

Article

Validity and Reliability of a Smartphone App for Vertical Jump Height Assessment Using the Marker Displacement Time Method

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Abstract: The correct assessment of the vertical jump height depends on an accurate and reliable measurement tool. This study aimed to determine the concurrent validity and reliability of the My Jump 2 app used for estimating the maximum height (MH) of the counter-movement jump (CMJ). Twenty-one male adults participated in this study. The MH of the CMJ was estimated based on the displacement of the jumper's center of mass (force platform), the displacement time of the reflective marker placed on the jumper's sacrum (smartphone, My Jump 2-DT) and the flight time of the jumper (smartphone, My Jump 2-FT). The assessment of the concurrent validity showed a poor agreement (ICC = 0.362; Bland–Altman bias = 12.4 cm) between the My Jump 2-FT and force platform ($p < 0.001$), and a good agreement (ICC = 0.858; Bland–Altman bias = -0.2 cm) between the My Jump 2-DT and force platform ($p < 0.001$). The ICC values for internal consistency (>0.9) indicated the excellent reliability of all measurement tools ($p < 0.001$). The findings revealed the high accuracy and good reliability of the My Jump 2 app for the new method of MH estimation for the CMJ, including the displacement time of the marker placed on the jumper's sacrum.

Keywords: validity; jump height; counter-movement jump; My Jump 2 app; force platform



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1. Introduction

The correct assessment of the maximum height (MH) in the vertical jump depends on an accurate and reliable measurement tool [1–3]. The validation of this new instrument related to the MH estimation method is commonly based on the comparison of this tool with the force platform considered the gold standard [2,4,5]. In particular, the analysis of the displacement of the jumper's center of mass (CoM) obtained after the double integration of the acceleration data vs. time as a result of the ground reaction force measurement enables a very accurate determination of the MH [6–9]. Moreover, using the force platform, the MH can be estimated based on the flight time according to Bosco's formula [10] and the velocity of the CoM at take-off [7,11].

The assessment of the jump height obtained from the flight time is made easier by the installation of the My Jump app on a smartphone, which is much cheaper than laboratory devices [12,13]. Importantly, the My Jump app was validated by comparing this application with the force platform as a criterion. Analyzing the MH calculated based on the flight time in the counter-movement jump (CMJ), some researchers demonstrated a very high agreement between the gold standard and these measurement tools [2,14–16]. Furthermore, similar results for the MH of the CMJ and very high correlation coefficients between the force platform and the My Jump app for the take-off velocity method [6] and for the impulse–momentum method [17] were observed.

The calculation of the MH based on the flight time is also provided by the contact plate [3,4], Optojump photoelectric cells [4,5,9] and high-speed cameras with the Kinovea 0.8.15 software [18,19]. In addition, the motion capture (mo-cap) system enables the determination of the MH value based on the recorded displacements of the reflective

markers [9,20,21]. An accelerometer sensor that measures vertical acceleration can also be used to calculate the velocity and MH [4,22,23]. Considering the Vertec system, the MH is estimated as the difference between the MH and the standing reach height of the jumper [20,22,24].

Validity tests of the alternative measurement tools used for MH estimation should include a very accurate method of the jumper's CoM trajectory associated with the force platform. Previous papers did not use this method to assess the agreement between the My Jump 2 app and the force platform, mainly comparing the MH results obtained from the flight time for both measurement tools. In this study, a new method was adopted to calculate the MH of the CMJ based on the displacement time of the reflective marker placed on the jumper's sacrum. Therefore, the main aim of the study was to determine the concurrent validity and reliability of the My Jump 2 app for this method of estimating the MH of the CMJ in recreationally active male adults.

2. Materials and Methods

2.1. Participants

Twenty-one male adults (age: 21.0 ± 1.9 years and in range: 18–24 years, body mass: 74.8 ± 14.0 kg and body height: 1.78 ± 0.10 m) from Poznan University of Physical Education participated in this study. All participants were healthy and recreationally active. The International Physical Activity Questionnaire (IPAQ) was used to determine the physical activity of the participants [25]. The IPAQ results indicated that the activity level was high in 18 participants and sufficient in 3 participants. The inclusion criteria included participants (1) aged between 18 and 24 years, (2) practicing sports non-professionally, (3) with no history of ankle, knee, hip and back injuries (one year before testing), (4) with a lack of potential medical problems, and (5) with at least a sufficient level of physical activity based on the IPAQ questionnaire. All participants were familiarized with the experimental procedures and provided informed consent to participate in this study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the Poznan University of Medical Sciences (number 546/16).

2.2. Experimental Procedures

The CMJ tests were performed in one day from 11 a.m. to 3 p.m. The air temperature in the laboratory was 24 ± 1 degrees Celsius. The tests were preceded by a 10 min warm-up involving treadmill running as well as static and dynamic stretching exercises. After a few trials, each jumper performed three successful CMJs from an upright standing position, with hands on their hips and a flexion angle in both knee joints of approximately 90° for the lowest CoM position during the braking phase. Half-minute rest periods between these jumps were assumed. In turn, the rest periods between the warm-up and CMJ trials, as well as between the CMJ trials and three successful CMJs, were approximately one minute. Moreover, the students were instructed to jump as high as possible and land on both feet. All CMJs were performed on the force platform while being recorded with the use of a smartphone camera and mo-cap system. Before the tests, a special spherical marker (diameter of 20 mm) reflecting infrared rays was placed on the sacrum between the posterior superior iliac spines of each jumper [26].

Force platform. The stationary force platform 800 Hz (BP400600, AMTI, Watertown, MA, USA) was used to assess the CMJ height. The AMTI force platform was adopted as the gold standard for comparisons with other measurement tools. The vertical ground reaction force (VGRF) was collected using the BTS Smart Capture software (BTS Bioengineering, Milan, Italy). The VGRF data vs. time for the 63 trials were exported as files with the .xls extension. Then, in Microsoft Excel 2016 software, the values of displacement of the jumper's CoM (s_z) were calculated based on the numerical integration of the acceleration (a_z) and velocity data (v_z), according to the method of least trapezoids. The following formulas were used:

$$a_z = \frac{1}{m}(R_z - g), \quad (1)$$

where m —body mass, R_z —vertical ground reaction force, and g —gravity acceleration ($9.81 \text{ m}\cdot\text{s}^{-2}$),

$$v_z(t) = v_{oz} + \int a_z(t)dt, \quad (2)$$

where $v_z(t)$ —vertical velocity vs. time, v_{oz} —initial vertical velocity, and $a_z(t)$ —vertical acceleration vs. time,

$$s_z(t) = s_{oz} + \int v_z(t)dt, \quad (3)$$

where $s_z(t)$ —vertical displacement of the jumper's CoM vs. time, and s_{oz} —initial vertical displacement. For the $s_z(t)$ graph, the highest value of s_z as the MH of the CMJ was determined.

The iPhone 13 smartphone (Apple Inc., Cupertino, CA, USA) with iOS 17 was used for testing. All CMJs were recorded using the camera (frame rate of 240 Hz, HD 1080p) of the smartphone, which was placed on a stand to ensure its stabilization and thus reduce the recording error. The smartphone was located approximately 1.5 m behind the participant (in the frontal plane), at the height of approximately 0.1 m from the ground, according to the guidelines of Bogataj et al. [27]. The estimation of the MH of the CMJ was performed in the My Jump 2 app (version 2.2.6), following its instructions [2].

My Jump 2-FT. The flight time (t_f) of the jumper, i.e., the time between point C and point D (Figure 1) when $\text{VGRF} = 0$, was analyzed. Using the My Jump 2 app, the t_f between the first frame of the recording when both feet of the jumper were lifted off the ground and the first frame of the recording when the first foot touched the ground during the landing was determined. The MH was calculated based on the t_f of the jumper according to Bosco's formula [10]:

$$\text{MH} = 1.22625 \cdot t_f^2 \quad (4)$$

This method of assessing the MH using t_f was called My Jump 2-FT.

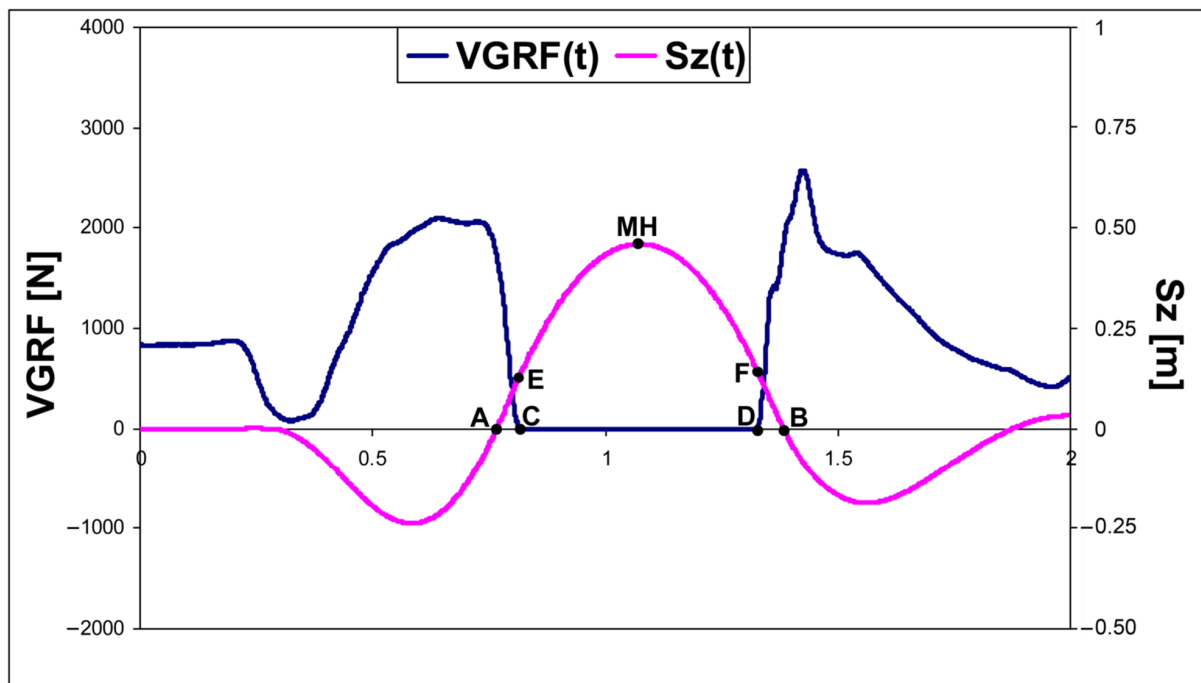


Figure 1. The $\text{VGRF}(t)$ and $s_z(t)$ graphs for the representative trial of CMJ. VGRF —the vertical ground reaction force, s_z —the vertical displacement of the jumper's center of mass, CMJ—the counter movement jump, MH—the maximum height in the CMJ, A—the point for the $s_z = 0$ during the take-off phase, B—the point for the $s_z = 0$ during the landing phase, C—the starting point of the jumper's flight phase, D—the ending point of the jumper's flight time, E—the ending point of the take-off phase, F—the starting point of the landing phase.

My Jump 2-DT. The My Jump 2 app was also used to estimate the MH according to the new My Jump 2-DT method, i.e., based on the displacement time (t_d) of the reflective marker placed on the jumper's sacrum. Considering the vertical zero position ($s_z = 0$) of this marker in the standing phase of the CMJ, t_d was defined as the time between the $s_z = 0$ during the take-off phase and the $s_z = 0$ during the landing phase. After the recordings, the analysis was performed in the My Jump 2 app while the smartphone was on the table. First, the $s_z = 0$ of this marker in the standing phase was set, and then the ruler was placed on the smartphone screen so that its lower edge coincided with the center of the marker. For the position of the center of the marker at the height of the lower edge of this ruler, the initial frame in the take-off phase at $s_z = 0$ and the final frame in the landing phase at $s_z = 0$ were determined. The t_d of the reflective marker between these frames was calculated, and the MH was then estimated according to Bosco's formula [10]. The analysis of one trial took the researcher approximately two minutes. The mean error resulting from the MH estimation method in the My Jump 2 app was 0.3 cm for the MH range between 0 cm and 65 cm. All recordings and calculations using the My Jump 2 app were performed by the same researcher.

Mo-cap system. The 8-camera system with a recording frequency of 200 Hz (Smart-D, BTS Bioengineering, Milan, Italy) and synchronized with a force platform was used. The reflective marker placed on the jumper's sacrum was tracked using the BTS Smart Tracker software. For each CMJ, the MH from the registered graphs of the vertical displacement of this marker was determined.

2.3. Statistical Analysis

A one-way repeated measures analysis of variance (ANOVA) and a Bonferroni correction for multiple pairwise comparisons were used. Sphericity was assessed using Mauchly's test. The Greenhouse–Geisser adjustment was made when the sphericity was violated. The effect size was determined using the partial eta-squared (η^2). According to Cohen's guidelines, values of η^2 were small at 0.01, medium at 0.06 and large at 0.14 [28]. Moreover, the statistical power was calculated. To analyze the absolute agreement between the two measurement tools, the intraclass correlation coefficient (ICC) with a 95% confidence interval (CI) related to the 2-way random single measures (2,1) was first used. Second, Bland–Altman plots showing systematic bias and the limit of agreement (LOA) for the two compared instruments were created [29]. Thirdly, the Pearson's product moment correlation coefficient (r) was calculated. The r was evaluated according to the following thresholds: <0.1 (trivial), 0.1–0.3 (small), 0.3–0.5 (moderate), 0.5–0.7 (large), 0.7–0.9 (very large) and 0.9–1.0 (almost perfect) [30]. Furthermore, a linear regression analysis was performed to assess the degree of relation between the two measurement tools. The absolute reliability of the measurement tools estimating the height jump for the 3 CMJ trials in each participant was examined using the ICC (2,1) [31], standard error of measurement (SEM) and the coefficient of variation (CV). The ICCs were interpreted based on the following scale: <0.5 (poor), 0.5–0.75 (moderate), 0.75–0.9 (good) and >0.9 (excellent) [32]. The SEM and CV were calculated using the following equations:

$$SEM = SD\sqrt{1 - ICC}, \quad (5)$$

where SD—standard deviation for the average of the SDs from 3 trials,

$$CV = \frac{SEM}{Mean}, \quad (6)$$

where mean—the arithmetic average of the 3 trials. The significance level alpha was set at $p < 0.05$. The statistical analysis was performed in SPSS Statistics software for Windows, version 28.0 (Armonk, NY, USA: IBM Corp.).

3. Results

The means and standard deviations of the MH of the CMJ are presented in Figure 2. The results of Mauchly's test were $W = 0.344$ and $p = 0.01$. Therefore, the violation of sphericity was corrected by adjusting the degrees of freedom using the Greenhouse–Geisser adjustment ($\epsilon = 0.639$). The value of $\eta^2 = 0.898$ at $F_{2,38} = 175.8$ and $p < 0.001$ (significant within-subject effect) indicated a large effect size for the MH results when comparing the four measurement tools. The statistical power for the MH values in CMJ was 1.0 (with a sample size of 21 subjects). Pairwise comparisons between the measurement tools revealed (1) a significant 27.7% ($p < 0.001$) lower mean MH value for the My Jump 2-FT than the force platform, and (2) non-significant differences (below 1.0%) between the My Jump 2-DT and force platform ($p = 1.0$), and between the mo-cap system and force platform ($p = 1.0$).

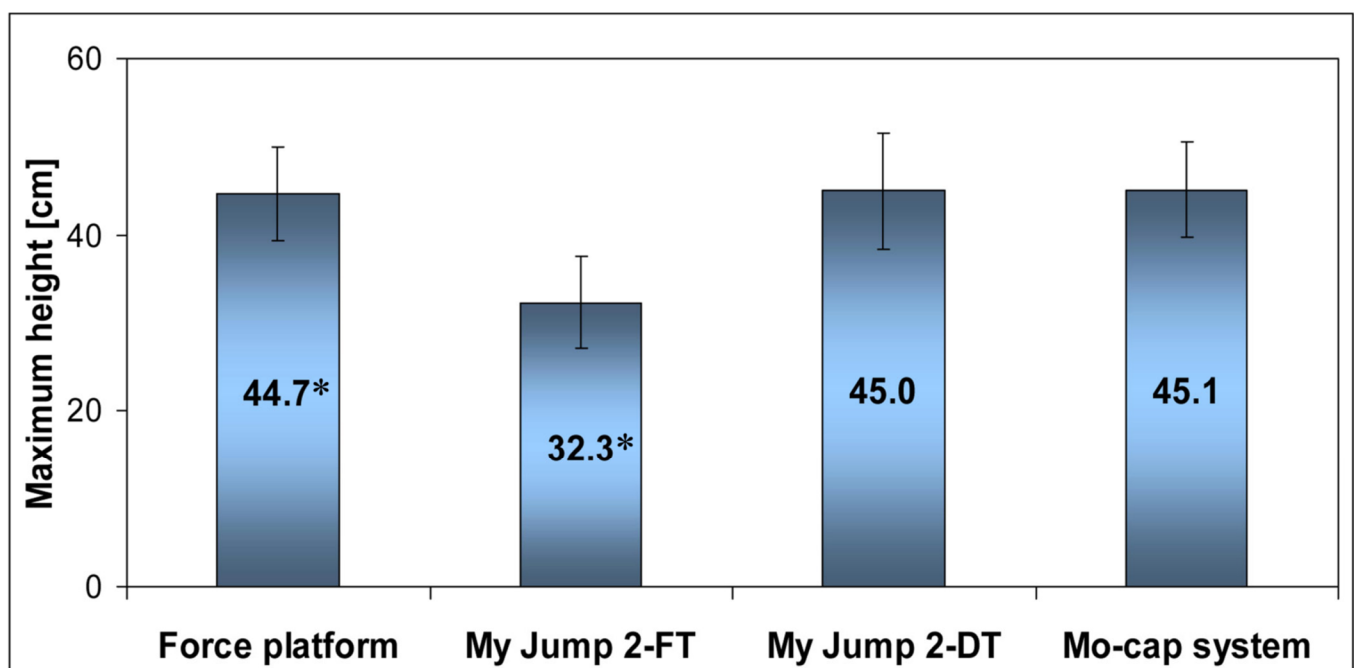


Figure 2. Means of the maximum height in a counter-movement jump, obtained using four testing methods. My Jump 2-FT—My Jump 2 app for the flight time of the jumper, My Jump 2-DT—My Jump 2 app for the displacement time of the marker placed on the jumper's sacrum (new method), mo-cap—motion capture, *—significant difference between the force platform and My Jump 2-FT.

The results of the ICC and 95% CI are presented in Table 1. The ICCs showed a poor agreement between the My Jump 2-FT and force platform ($p < 0.001$), a good agreement between the My Jump 2-DT and force platform ($p < 0.001$), and excellent agreement between the mo-cap system and force platform ($p < 0.001$).

Table 1. The concurrent validity of the My Jump 2 app and mo-cap system compared to the force platform for estimating the maximum height in a counter-movement jump.

Variable	My Jump 2-FT vs. Force Platform	My Jump 2-DT vs. Force Platform	Mo-Cap System vs. Force Platform
ICC (–)	0.362	0.858	0.955
95% CI (–)	–0.050–0.762	0.648–0.943	0.891–0.982

Notes: My Jump 2-FT—My Jump 2 app for the flight time of the jumper, My Jump 2-DT—My Jump 2 app for the displacement time of the marker placed on the jumper's sacrum (new method), mo-cap—motion capture, ICC—intraclass coefficient correlation, CI—confidence interval.

Considering the Bland–Altman plots (Figure 3), the following bias was observed: 12.4 cm for the My Jump 2-FT vs. force platform (Figure 3a), –0.2 cm for the My Jump

2-DT vs. force platform (Figure 3b), and -0.4 cm for the mo-cap system vs. force platform (Figure 3c). Furthermore, the ranges between the upper LOA and lower LOA were 14.0 cm for the My Jump 2-FT vs. force platform, 19.3 cm for the My Jump 2-DT vs. force platform, and 10.8 cm for the mo-cap system vs. force platform.

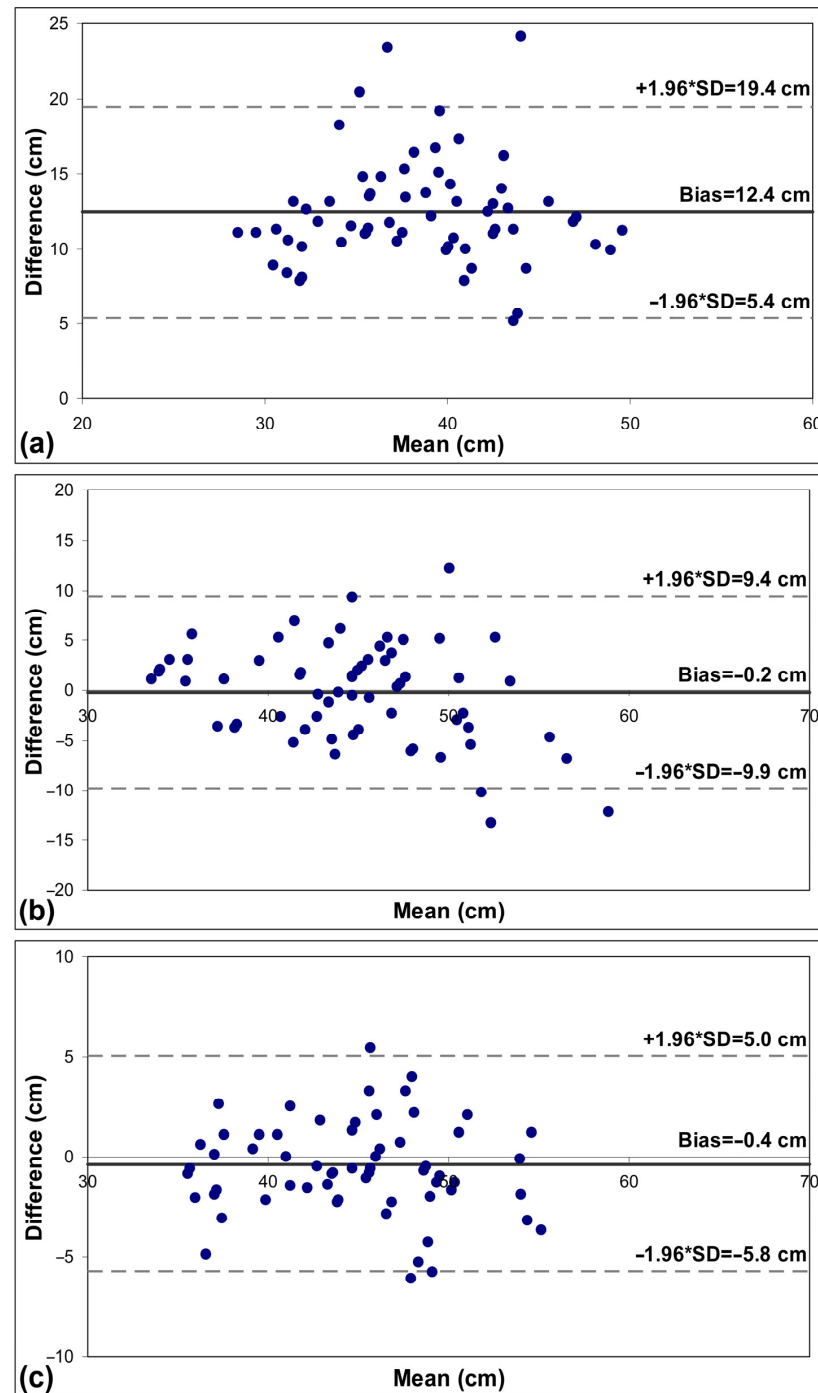


Figure 3. Bland–Altman plots for the following: (a) the My Jump 2-FT and force platform; (b) the My Jump 2-DT and force platform; (c) the mo-cap system and force platform. My Jump 2-FT—My Jump 2 app for the flight time of the jumper, My Jump 2-DT—My Jump 2 app for the displacement time of the marker placed on the jumper’s sacrum (new method), mo-cap—motion capture, SD—standard deviation for the average difference between the two instruments, $+1.96*SD$ —upper limit of agreement, $-1.96*SD$ —lower limit of agreement, bias—average difference between the two instruments.

In addition, there was a very large correlation ($0.7 < r < 0.9$) between the My Jump 2-FT and force platform ($p < 0.001$) (Figure 4a), between the My Jump 2-DT and force platform ($p < 0.001$) (Figure 4b), and between the mo-cap system and force platform ($p < 0.001$) (Figure 4c).

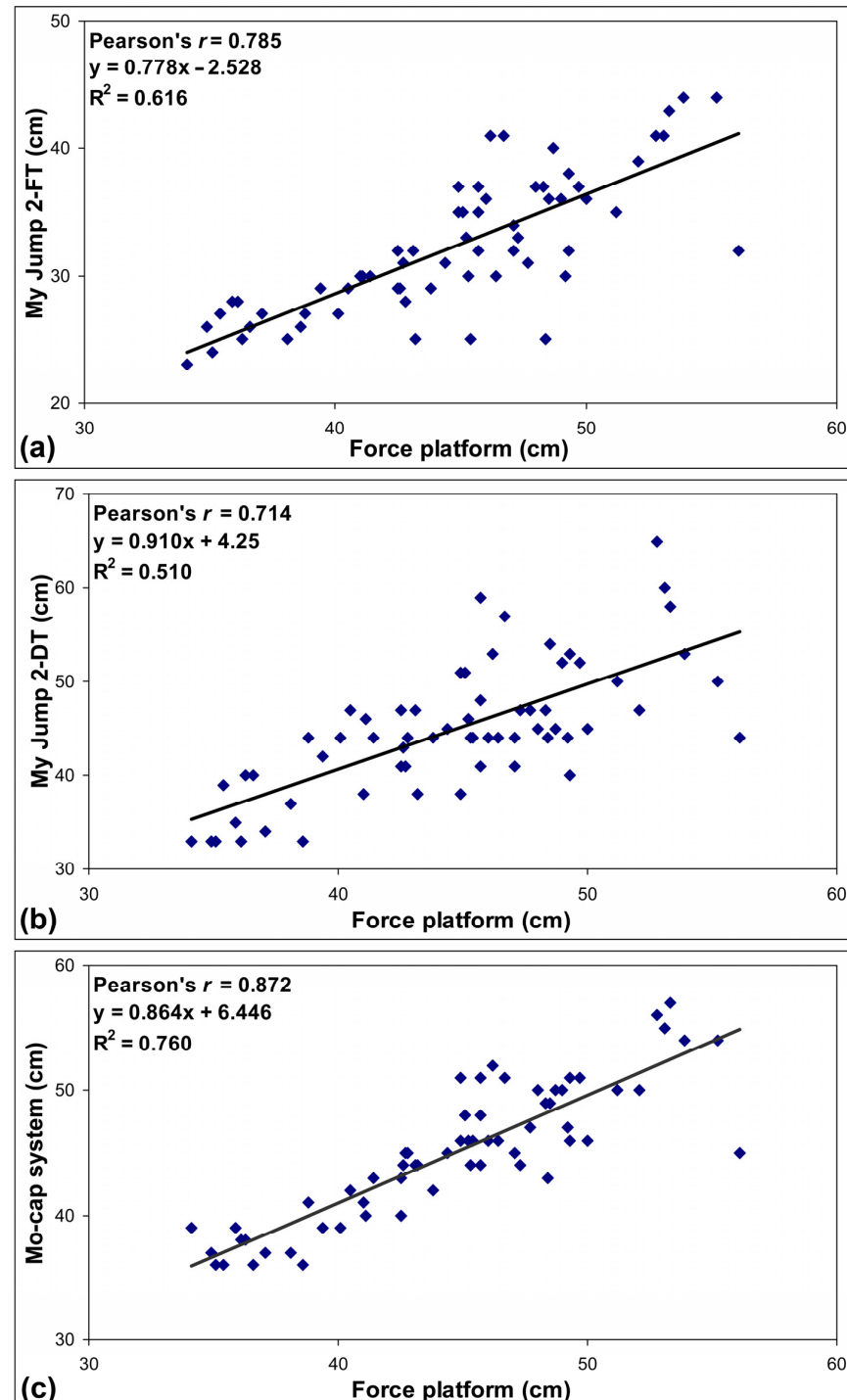


Figure 4. Correlation between the following: (a) the My Jump 2-FT and force platform; (b) the My Jump 2-DT and force platform; (c) the mo-cap system and force platform. My Jump 2-FT—My Jump 2 app for the flight time of the jumper, My Jump 2-DT—My Jump 2 app for the displacement time of the marker placed on the jumper's sacrum (new method), mo-cap—motion capture, r —Pearson's product moment correlation coefficient, x and y —variables for the linear regression, R^2 —the coefficient of determination.

The ICC values for internal consistency (>0.9) at SEM = 0.2–0.6 and CV = 0.006–0.013 indicated the excellent reliability of all measurement tools estimating the MH for the three CMJs performed by each participant ($p < 0.001$) (Table 2).

Table 2. The reliability of the measurement tools for the maximum height in a counter-movement jump.

Variable	Force Platform	My Jump 2-FT	My Jump 2-DT	Mo-Cap System
ICC (–)	0.958	0.935	0.931	0.987
95% CI (–)	0.912–0.981	0.865–0.971	0.858–0.970	0.973–0.994
SEM (–)	0.377	0.411	0.533	0.255
CV (–)	0.008	0.013	0.012	0.006

Notes: My Jump 2-FT—My Jump 2 app for the flight time of the jumper, My Jump 2-DT—My Jump 2 app for the displacement time of the marker placed on the jumper’s sacrum (new method), mo-cap—motion capture, ICC—intraclass correlation coefficient, SEM—standard error of measurement, CV—coefficient of variation.

4. Discussion

The present study evaluated the validity and reliability of the My Jump 2 app for MH estimation during the CMJ in recreationally active students. The MH data obtained from the $s_z(t)$ graphs after measuring the VGRF using the AMTI force platform (gold standard) were used for comparisons. Using the iPhone 13 smartphone with the My Jump 2 app, the MH was calculated based on the flight time (VGRF = 0) and the displacement time of the reflective marker placed on the jumper’s sacrum according to the new concept. Moreover, the MH values were estimated based on the displacement of this marker using the BTS mo-cap system.

The data analysis revealed poor agreement (ICC = 0.362) and a large systematic bias in the MH difference (12.4%) between the My Jump 2-FT and force platform, as well as a significantly lower MH (by 27.7%) for the My Jump 2-FT compared to the force platform. This significant difference results from the use of different methods of MH estimation, i.e., based on the flight time for the My Jump 2-FT and based on the $s_z(t)$ graph for the force platform. Importantly, the CoM of the jumper performing the CMJ is at a certain height (relative to the vertical zero position) at the end of the take-off phase (plantar flexion) and at the beginning of the landing phase (dorsiflexion). Therefore, the flight time is shorter than the time of the CoM displacement between its vertical zero positions during take-off and landing. The analysis of the $s_z(t)$ and VGRF(t) graphs showed that the CoM was at a height of 13.2 ± 1.9 cm at the ending point of the take-off phase (point E, Figure 1) and at a height of 11.3 ± 5.8 cm at the starting point of the landing phase (point F, Figure 1).

In this study, using the My Jump 2 app, the displacement time of the marker placed on the jumper’s sacrum between its vertical zero positions during the take-off and landing phases was determined. The comparisons showed good absolute agreement (ICC = 0.858) and a small systematic bias in the MH difference (–0.2 cm) between the My Jump 2-DT and force platform, as well as a non-significantly higher MH value (only by 0.7%) for this method than for the force platform. Thus, the use of the My Jump 2-DT in the CMJ test provided similar MH results to those obtained based on the displacement of the jumper’s CoM from the registered VGRF, commonly considered the most accurate method [33–35].

Previous studies have also assessed the validity of using My Jump for determining the MH during vertical jumps [2,3,6,9,12–16,24,27]. Considering the comparison of this app with the force platform, Balsalobre-Fernandez et al. [2], Carlos-Vivas et al. [6], Driller et al. [14] and Stanton et al. [15] reported very close MH results and an almost perfect agreement (ICC greater than 0.970) between both methods, recommending the My Jump app as a valid tool for evaluating the CMJ height. However, these researchers estimated the MH based on the flight time according to Bosco’s formula [10] for both this application and the gold standard. Thus, they took the incorrect approach because the force platform is not used to assess the jump height from flight time. Using the force platform and software analysis system (e.g., BioWare), the MH is estimated according to the displacement of the jumper’s CoM ($s_z(t)$ graph). Compared to this best method, the present study showed the high accuracy of the new MH estimation method for the CMJ, i.e., My Jump 2-DT.

Additionally, this study assessed the MH values obtained as a result of registering the displacement of the marker placed on the jumper's sacrum using the BTS mo-cap system. The ICC value of 0.955 showed a very good absolute agreement between the mo-cap system and the force platform (at a small systematic bias of -0.4 cm), thus demonstrating the high accuracy of this method in the CMJ testing. Moreover, a non-significantly higher MH value (only by 0.9%) for the BTS mo-cap system compared to the force platform was observed. In contrast, Slomka et al. [9] reported significantly lower MH values for the CMJ estimated using the BTS mo-cap system than those estimated using the Kistler force platform. However, these authors analyzed the trajectory of the two markers placed on a shoe at the toe and heel. The results of the present study indicated that the correct estimation of the MH during the CMJ using the BTS mo-cap system should be based on an analysis of the displacement of the marker placed on the jumper's sacrum.

The results of the MH for the three CMJ trials performed by each participant showed excellent reliability, i.e., an ICC value greater than 0.9 at a low SEM (below 0.6) and CV (below 0.02) for all measurement tools. These values mean that the MH estimation performed using the force platform, My Jump 2 app and mo-cap system in this study had a high internal consistency. Other researchers who examined the MH for the five CMJ trials in each participant also reported the very good reliability of the force platform and My Jump app [2], and the contact platform and My Jump app [3]. Furthermore, excellent reliability was demonstrated by Glatthorn et al. [5] for the Kistler force platform and Optojump system, as well as by Slomka et al. [9] for the Kistler force platform, Optojump system and BTS mo-cap system.

This study has limitations. The test–retest reliability was not evaluated due to the lack of data for the second measurement session. Some participants' health problems prevented them from repeating the CMJ tests in the scheduled second session.

5. Conclusions

The MH of the CMJ is commonly estimated based on the displacement of the jumper's CoM, which is obtained after the numerical integration of the a_z data as a result of the GRF measurements on the force platform (jumper's CoM trajectory method). Therefore, evaluating the validity of the My Jump app via a comparison with the force platform, which is considered the gold standard, should include this very accurate method and not the flight time method. In contrast to My Jump 2-FT, the MH estimation using the My Jump 2-DT provided similar results to the method involving the displacement of the jumper's CoM from a registered VGRF; thus, a correct assessment of the CMJ height was obtained. In summary, a smartphone with the My Jump 2 app and this new method of MH estimation based on the displacement time of the marker placed on the jumper's sacrum can be used by researchers, coaches, teachers and physiotherapists as a commonly available and accurate measurement tool. Further research is needed to assess the validation and reliability of a smartphone app that will enable the automatic calculation of the vertical jump height according to the new method and thereby facilitate the analysis.

Author Contributions: Conceptualization, M.M. and J.K.; methodology, M.M., W.K. and J.K.; software, M.M., W.K. and J.K.; validation, M.M. and J.K.; formal analysis, M.M. and J.K.; investigation, M.M. and W.K.; resources, M.M., W.K. and J.K.; data curation, M.M. and J.K.; writing—original draft preparation, M.M., W.K. and J.K.; writing—review and editing, M.M. and J.K.; visualization, J.K.; supervision, M.M. and J.K.; funding acquisition, M.M. and J.K. All authors have read and agreed to the published version of the manuscript.

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

Data Availability Statement: The data are available upon request from the corresponding author.

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

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