Concurrent validity and reliability of mobile applications in measuring vertical jump performance

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Abstract

The purpose of this study was to test the concurrent validity and intraclass reliability of two mobile apps designed to measure countermovement jump (CMJ) height. The concurrent validity and reliability of two mobile applications (*MyJump2* and *What'smyvertical)* designed to measure vertical jump heights were analyzed using a force platform and 3D motion analysis as criterion methods. Twenty-two healthy, adult participants (female: n=15; male: n=7; ages: 18-26; height 1.74 m, mass: 69.7 kg) performed ten CMJs with instructions to jump as high as possible on a force platform with their hands on their hips, maintaining extended legs during flight. Both the *MyJump2* and *What'smyvertical* apps exhibited strong agreement with COM displacement measured by 3D motion capture system with ICCs of 0.960 (95% CI: 0.143-0.991, $p < 0.001$) and 0.887 (95% CI: .177-0.970, $p < 0.001$), respectively. The results showed that jump height can accurately and reliably be estimated using these mobile applications, providing a valid and feasible tool in evaluating jump performance.

Key words: biomechanics, vertical jump, countermovement jump, mobile apps

LITERATURE REVIEW

In 1921, Dr. D. A. Sargent deemed the conduction of a vertical jump a reliable physical performance test (Özdirenç, 2005; Sargent, 1921). Currently, vertical jump tests are among the most common means of evaluating physical fitness in a variety of populations. Defined as force over a given time, vertical jump tests are principally used to measure leg power in sports. However, vertical jump tests have also been used to assess non-athletic populations. Due to its evaluation of explosive strength, the use of vertical jump testing has been utilized to identify lower leg strength, physical talent, and to monitor fatigue (Özdirenç, 2005; Haynes, 2018; Sayers 1999; Gathercole, 2015; Sanchez-Medina, 2011; Balsalobre-Fernandez, 2014).

Vertical jump tests are a popular evaluative tool of physical ability in sports performance (Haff, 2016; Klavora, 2000; Aragón, 2000; Chelly, 2010; Hermassi, 2014; Janot, 2015). Vertical jump tests are often utilized in physical education, fitness, and sports program fields to measure productivity of lower limb power (Aragón, 2000). Vertical jumps have additionally been used as a testing measure for activities such as weightlifting (Garhammer, 1992; Garhammer, 1993) football, basketball, (Brown, 1986; Decker, 1996), volleyball, (Powers, 1996), and swimming (Ballow, 1979). Categorically, lower extremity ballistic movements which generate maximal body mass acceleration over one repetition of bilateral leg extension are a strong indicator of physical performance (Jimenez-Reyes, 2017). Thus, jump ability can gauge athletic competitive success (Andersson, 2010; Fry, 2006; Gallardo-Fuentes, 2015) and assist professionals in identifying athletes' strengths and weaknesses, document progress, and assign positions and ranking to individuals on sports teams (Graham, 1994; Klavora, 2000). As a result of peak power production, vertical jump test have been applied to exercise programs such as strength training (Hedrick, 1996), plyometrics (Miller, 1982), and periodization training (Decker, 1996; Klavora, 2000).

Peak power produced via vertical jump reflects kinematics of the lower extremity. Optimal muscle power at the hip, thigh, and calf are greatly determined by muscle conditioning. However, force production can be influenced by a variety of factors such as age, Achilles tendon functionality, and biomechanics of the foot and ankle joints (Stanton, 2016; Hardcastle, 2014). Consequently, improvement in performance of vertical jumps are indicative of increased plantar flexor strength at the ankle (Stanton, 2016;Caserotti, 2008; Hardcastle, 2014) and may be correlated to tibial bone strength and hip bone mineral density (Stanton, 2016;Caserotti, 2008; Hardcastle, 2014). The Tibial Strength Strain Index (TSSI) has supported this hypothesis in their identification of bone strength positively impacting peak jump force and power (Hardcastle, 2014).

There are multiple variations of vertical jumps that may produce peak power. Countermovement jumps (CMJs) are a common form of vertical jumps and are proven to be a valid and practical calculation of lower limb power and are the most reliable form of jump testing (Markovic, 2004). A CMJ is characterized by the jumper starting from an upright standing position, making a preliminary downward movement by flexing at the knees and hips, then immediately extending the knees and hips again to propel the body vertically up off the ground. There are three main components of the CMJ: countermovement depth, flight, and jump displacement. Countermovement depth is defined as the maximum dimensions the jumper will drop during the quick countermovement action prior to take-off. This is the pre-stretch action needed to propel the jumper into an explosive jump. Research suggests that larger countermovement depths are correlated to a greater jump height and peak power produced (Gheller, 2014; Laffaye, 2014). The CMJ requires the jumper to maintain full extension at the hip, knee, and ankle joints to prevent any compromise to the flight time (Markovic, 2004; Glatthorn, 2011). Biomechanics has indicated that the CMJ is a more effective jump as the leg muscles maintain a higher activation level before shortening (Linthorne, 2001). In the sports performance world, CMJs are confidently correlated with maximal speed, acceleration, and explosive strength (Haynes, 2018; Stanton). The production of maximum jump height and the increase in power results from the elastic component of the muscle tendon complex. The CMJ has a favorable effect on the stretch shortening cycle resulting in an increased work output (Williams, 2017). In relation to evaluating peak power, CMJs can be used as an accessible indicator of fatigue in athletes (Haynes, 2018). Fatigue can be indicated by a decrease in jump performance; therefore, suggesting a decreased efficiency of the muscle tendon complex, ultimately hindering work output.

In terms of biomechanics, the jumper must overcome the force acting on their center of mass and their body weight to defy gravity and propel oneself into the air. The CMJ test is primarily measured by jump height (cm). Jump height is a calculation of the jumper's change in height based of their center of mass over time (Aragón, 2000). This can be measured by subtracting the jumper's initial standing center of mass (BCOM) from the peak BCOM measured during flight (Aragón, 2000). The jumper's peak power produced by CMJ is the product of force and velocity (Ward, 2009; Rittweger, 2004). Additional factors that allow the professional to obtain a more comprehensive physical profile for the jumper may include peak force (N), relative peak force ($N \cdot kg^{-1}$), peak power (W), peak velocity ($M \cdot s^{-1}$), rate of force development ($N \cdot s^{-1}$), and impulse ($N \cdot s$) (Balsalobre-Fernandez, 2014; Laffaye, 2014).

Newton's Third Law of Physics states that for every action, there is an equal and opposite reaction. Therefore, if a jumper is exerting force on the ground, then the ground is exerting an equal force on the jumper. Ground reaction forces are these equal and opposite forces exerted onto the jumper. The ability for a jumper to propel their body in the air is defined by the formula $\Sigma F = m * a$, where m is the mass of the jumper, and a is acceleration of his or her center-of-mass (COM). The net force is equal to the sum of the jumper's weight, which is the product of mass and the acceleration of gravity (g = 9.81 m/s/s), and the ground reaction force (GRF). Thus, if the GRF is greater than the jumper's weight, the jumper would accelerate upward and take off if the acceleration is greater than that of gravity. Thus, the GRF is equal to the jumper's weight when he or she is standing on the ground.

There are 5 dynamic phases of a vertical jump (figure 1 and 2). In phase 1 of a vertical jump, the jumper accelerates into a downward movement (Rauh, 2019). This phase requires the jumper to lower their center of gravity by bending their knees. Here, the GRF is lower than the jumper's weight, allowing the athlete to accelerate downward. This can be described by equation $F_{Jumper} = F_{GRF} - F_{Jumper}$ (Linthorne, 2001). Phase 2 of the jump requires the deceleration of the downward movement, characterized by reaching the deepest countermovement depth. This requires an equal force in the opposite direction of phase 1. Phase 3, is initiated by explosive propulsion upwards from the countermovement depth. Here, the jumper does not experience GFR once both feet leave the ground (Rauh, 2019). This phase is defined by peak ground reaction force in order to achieve propulsion. Phase 4 identifies the jumper during flight in air. The sole force acting on the jumper during this phase is gravity working to pull the body back to the ground. It is important to note that the height of the jump was predetermined by the velocity of take off in phase 3 (Rauh, 2019). At the peak of the jump flight, vertical velocity is zero (Linthorne, 2001). Variables from phase 4 enable peak jump time to be calculated; consequently, peak jump height can be derived from this equation. The final landing phase generates an equal but opposite force from phase 1 as the jumper returns to the ground (Rauh, 2019). The jumper must produce an adequate amount of force to alleviate the vertical speed of the landing to reach a standstill of 0 m/s^2 (Linthorne, 2001).

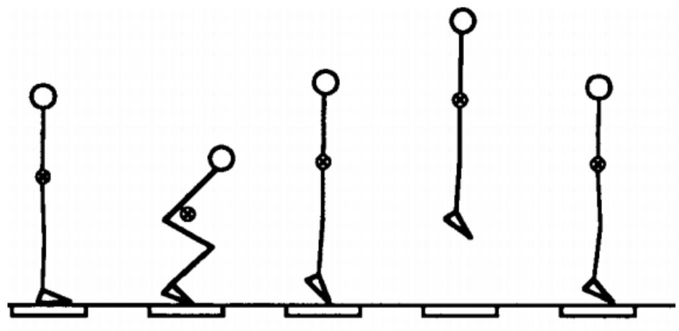

Figure 1: Illustration of the five phases of a CMJ (Linthorne, 2001).

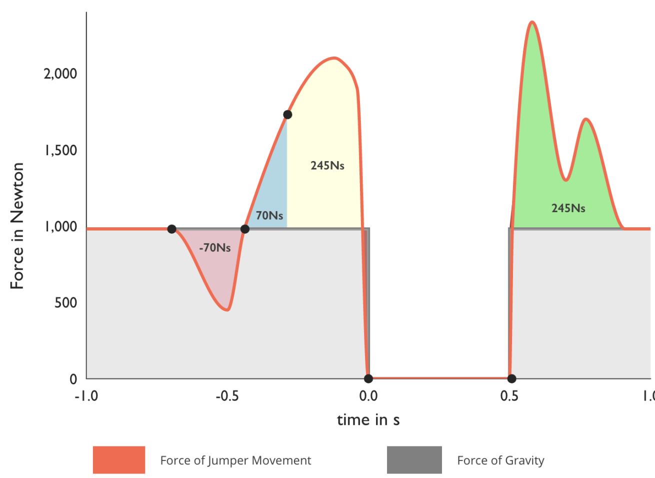

Figure 2: Graph of the five phases of a vertical jump, comparing time and force (N) (Rauh, 2019).

Vertical jump height can be additionally measured by the amount of time the jumper was airborne. Jump hang time can be recorded from high frame rate cameras. Jumpers achieve peak jump height at the halfway point of their flight. Jump height as a result of hangtime can be derived from velocity as a linear function, $v=at$, where v is velocity, a is acceleration, and t is time. This formula is embedded in the vertical jump measurement algorithms in the mobile applications in order to calculate the height of jump (figure 3).

$$h_{jump} = \frac{1}{8} a \, t^2_{hangtime}$$

Figure 3: Equation for calculating vertical jump height from hang time. *h is the jump height in meters, a* is the acceleration of gravit,y and $t^2_{hangtime}$ is the total duration of the time the jumper is in the air (Rauh, 2019).

Depending on the environment and equipment used to measure the vertical jump, it can be deemed either a field or laboratory test. Although more expensive and less feasible, laboratory jump tests produce a higher level of precision and accuracy. In comparison, field vertical jump test are more practical in terms of time, physical effort, and level of equipment needed (Klavora, 2000). There are multiple methods to measure vertical jump performance including force platforms, high-speed cameras, and infrared motion analysis system. It is important to be aware of the difference in values measured according to each method being used since some calculations require assumptions and equipment may be difficult to operate (Aragon, 2000).

The gold standard for measuring vertical jump height is the utilization of high speed motion analysis cameras that measure the vertical distance between standing and the highest point of the jump (Baumgart, 2017). 3D real-time motion capture utilizes the subject's body as an anatomical model to calculate the subject's COM displacement against time. This system provides kinematic and kinetic evaluation of the subjects lower extremity and performance mechanics. Motion Analysis JumpTrak software measures joint actions over time to record the body's kinematics during jump performance (Figure 4)(Motion Analysis Corp, Santa Rosa, Calif). Additionally, this system is feasible in the sports performance setting as it only requires basic knowledge of subject set-up and processing. If a biomechanics lab is not accessible, the gold standard for measuring mechanical outputs of a vertical jump are force plates (Jimenez-Reyes et al., 2017).

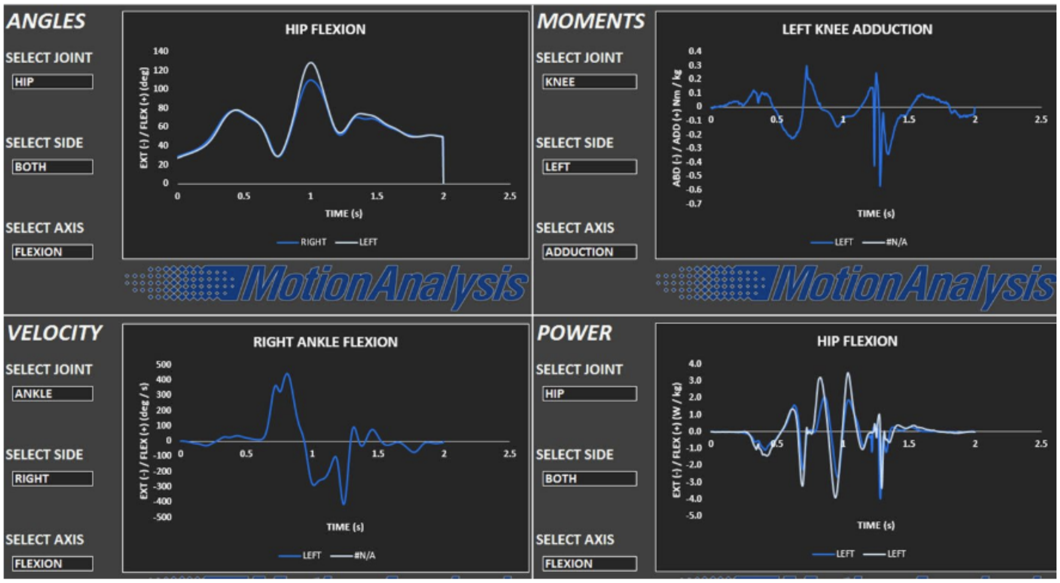

Figure 4: Cortex software JumpTrak motion analysis of body kinematics per anatomical segment measured by joint movement over time (Motion Analysis Corp, Santa Rosa, Calif).

Force platforms are the most common laboratory equipment used in vertical jump studies. Force platform systems can be an expensive investment as commercial systems cost about $10,000 to $30,000. Force platforms are metal plates typically 0.4 m by 0.6 m that produces an electrical output proportional to the force measured by either piezoelectric or strain gauge transducers attached at each corner of the plate. This measures the amount of force exerted on the plate by the subject, and the amount of force exerted on the subject by the plate. Force platform technology can either calculate vertical jump height via the time in air or takeoff velocity methods. Based on previous literature, the method that is considered most accurate when measuring vertical jump height is take off velocity (Moir, 2008). The equation used to calculate jump height when measuring with force platforms is as follows: Jump Height = (take-off velocity)^2 / (2 * acceleration due to gravity) (Moir, 2008). Force platforms essentially use GRF to measure time of take off versus time of landing to calculate vertical jump height. This is a simple algorithmic parabola of the time two feet leave the force plate and the time they land back down. Ultimately, validating the measurement of time with time. In contrast to isometric testing methods, measurement of ground reaction forces from jumping on a force plate enables maximal muscle forces to be assessed. This can be beneficial in the ability to infer peak muscle strains contribution to skeletal adaptation (Anliker, 2011). Studies suggest that jump height is most accurately measured using the impulse-momentum method by using a force platform to calculate it (Balsalobre-Fernandez, 2014; Laffaye, 2014). The impulse-momentum method allows for the calculation of the jumper's change in momentum through integration of the force-time curve. In a vertical jump, this can be applied to the ground contact phase when the GRF acting on the COM results in a take-off velocity that determines jump height. However, recent literature explains that through the use of high speed cameras and other methodologies, the time in the air method is highly reliable and valid as well (Glatthorn, 2011; Balsalobre-Fernández et al., 2014).

In 2013, Apple Inc. developed a high speed camera recording at 120 Hz on the iPhone 5s mobile device. With this update, applications (apps.) compatible with the iPhone have the ability to measure vertical jump height using the flight time method. For this particular study, two iPhone vertical jump applications were analyzed for reliability and validity. The first of the two applications being analyzed, *MyJump2 ,* has been scientifically proven to have almost near perfect validity and reliability (Balsalobre-Fernández et al., 2015). The purpose of the *MyJump2* (Balsalobre-Fernandez, 2014) is to calculate quickly, with reliability and validity, the flight time of the CMJ by identifying the takeoff and the landing frames of the video (figure 5). Flight time is then transformed it into a measurement of jump height using this equation $h = t^2 \times 1.22625$ (Bosco et al. 1983) with "h" being the jump height in meters and "t" being the flight time of the jump in seconds. The reliability and validity research that has been published on *MyJump2* was performed using time in the air method on force platforms. However, the evidence in the current literature regarding the validity of *MyJump2* is limited by exclusively using force plate data as a criterion method. This is restrictive in that it compares the factor of time against time.

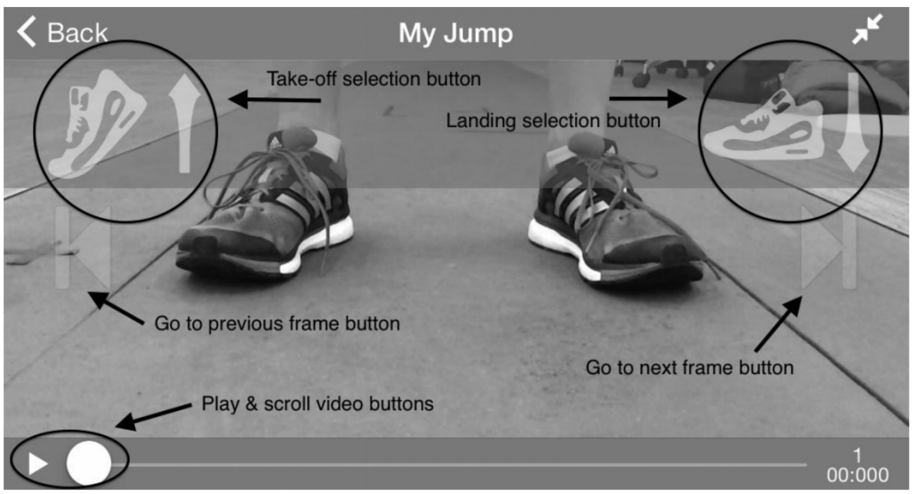

Figure 5: User interface of the *MyJump2* app (Balsalobre-Fernandez, 2015).

The second application analyzed in this study was called *Whatsmyvertical.* This application utilizes the "Slo-Mo" feature of the camera app to calculate vertical jump height by measuring the jumper's hang time. This application requires the user to determine when the subject jumping has officially taken off and landed (figure 6). *Whatsmyvertical* promotes the ability to keep track an athlete's progress during vertical jump training.

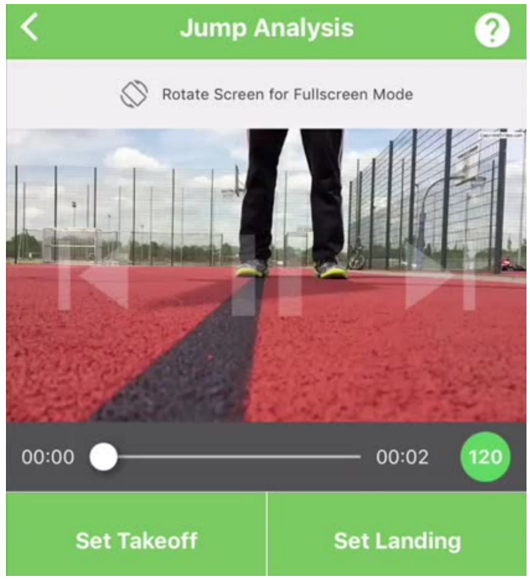

Figure 6: User interface of the *Whatsmyvertical* app.

This study aimed to utilize a more accurate form of measurement to validate these apps. The purpose of this study was to test the concurrent validity and intraclass reliability of two mobile apps, *MyJump2* and *Whatsmyvertical,* designed to measure countermovement jump (CMJ) height against the gold standard of COM displacement by the motion analysis system and take off velocity recorded by force plates.

METHODS

Participants

Twenty-two healthy, adults (female: n=15; male: n=7; ages: 18-26; height 1.74 m, mass: 69.7 kg) participated in this study. The study received Institutional Review Board approval and written informed consent was obtained from all participants.

ID#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Weight kg	63.6	72.6	62	70.3	63.1	59.09	92.9	63.5	70	75	89	92.98	58.97	61.23	55.22	54.5	74.84	85.45	79	61.23	68	61.69
Leg Length	94	90.7	94	98	77.5	81	93	81	89	98	97	100	80	80	83	83	96	94	90	87	94	89
Height cm	177.8	185.4	170	187.96	168.5	165.1	181.5	157.5	182.8	185.42	182.88	195.58	162.56	152.4	157.48	162.56	179.07	186	176	162.56	180.34	172.72

Figure 7: List of subject profile including weight (kg), leg length (cm), and height (cm).

Study Design

Subjects completed a standardized warm up, comprising of a five minute brisk walk at a user selected pace on a treadmill prior to data collection. The participant then performed ten maximal countermovement jumps (CMJ's) being instructed to jump as high as possible on the force platform with their hands on their hips, maintaining extending legs during flight and landing with both feet simultaneously at the same location as take-off. It was essential for the jumper to return to the same location from which they took off to prevent any discrepancies in results. Each jump was succeeded by a one minute rest period. A total of 220 jumps were collected.

Equipment

For each CMJ trial, jump height was determined from the force platforms, 3D motion analysis camera system connected to motion analysis software Cortex, *MyJump2*, and *Whatsmyvertical.* Significant variables were recorded including: jump height (cm), center of mass height (cm), contact time (m/s), and mean power (W). To estimate the vertical displacement of the whole body center-of-mass (COM), the 3D global locations of 29 (9 mm DIA) reflective markers based on the Helen Hayes marker set were captured using 8 motion capture cameras (Motion Analysis Corp., Santa Rosa, CA) at a sampling rate of 240 Hz. These passive, reflective markers were placed on bony anatomical landmarks that approximate joint locations and bone segments (figure 8 and 9). CMJ heights were determined using Cortex, a motion analysis software which is integrated and used in conjunction with the physical motion analysis system of the 8 visible-red cameras. Additionally, two force plates (AMTI, Watertown, MA) were used to measure flight time and take off velocity at a sampling rate of 1800 Hz. Simultaneously, two iPhone 7s mobile phones were used to run camera technology of the *MyJump2* and *What'smyvertical* apps to identify takeoff and landing frames of each jump. To record with the iPhones, two researchers lay prone on the ground with the camera focused on the feet of the participant in the sagittal plane. The researcher was then prompted by the apps to manually select the initial take-off frame identified as the moment when both feet elevated off the ground and the final landing frame of each jump defined by at least one foot returning in contact with the floor (Figure 5 and 6).

Figure 8: Helen Hayes 29 marker set placed on anatomical landmarks.

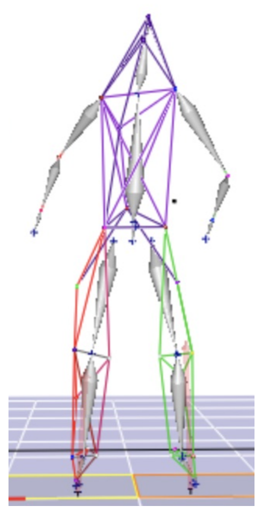

Figure 9: Cortex software measures uses 3D motion analysis cameras to record kinematic and kinetic body movement.

Statistical analyses

Estimates of the intraclass correlation coefficient (ICC) (2,1) and their 95% confidence intervals were calculated to assess the reliability of each app in measuring jump height as compared to force platform and COM data. In addition, the concurrent validity of each app was estimated using the Pearson correlation coefficient. Bland-Altman plots were created to represent the degree of agreement between each app and the force platform as well as between each app and COM data. To analyze the stability of each app in measuring the ten jump heights of each participant, Cronbach's alpha coefficient was used. All reliability analyses were performed using SPSS (IBM SPSS, Chicago, IL) at a significance level of 0.05.

RESULTS

Both the *MyJump2* and *What'smyvertical* apps exhibited strong agreement with force platform jump heights with intraclass correlation (ICCs) of 0.960 (95% CI: 0.143-0.991, $p < 0.001$) and 0.887 (95% CI: .177-0.970, $p < 0.001$), respectively. When compared to COM jump heights, the apps showed similarly strong reliabilities with 0.969 (95% CI: 0.671-0.992, $p < 0.001$) and 0.903 (95% CI: 0.418-0.972, $p < 0.001$) for *MyJump2* and *What'smyvertical*, respectively. The concurrent validity of the *MyJump2* app was high when estimated using either the force platform ($r = 0.956$, $p < 0.001$) or COM jump height ($r = 0.943$, $p < 0.001$) as the criterion method. The concurrent validity of the *What'smyvertical* app was also high when estimated using either the force platform ($r = 0.897$, $p < 0.001$) or COM jump height ($r = 0.885$, $p < 0.001$) as the criterion method. Bland-Altman plots show that *MyJump2* and *What'smyvertical* underestimated jump heights by 0.019 ± 0.044 m and 0.022 ± 0.056 m, respectively (figures 10-14).

Countermovement Jump	*MyJump2* , Mean (SD)	Force Plates, Mean (SD)	r (p<0.001)	ICC (2,1) (95% CI)	COM, Mean (SD)	r (p<0.001)	ICC (2,1) (95% CI)
Jump height (cm)	29.1 (9.0)	31.80 (8.9)	0.943	0.96	31.48 (9.1)	0.943	0.969
Countermovement Jump	***Whatsmyvertical* , Mean (SD)**	**Force Plates, Mean (SD)**	**r (p<0.001)**	**ICC (2,1) (95% CI)**	**COM, Mean (SD)**	**r (p<0.001)**	**ICC (2,1) (95% CI)**
Jump height (cm)	28.8 (9.2)	31.80 (8.9)	0.897	0.887	31.48 (9.1)	0.885	0.903

Figure 10: Jump performance measures of force plate, COM, *MyJump2,* and *Whats My Vertical apps.*

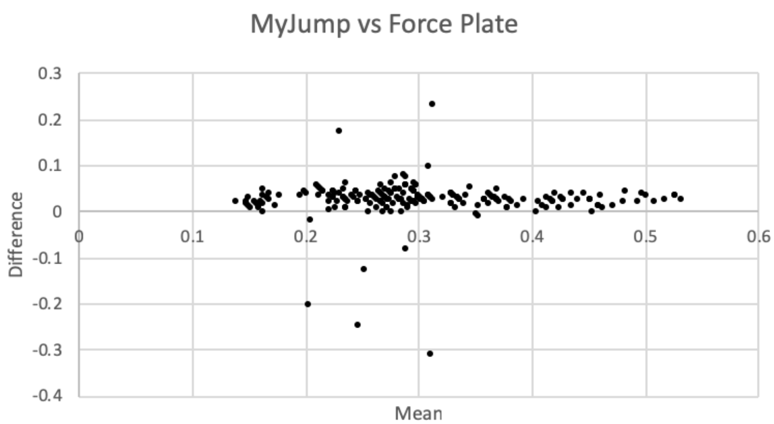

Figure 11: Bland-Altman plots for jump heights estimated with *MyJump* and force plate measurement (mean difference ± 2.28 SD)

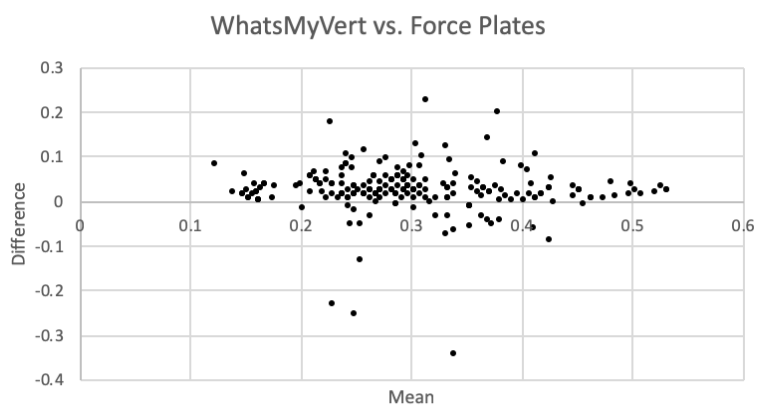

Figure 12: Bland-Altman plots for jump heights estimated with *Whatsmyvertical* and force plate measurement (mean difference ± 2.54 SD)

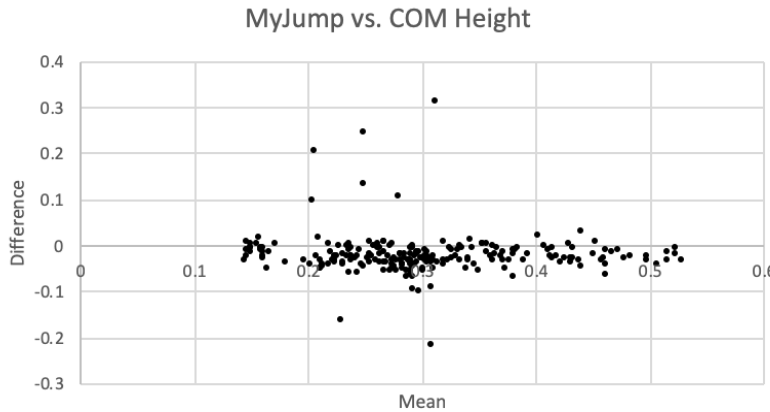

Figure 13: Bland-Altman plots for jump heights estimated with *MyJump2* and the COM method (mean difference ± 1.96 SD)

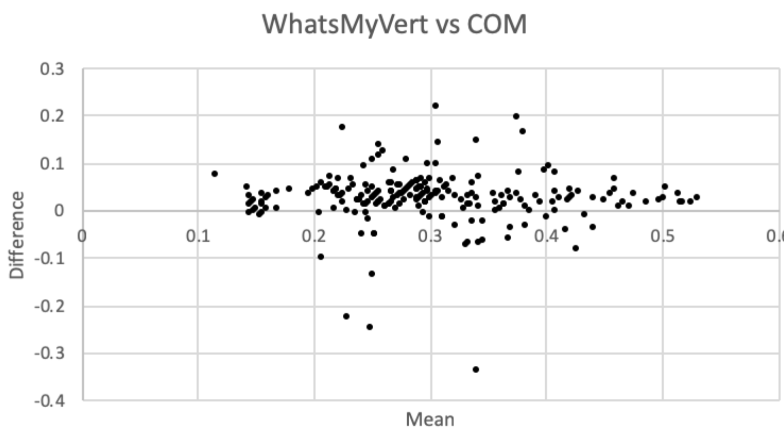

Figure 14: Bland-Altman plots for jump heights estimated with *Whatsmyvertical* and the COM method (mean difference ± 2.23 SD)

DISCUSSION

The aim of this study was to analyze the concurrent validity and reliability of the iPhone apps, *MyJump2* and *Whatsmyvertical* against gold standards of high speed motion analysis system and validated method of force platforms. Results found both apps to be highly valid and reliable in measuring the jump height of a CMJ in comparison to high speed motion analysis system and force platforms.

Near perfect reliabilities and ICCs between both applications and the COM support the validity of these mobile applications in measurement of CMJ height, due to the use of motion analysis capture as the gold standard of measurement. Compatible reliabilities and ICCs between both applications and force plates support this validation. Additionally, Bland-Altman plots illustrate a strong agreement between variables.

Previous studies have evaluated *MyJump2* in comparison to force platform measurements. Balsalobre-Fernandez (2014) demonstrated near perfect correlation (r=0.995) and intraclass correlation (ICC=0.997) when testing CMJs. However, Carlos Balsalobre-Fernández (2014) is the co-creator of the *MyJump2* app and author of the two articles validating the app, thus creating experimenter bias in these studies. Furthermore, Gallardo-Fuentes (2015) produced near perfect correlation (r=0.97-0.99) and intraclass correlation (ICC= 0.98-0.99) when measuring jump heights performed by CMJ, squat jump, and drop jumps. In further support of the validity of *MyJump2* against force plates, Driller (2017) presented a similar correlation of r=0.96 for both jump height and jump flight with an congruent ICC of 0.97. In conjunction with these systematic studies, Stanton (2016) remains consistent with an extremely valid ICC of 0.993 for CMJ of force plate. However, Stanton identified a systematic bias of *MyJump2* slightly underestimated force plate measurements. Additionally, Carlos-Vivas (2018) was profound in its study's results of perfect ICC using the time in air method (ICC=1.00, P<0.001). In contrast to Stanton (2016), Carlos-Vivas (2018) found that *MyJump2* measured jump heights slightly higher than the force plate calculations. These complementary findings indicate *MyJump2* is a reliable assessment of vertical jump performance due to its almost perfect correlation.

However, these studies failed to include high speed motion analysis system as their gold standard of measurement. The gold standard for measuring vertical jump height is the utilization of high speed motion analysis cameras that measure the vertical distance between standing and the highest point of the jump (Baumgart, 2017). 3D real-time motion capture utilizes the subject's body as an anatomical model to calculate the subject's COM displacement against time. This is a more accurate and precise method in comparison to the time in air method utilized with both force plates and iPhone apps. The time in air method is a simple algorithmic parabola of the time two feet leave the force plate and the time they land back down. Ultimately, validating the measurement of time with time; in contrast, to the multifaceted measurement of COM displacement against time in air.

Most devices to evaluate jump height mentioned previously are expensive, bulky, and time consuming for professionals to evaluate sports performance. Consequently, the use of this equipment is commonly confined to a laboratory setting. This restricts efficiency of power performance testing in field situations. However, mobile applications provide an inexpensive, portable, and valid alternative for measuring vertical jump performance. This study further highlights the usability of *MyJump2* and *What'smyvertical* as the researchers had no previous experience with the apps or videography in this setting. iPhone apps may provide professionals a practical implication of low-cost, high-speed camera, user friendly, and license-free computer software to evaluate vertical jump height.

To strengthen the validity and reliability of mobile apps designed to measure vertical jump heights, further research is needed to perform similar gold standard tests on other forms of vertical jumps, such as the drop jump and squat jump. This would increase the app's reliability to measure varying modes of jumps, thus, making it a more practical tool.

CONCLUSION

The findings of this study reinforce previously reported evidence that show the *MyJump2* mobile app is a valid and reliable tool in measuring CMJ height (Balsalobre-Fernández, C. et al. 2015). Similarly, this study has shown that the *What'smyvertical* app accurately and reliably measures vertical jump height during a CMJ. The efficient analysis of peak power production by means of vertical jump tests are a beneficial tool to fields within the science of kinesiology. The soundness of a mobile application to monitor performance ability is a economic, portable, and accurate technique that can be used as an alternative to laboratory equipment.

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