occurs at the take-off, the second occurs when the person lands on the ground. The time between these two peaks gives the FT of the athlete. The vertical height is calculated using FT. Different parameters such as velocity, force, total work, and mean power can also be calculated using this time in the designed jump meter. The flow chart of parameter calculations is shown in Figure 6.

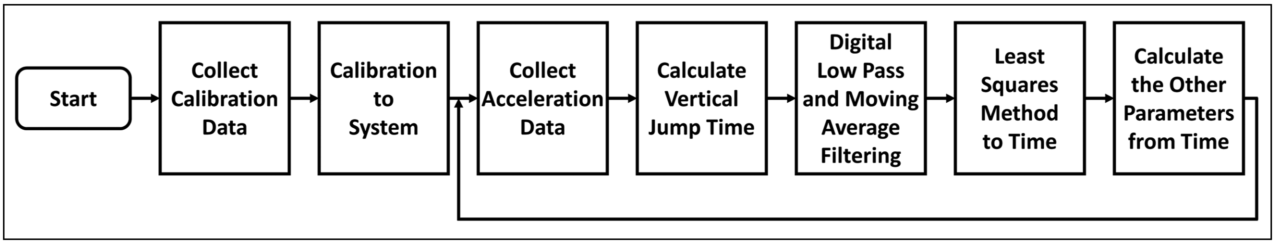

Figure 3. Flow chart of the system.

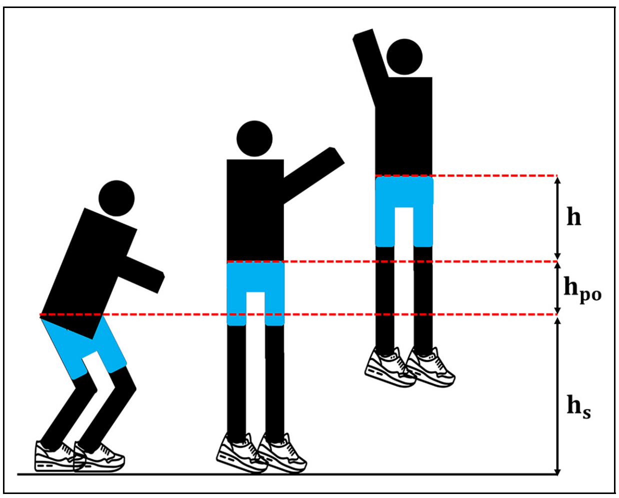

Figure 4. The jump movement and height parameters used at the equations. In the figure h, h_s, and h_{po} are jump height, height of COM and vertical push-off distance, respectively.

The first parameter calculated using FT is the vertical height (h, m). This parameter is calculated with equation (1) (Samozino et al., 2008)

$$h = \frac{1}{8} g t^2 \tag{1}$$

where h, g, and t are vertical height, gravitational acceleration, and FT, respectively.

The second and third parameters calculated are the TOV (V_{to}, m/s) and mean velocity (V_m, m/s). These parameters are calculated with equations (2) and (3), respectively (Samozino et al., 2008).

$$V_{to} = \sqrt{2gh} \tag{2}$$

$$V_m = \sqrt{\frac{gh}{2}} \tag{3}$$

The fourth parameter calculated is the force (F, Newton). In this calculation, the athlete's mass (m, kg) and vertical push-off distance (h_{po}, m) are measured before jumping, and these values are recorded. The force is calculated with equation (4) (Samozino et al., 2008)

$$F = mg\left(1 + \frac{h}{h_{po}}\right) \tag{4}$$

where h_{po} is the vertical push-off distance, shown in Figure 4.

The last two parameters are total work (W) and mean power (P, Watt). These parameters are calculated with equations (5) and (6) (Samozino et al., 2008).

$$P = mg\left(1 + \frac{h}{h_{po}}\right)\sqrt{\frac{gh}{2}} \tag{5}$$

$$W = mg\left(h + h_{po}\right) \tag{6}$$

Data acquisition and filtering

The VJH was measured with the acceleration data from IMU in this study. The ESP32 microcontroller in the system collects these data at a 250 Hz sampling rate. Since the movement to be measured is jumping and due to the easy changing of acceleration values, noise may occur. Filters are used to prevent this noise. One of these filters is digital low-pass filter (DLPF).

Fourth-order Butterworth DLPF filters the acceleration data with 5 Hz to prevent noise in this study. In addition to this, moving average (MA) filter (160 ms window size) is used to filter acceleration data. Thus, the peaks to find VJH could be found in the signal. The effect of the filter on the signal is shown in Figure 7.

The DLPF's frequency was selected to be 5 Hz in order to avoid all noise as much as possible. The MA filter's window size was selected 160 ms. These values were determined by testing. When the frequency and window size are selected to be higher, the noise is not filtered enough, and the peak values are not determined clearly. Otherwise, the peak values in the signal may be lost when the values are selected be lower.

Curve fitting

Curve fitting is a method used to fit an nth degree of polynomial to the available data points. Then this curve can be used to estimate the unknown data points in future measurements (Guest, 2012). In this study, the first degree of the polynomial (a line) is fitted to the measurements of the designed jump meter with the least squares method (LS). For this purpose, the number of samples between two peaks in the acceleration signal measured with jump meter and the FTs obtained with the jump mat is used to fit the line as shown in Figure 8, where the values on the x-axis are the number of samples between two consecutive peaks in the acceleration sign multiplied by two, and the values on the y-axis are the FT in seconds. By

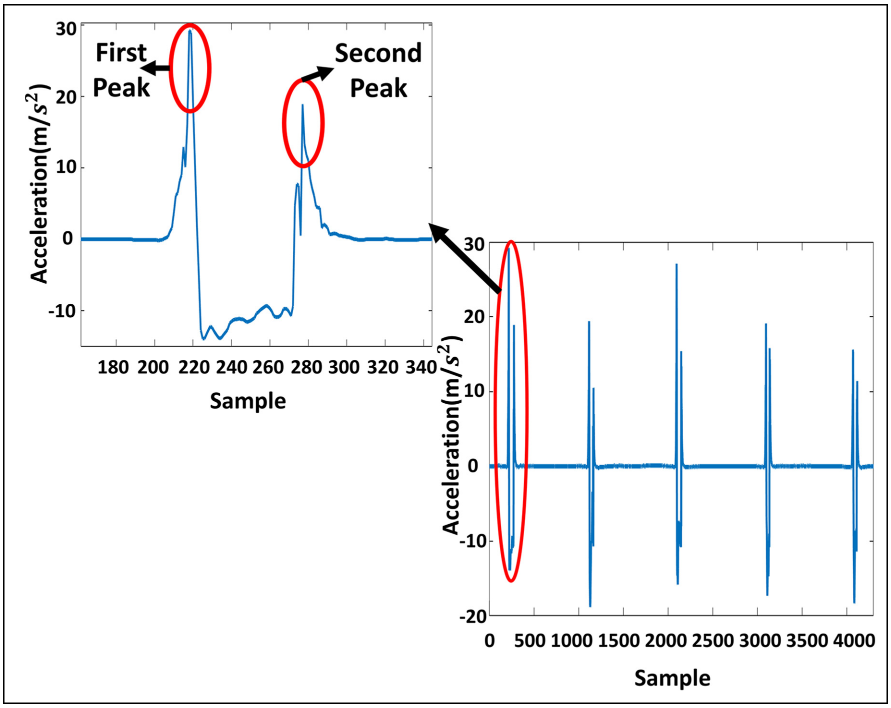

Figure 5. Acceleration values for five consecutive vertical jump. While the first peak occurs at the take-off, the second occurs when the person lands to the ground.

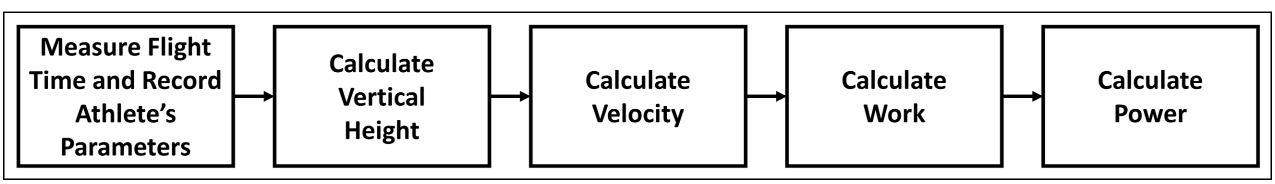

Figure 6. Flow chart of parameter calculations.

using the fitted line, the designed system calculates the FT for the intermediate samples.

Each point's distance to this line, called error, is minimized, so the best line is fitted to available points (Moritz, 1972). According to this explanation, the LS is performed using the following equations. First, equation (7) is used to obtain a second value according to twice the sample difference between two acceleration signal peaks. The reason for multiplying by two is that the jump mat's parameter is the FT

$$y(x_i) = a_0 + a_1 \cdot x_i \qquad i = 1, 2, 3, \ldots, n \tag{7}$$

where x, y, a, and n represent the samples' number between two peaks in the acceleration signal, the FTs obtained with the jump mat, coefficient, and number of jump, respectively.

This value is then subtracted from the actual value, so an error value (e) is found. The sum of squares of the errors (E) is obtained using these error values obtained for each point. These equations are given from equations (8)–(10).

$$e_i = y_i - y(x_i) \tag{8}$$

$$e_i^2 = [y_i - y(x_i)]^2 \tag{9}$$

$$E = \sum_{i=1}^{n} (e_i^2) = \sum_{i=1}^{n} (y_i - a_0 - a_1 . x_i)^2 \tag{10}$$

The best line is fitted when E is minimum. Therefore, the derivative of E with respect to a_0 and a_1 should be 0. These two equations are given in equations (11) and (12).

$$\frac{dE}{da_0} = \sum_{i=1}^{n} -2(y_i - a_0 - a_1 . x_i) = 0 \tag{11}$$

$$\frac{dE}{da_1} = \sum_{i=1}^{n} -2(y_i - a_0 - a_1 . x_i).(x_i) = 0 \tag{12}$$

These two equations are transformed into matrix form, and then the values a_0 and a_1 are found using this matrix. The matrix form, a_1, and a_0 are given from equations (13)–(15).

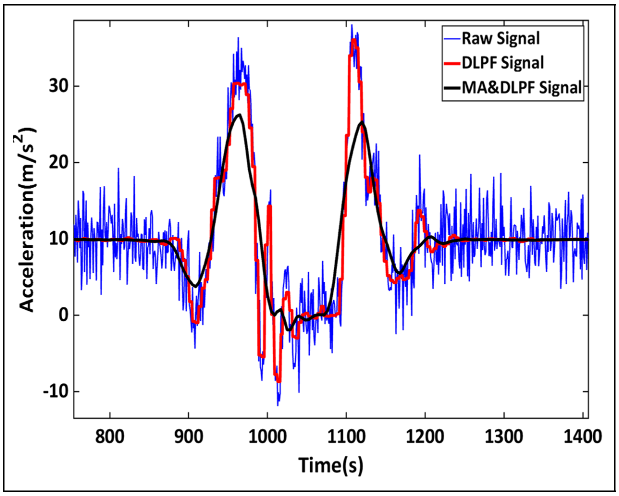

Figure 7. Filter effect on the acceleration signal. While the blue graph shows the raw signal, the red graph shows the signal filtered with 5 Hz DLPF, and the black graph shows the signal filtered with 5 Hz DLPF and moving average filter with 160 ms window size.

$$\begin{bmatrix} n & \sum_{i=1}^{n} x_i \\ \sum_{i=1}^{n} x_i & \sum_{i=1}^{n} (x_i{}^2) \end{bmatrix} \cdot \begin{bmatrix} a_0 \\ a_1 \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} (x_i . y_i) \end{bmatrix} \tag{13}$$

$$a_1 = \frac{n.\left(\sum_{i=1}^{n} (x_i . y_i)\right) - \left(\sum_{i=1}^{n} x_i \;.\; \sum_{i=1}^{n} y_i\right)}{n.\left(\sum_{i=1}^{n} (x_i{}^2)\right) - \left(\sum_{i=1}^{n} x_i\right)^2} \tag{14}$$

$$a_0 = \frac{\sum_{i=1}^{n} y_i - a_1 \;.\; \sum_{i=1}^{n} x_i}{n} \tag{15}$$

Statistical analysis

Statistical analysis is important for the correct interpretation of the results, and it evaluates the systems' validity with the data taken in a sufficient number and from different groups in the analysis. Therefore, 350 vertical jumps were measured from 14 volleyball players. For the statistical analysis of the data, the standard deviation and mean value were calculated. The correlation coefficient and Bland–Altman method were used in this study to evaluate the designed system's validity (Klein, 2020).

Designing GUI

The designed system is supported with a GUI designed in LabVIEW to show the performance parameters to the trainer in real-time during the training. In this way, the coach can monitor the athlete's jumping performance in real-time through the GUI shown in Figure 9. Therefore, the developed system provides more functionality than the other

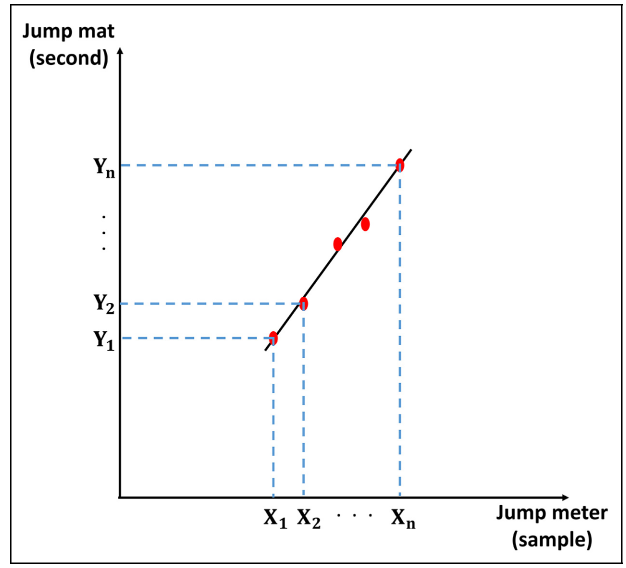

Figure 8. The curve fitting with the least square method to results obtained from jump meter and jump mat. In the figure, x and y represent the samples' number between two peaks in the acceleration signal, and the flight times obtained with the jump mat, respectively.

measurement methods such as Jump mat and Vertec, for VJH. The measurements can also be saved using the developed GUI for the athletes' retrospective analysis and development tracking.

The GUI consists of four parts "File and Port Settings," "User Information," "Jump Information," and "Graphs." In the first part, file and port settings are made, and the program's start–stop control is performed. The second is where user information, such as age, height, and weight, is entered. The last two are the parts where the parameters, such as jump height and velocity, are displayed numerically and on the graph in real-time.

Results

Fourteen volleyball players took part in the study. Their physical details are given in Table 1. A total of 350 CMJ measurement data were taken from these players. Measurements were carried out simultaneously with both systems, the jump mat, and the designed system.

The mean VJH values for the jump mat and designed system were 13.43 and 13.36 cm, respectively. The two systems' bias was found −0.06 cm (lower limit of agreement (LOA): −3.4 cm, upper LOA: 3.3 cm). This Bland–Altman plotting is shown in Figure 10(a).

When the VJH measured with the designed system and jump mat are examined, a high correlation coefficient was found between them ($r^2 = 0.92$, $n = 350$). The measurements of both are shown in Figure 10(b).

When the error values of each VJH measurement are calculated, minimum error, maximum error, mean error, and standard deviation are founded as 0.005 cm, 3.583 cm, 1.413 cm, and 0.986, respectively. The histogram of error values is shown in Figure 10(c).

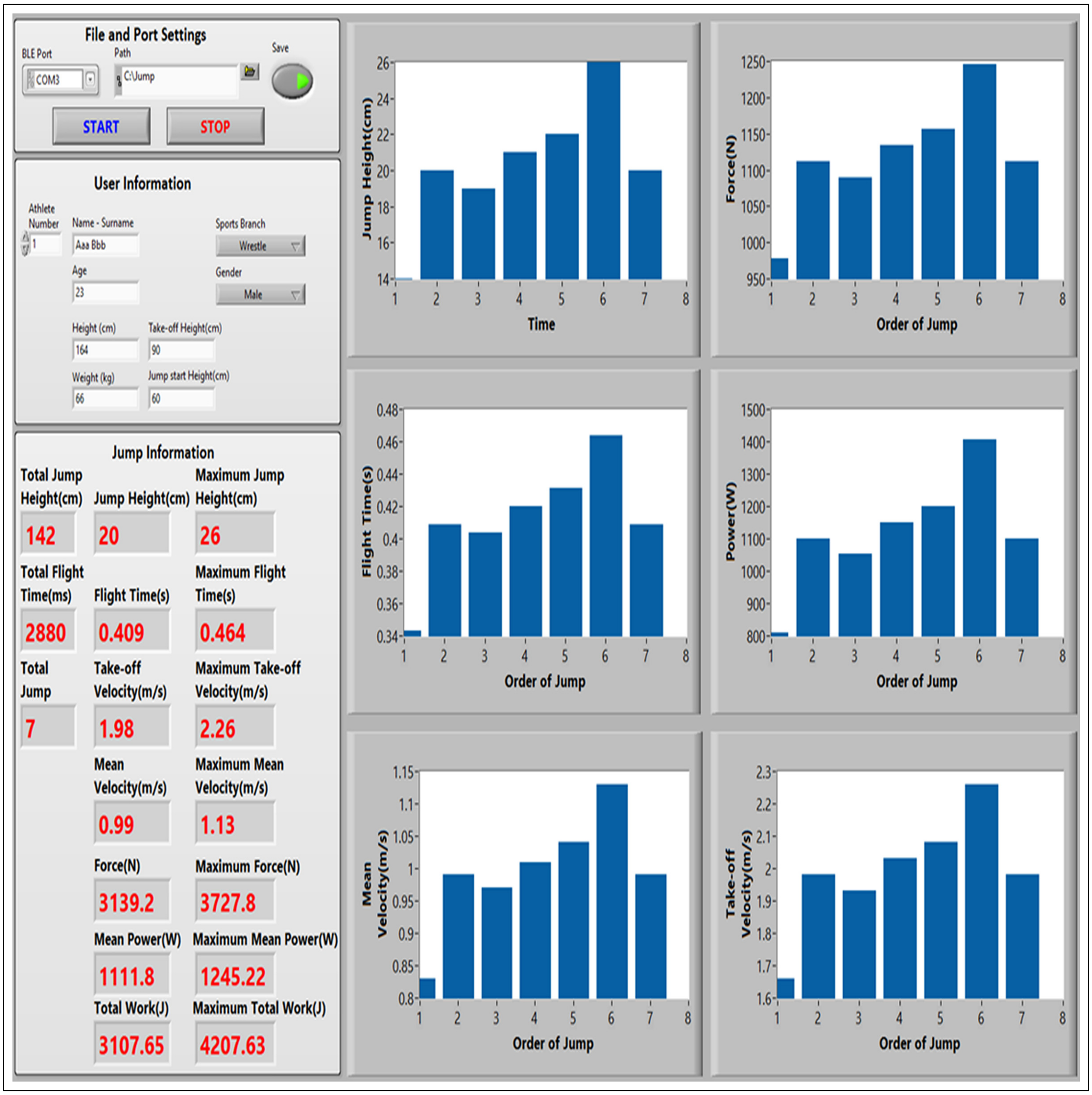

Figure 9. The GUI of the system and the measured parameters.

Table 1. Information of players in this study (N = 14).

	Mean	Standard deviation	Min	Max
Age (y)	12.64	1.15	11	14
Height (cm)	160.79	7.65	142	172
Body mass (kg)	52.07	8.73	29	62

Discussion

VJH measurement is a parameter that must be measured to evaluate athletic performance in many sports branches. In this study, a microcontroller and IMU-based jump meter was designed, and its performance was controlled with a jump mat. The measurements made with the designed system have a high correlation value (r^2 = 0.92). Therefore, the system's accuracy is relatively high. The system's bias, lower and upper LoA values are −0.06, −3.4, and 3.3 cm, respectively. The obtained results show that the measurements performed with designed systems have a low standard deviation value, and thus, the system is stable.

Different studies using IMU were performed in the literature. Rantalainen et al. used IMU and compared it with a jump mat. They used two different methods based on FT with IMU. While they found −0.1 cm bias, 0.97 ICC, −4.5 cm lower LoA, and 4.4 cm upper LoA with the first method, they found 3.9 cm bias, 0.93 ICC, the lower and upper LoA values were −2.3 and 12 cm, respectively with the second method of their study (Rantalainen et al., 2020).

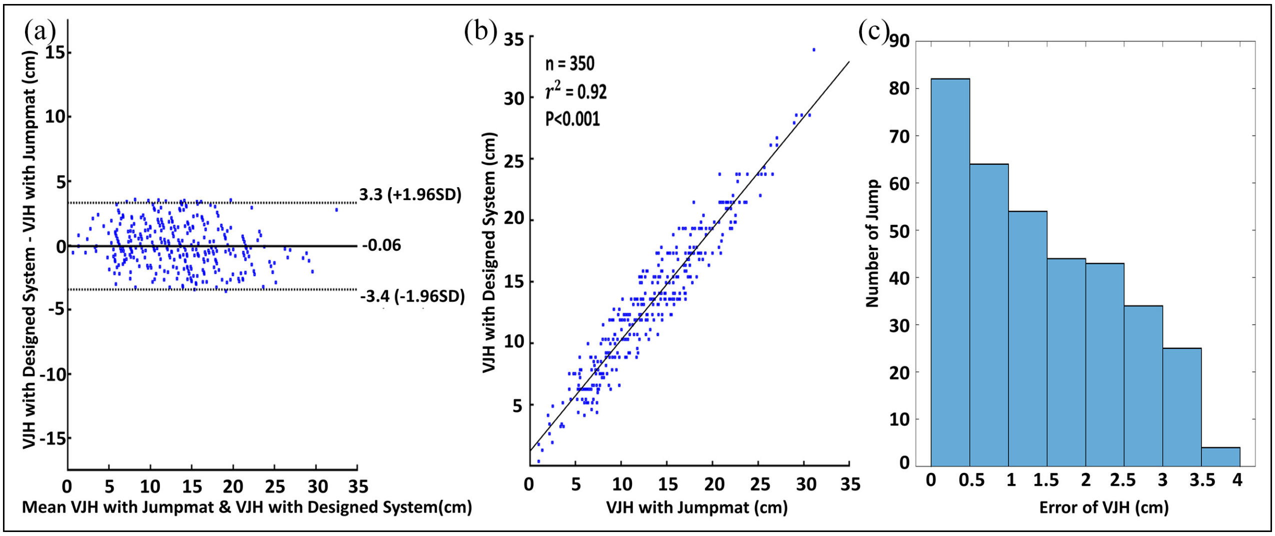

Figure 10. (a) Bland–Altman plots for VJH of designed system and jump mat. While the x-axis represents the mean VJH value in each jump measurement with both systems, and the y-axis represents the difference VJH value. (b) The VJH measurements with jump mat and designed system (n = 350, r^2 = 0.92, p < 0.001). (c) The histogram of error values. The horizontal axis shows the ranges of error values in cm, the vertical axis shows the number of jumps in these ranges.

Table 2. The results of this study and different studies using IMU in the literature.

	Correlation coefficient	Mean bias (cm)	Lower LoA (cm)	Upper LoA (cm)
This performed study	0.92	−0.06	−3.4	3.3
Rantalainen et al. (the first method)	0.97	−0.1	−4.5	4.4
Rantalainen et al. (the second method)	0.93	3.9	−2.3	12
Grainger et al. (the best condition)	0.94	−8.89	−15.7	−2.1
Grainger et al. (the worst condition)	0.76	−5.7	−15.2	3.8
Wang et al. (positioned toe)	0.98	–	–	–
Wang et al. (positioned heel)	0.99	–	–	–

Grainger et al. performed a similar study with IMU and motion capture system in different conditions. They found a mean difference to −6.9 cm, and LoA from −15.6 to 1.8 cm using all states. In their study, the highest correlation was 0.94 in the floor straight jump condition, and the lowest correlation was 0.76 in the trampoline jump with 180° rotation condition (Grainger et al., 2020). Wang et al. used IMU and motion capture systems in VJH measurement. They positioned IMU both toe (r = 0.98) and heel (r = 0.99), and they found IMU highly correlated with the motion capture system (Wang et al., 2018). These results are given in Table 2.

The designed system can calculate some extra parameters, such as velocity, force, and power. These parameters are very important for a more detailed evaluation of jumping. Besides, the designed system has a GUI and can be used in real-time and wirelessly with a computer. The studies mentioned above cannot calculate these parameters, and they cannot be used in real-time with a computer. Therefore, the developed system provides some extra tools for a more detailed evaluation, and it easily allows performance analysis compared to the other studies in the literature (Rantalainen et al., 2020). Besides, the designed system can calculate these parameters in real-time and it can operate wirelessly, so unlike other systems such as vertec and jumpmat, it can be easily used anywhere (Nuzzo et al., 2011; Whitmer et al., 2015). My jump 2 app can calculate these extra parameters, but it is based on the video method and works according to the person marking the take-off and landing moments. Therefore, the designed system is more useful than this app. In addition to this, the designed system does not allow user errors because of its properties in real-time and automatic sensing (Bogataj et al., 2020a, 2020b).

When the designed system's results were examined, it was found that the system has a high correlation coefficient and low standard deviation, so this system is suitable for VJH measurement. It has advantages such as small form factor, operating wirelessly, and being wearable. It is also low-cost to other similar commercial IMU-based systems such as WIMU, Optojump, and VERT.

Conclusion

The VJH measurement in sports branches such as basketball, athletics, volleyball, etc., is essential for tracking athletic performance. There are systems such as motion capture system, Vertec, and Jump mat used for this measurement. However, these systems are designed to operate in a laboratory environment generally, and most of them do not give information about the athlete's performance in real-time at the field.

For these reasons, in this study, a wearable and wireless IMU-based jump meter is developed to address these problems and provide high accuracy, resolution, and stability at the measurements. The developed system is highly portable and cheap compared to the currently available commercial systems. This system can be attached to the athletes and measure VJH in real-time during competitions or trainings without restricting their movements.

With this system, the VJH can be measured in real-time; however, the horizontal movements cannot be measured since horizontal acceleration is not included in the system.

In future works, horizontal acceleration will also be included in the system. So, the horizontal jump movement will be measured in real-time. In this way, different jump movements in different branches are going to be measured with this system and evaluated in different athletes. In addition to this, the GUI is also detailed to upper and lower extremities for detailed analysis.

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Institutional Review Board Statement

The Ethics Committee of Çukurova University Faculty of Medicine has approved this study (05.03.2021/109/23) and carried it out under Helsinki's Declaration.

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