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# Validity, reliability and usefulness of smartphone and Kinovea motion analysis software for direct measurement of vertical jump height

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# Highlights

- A smartphone and free motion analysis software can measure jump height accurately
- Low-cost instruments are a valid alternative to laboratory-based equipment
- Vertical jump tests measure physiological and biomechanical parameters
- The Smartphone-Kinovea method can detect changes over the noise of the measure

# Validity, reliability and usefulness of smartphone and Kinovea motion analysis software for direct measurement of vertical jump height

**Head Title:** Validation of smartphone and Kinovea for direct measure of jump height

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## Abstract

Jumping is a simple exercise determined by several biomechanical and physiological factors. Measures of vertical jump height are common and easy to administer tests of lower limb muscle power that are carried out with several types of equipment. This study aimed to validate and address the usefulness of the combination of smartphone and computer-based applications (Smartphone-Kinovea) against a laboratory-based Motion Capture System. One hundred and twelve healthy adults performed three maximal-effort countermovement jumps each. Both instruments measured the heights of the 336 trials concurrently while tracking the excursion of the body center of gravity. The vertical velocity at take-off $v_{\mathrm{to}}$ and the impulse $J$ were computed with jump height $h$ measures. Intraclass correlation coefficient (ICC) results indicated very high agreement for $h$ and $v_{\mathrm{to}}$ (0.985) and almost perfect agreement for $J$ (0.997), and Cronbach's $\alpha=0.99$. Low mean differences were observed between instruments for $h$: -0.22 ± 1.15 cm, $v_{\mathrm{to}}$: -0.01 ± 0.04 m/s, and $J$: -0.56 ± 2.92 Ns, all $p<0.01$. The smallest worthwhile change (SWC) and the typical error of measurement (SEM) were 1.34 cm, 0.81 cm for $h$; 1.15 m/s, 0.03 m/s for $v_{\mathrm{to}}$, and 2.93 Ns, 2.25 Ns for $J$, so the usefulness of the method is established (SWC/SEM>1). Bland-Altman plots showed very low mean systematic bias ± random errors (-0.22 ± 2.25 cm; -0.01 ± 0.08 m/s; -0.56 ± 5.73 Ns), without association between their magnitudes ($r^2=0.005$, $r^2=0.005$, $r^2=0.001$). Finally, very high to practically perfect correlation between isntruments were observed ($r= 0.985$; $r= 0.986$; $r= 0.997$). Our results suggest that the Smartphone-Kinovea method is a valid and reliable, low-cost instrument to monitor changes in jump performance in a healthy, active population diverse in gender and physical condition.

**Keywords:** instrument, countermovement jump, application, performance, SWC, lower limb

## INTRODUCTION

Regular physical activity is one of the most beneficial strategies to enhance health status in healthy or pathological populations. Physically active people show improvements in brain health [1], weight maintenance [2], disease prevention [3], and bone and muscle strength [4], among others. There is plenty of evidence that lifelong physically active people of all age groups, races, and ethnicities for both sexes sustain and improve their quality of life [5] and prevent many chronic diseases causing high mortality [6]. Not only long and intense exercise sessions typical from the trained population correlate with the above improvements, but 150 to 300 minutes of moderate-intensity a week provide protective health benefits [7] when exercise is properly prescribed [8].

From a technical point of view, physical activity can be considered a behavior involving bodily movements that result in energy expenditure [9], whereas sports involve such physical activity but in a competitive and regulated form aiming at training and excelling in athletic skills. However, since physical activity is progressively conducted in an organized way, physical activity and sport have become increasingly important for the individual and public health.

Both sport and physical activity must be monitored for the prescription of adequate training loads [10], performance analysis [11], injury prevention [12], and recovery [13]. Among all human indicators of physical activity, muscular power is the most important attribute of skeletal muscle, reflecting the ability of strength and speed of movement [14]. Available research indicates that the most dynamic muscle function is the power of the lower limbs [15], which is accepted as a reliable indicator of functional capacity.

Vertical jump tests are frequently used, simple, and reliable tests of muscle power of the lower limbs [16] and lower- and upper-body segments motor coordination [17]. Health and sports professionals can use jump height measures to monitor the performance and status of the lower-body muscle structure of both athletic and non-athletic populations [18].

Vertical jump height can be measured directly as the difference between apex and baseline heights of the excursion of the body with position-based instruments [19]. Jump-and-reach tests are direct and simple instruments showing adequate ecological validity but limited accuracy [20]. Another direct method relies on multiple infrared video cameras tracking the body center of gravity during the jumping movement. This motion capture method is a piece of expensive laboratory equipment that requires the placement of a number of retro-reflective markers on each subject to allow capture of body movements during jump performance [21]. Despite being highly precise and reliable, this “gold standard” method is not frequently used by sports or health professionals because of the cost, marker placement, and accurate transport, calibration, and operation by trained personnel.

Alternatively, the displacement of the body center of gravity can also be tracked with a single video camera and the use of basic biomechanical software. The use of a single camera restricts the analysis to one plane only, so the camera should capture displacements in the sagittal plane. This practical and cost-effective method can be implemented with affordable cameras, such as consumer models or regular smartphones [22], and open-source, free biomechanical software like Tracker [23] or Kinovea [24].

However, to the best knowledge of the authors, no previous work has conducted a validation study of position-based instruments concurrently to explore their usefulness among sports and health professionals. A study with multiple paired measurements of the same jump execution would provide the level of agreement between established measurement methods, considered as “gold standard” but with practical disadvantages, and new cost-effective, practical methods. If the measurements from the methods under test are sufficiently close, the new method could replace the criterion method in clinical and professional practice [25].

In this paper, we have conducted a validation study for position-based instruments between a criterion method and an alternative practical method for vertical jump test measurement. Smartphone high-speed video and Kinovea open-source motion analysis software (Smartphone-Kinovea method) were quantified against 3D Motion Capture System as the criterion. A broad sample of subjects executed a set of countermovement jump trials, a natural jumping movement very easy to administer to an unskilled population, while the two instruments measured jump heights concurrently. Therefore, the study aimed to address the validity, reliability, and usefulness of the open-source computer-based Smartphone-Kinovea method against a laboratory-based Motion Capture System instrument to assess health status and sports performance in a healthy, active population diverse in gender and physical condition.

## MATERIALS AND METHODS

### Subjects

One hundred and twelve healthy adults (67 male and 45 female: mean age: 33.1 ± 7.4 years, body mass 72.3 ± 10.8 kg, height 173.8 ± 8.5 cm) were recruited for this study. The inclusion criteria consisted of non-competitive sports subjects participating in recreational aerobic exercise and resistance training, not being obese, no lower extremity surgery in the last 6 months, and lack of lower limb pain. Subjects were instructed to abstain from drinking caffeinated beverages or alcohol for 24 hours before testing. All jumps were performed by each participant at the same time of the day to ensure that no circadian variation was present. The study was carried out in accordance with the guidelines of the ethical principles of the Declaration of Helsinki. All subjects provided informed written consent before the beginning of this study, which was approved by the University Institutional Review Board (IRB No. UA-2019-02-25).

### Procedures

This was an observational study consisting of repeated measurements of maximum vertical jump height on subjects during a single test session. A standardized warm-up session of 5 minutes was performed by each subject on a cycle ergometer (Cardgirus Pro Medical, Alava, Spain) set at a light intensity (60-W power load) and 55- to 65-rpm cadence. Subjects were then educated on how to achieve a proper countermovement jumping technique and keep balance while landing. The subjects were instructed to start from an upright position with their hands on hips, feet shoulder-width apart, and eyes looking at a freely chosen point on the opposite wall. Every recorded trial started with the same initial position to ensure that the center of mass was at the same initial height. After an acoustic signal, subjects moved into a 90º knee flexion semisquat position and immediately performed a quick lower limb extension to jump vertically off the ground. No arm swimming was present in all executions to maintain as much as possible unaltered the center of mass during body excursion. Real-time video digitizing software was used to ensure subjects achieved the right knee angle (90º) before extension. After warm-up, each subject performed three trials of countermovement jump with one minute rest period between trials. All jumps performed incorrectly were repeated, so only successful trials were considered. Countermovement jump type was chosen for this broad sample as it is a simple jump type, easily executed by unskilled subjects, in which a movement downwards is followed by a sudden movement in the opposite direction. This countermovement benefits from the ‘‘stretch–shorten cycle’’, which is the main force production in many activities such as running, jumping, or throwing [26].

**Data collection**

All trials were collected simultaneously with two position-based instruments.

The optical motion capture system (OptiTrack Motive, Corvallis, OR, USA), comprising 8 infrared digital video cameras, was used as the gold standard. All cameras were synchronized at 100 Hz, shutter speed of 20 us to obtain 3D tracking of body markers over an area of 4x4 m with 1-mm resolution. Three retroreflective circular markers (4 cm diameter) were distributed following the Helen Hayes-Davis marker set to track the center of gravity displacements [27] in the anatomical locations of the Anterior Superior Iliac Spine and the midpoint between the Posterior Superior Iliac Spine, also referred to as the Sacrum marker. Jump height was given by the difference between the peak height during the vertical displacement and the initial standing position with the Mokka open-source motion kinematic & kinetic analyser software (v. 0.6 , Mokka, Montréal, Canada).

The alternative method consisted of a regular smartphone with high-speed video recording (1920 x 1080 pixels at 60 fps) and further analysis with biomechanical open-source software. The smartphone was placed on a level tripod at 90 cm height, with the sensor parallel to the back frontal plane of subjects to avoid errors due to optical misalignments [22]. In order to maintain the same field of view of all recordings, a Bluetooth remote shutter was used to operate the smartphone video app. The vertical excursion of the sacrum marker was recorded throughout the jump to track the vertical displacement of the center of gravity from a standing position to the highest jump height. All recorded videos were analyzed with the stable version of Kinovea (v. 0.8.15, Kinovea, Bordeaux, France) [28]. Once the work area had been calibrated, the automatic track path tool was used to follow the marker trajectory without further adjustment, due to the contrast between the reflective surface of the marker and the dark subject’s clothes. Three raters with 5.6±2.8 years of expertise visualized independently all videos and gave outcomes for each jump execution. The mean value of the three raters was considered. The inter-rater reliability was calculated by the percentage ratio of the paired between-rater SD and the mean (coefficient of variation), resulting in 1.51±0.86%. All paths were exported to an XML file and opened with spreadsheet software (Microsoft Excel v.14, Microsoft, Redmond, USA).

The measured values of jump height were used to compute lower limbs muscular and kinematic variables produced in the jump execution. Jumping height is determined by the vertical velocity at take-off $v_{to}$, which depends on the subject body mass and the impulse $J$, as the result of the upward acceleration of all body segments. In the upward motion before take-off, the athletes reach maximum vertical force shortly after starting the propulsion phase [29]. Muscular power of the lower limbs can be measured during this phase using the impulse due to the resultant vertical force impulse, as the difference between the impulses of the vertical ground reaction force and body weight. In the remainder of the propulsion phase, athletes accelerate their bodies through a quick lower limb extension to propel their center of gravity vertically until take-off, starting the flight phase with no ground reaction force available. Shortly after the maximum vertical velocity is attained when the ground reaction force drops below body weight, the velocity at take-off is achieved as the start of the flight phase, indicating the beginning of the body center of gravity deceleration. The take-off velocity is calculated as $v_{\mathrm{to}} = (g \cdot h)^{1/2}$, where $h$ is the jump height and $g$ is the gravity acceleration (9.81 $\mathrm{m/s^2}$). Impulse due to the resultant vertical force is computed with $J = m \cdot v_{\mathrm{to}}$, where $m$ is the body mass of each athlete.

## Statistical analysis

Descriptive statistics (mean ± SD) were used to report the characteristics of the 336 jumps recorded. The reliability of the Kinovea method in comparison with the criterion motion capture system was tested using 2-way random single measurements (consistency and absolute agreement) intraclass correlation coefficient (ICC) (2,1) and Cronbach's $\alpha$ [30]. ICC values were interpreted as poor (<0.5), moderate (0.5-0.75), good (0.75-0.9), and excellent (>0.9) reliability [31]. Additionally, the outcome differences between the motion capture system and the Kinovea method were compared using paired samples *t*-tests and mean differences with 95% confidence interval, which represent uncertainty in the true value. The minimum improvement likely to have a practical impact was calculated with the smallest worthwhile change (SWC), as 20% of the between-subjects standard deviation [3]. The usefulness of the Kinovea method was evaluated by comparing SWC and the typical error of measurement (SEM) [32]. The ratio SWC to SEM is a measure of the ability of the instrument to detect changes, interpreted as good (>1), satisfactory (1), and marginal (<1). [33]. The agreement between the two instruments was also explored using Bland-Altman plots [34], which show mean outcomes pairs against their difference between values to identify any random error and proportional bias with bivariate Pearson's product moment correlation coefficient as $r^2>0.1$ [35]. Finally, the bivariate Pearson's product moment correlation coefficient ($r$) with 95% confidence intervals (CI) was used jump height outcomes to study the validity of two instruments using the following thresholds: trivial (<0.1), small (0.1-0.3), moderate (0.3-0.5), high (0.5-0.7), very high (0.7-0.9) and practically perfect (>0.9) [36]. The standard error of estimate (SEE) was computed in raw units and standardized, evaluated via $r$ to allow estimation of confidence limits [37], and interpreted using half the thresholds of the modified Cohen's scale: trivial (<0.1), small (0.1-0.3), moderate (0.3-0.6), large (0.6-1.0), very large (1.0-2.0) and extremely large (>2.0) [36]. All statistical analyses were computed with IBM SPSS v. 22 (IBM Corp, Armonk, NY) and an available spreadsheet for validity [38].

# RESULTS

The agreement between the laboratory-based Motion Capture System and the Smartphone-Kinovea motion analysis software was tested, collecting 336 jumps from 112 participants performing three countermovement jump repetitions each. The descriptive statistics showed jump heights (mean ± SD) of 40.59 ± 6.71 cm for the Motion Capture System and 40.81 ± 6.63 cm for the Smartphone-Kinovea system. The computed take-off velocity from collected jump height resulted in 2.81 ± 0.23 m/s for the Motion Capture System and 2.82 ± 0.23 m/s for the Smartphone-Kinovea system and computed impulse due to resultant vertical force exerted by athletes led to 204.6 ± 41.1 Ns for the Motion Capture System and 205.2 ± 41.0 Ns for the Smartphone-Kinovea system.

The intraclass correlation coefficient between the two methods showed very high consistency and absolute agreement for jump height (ICC=0.982−0.988, 0.981−0.988), and take-off velocity (ICC=0.981−0.988, 0.982−0.988) an almost perfect agreement for impulse (ICC=0.997−0.998), as shown in Table 1. Likewise, excellent reliability was observed between instruments with Cronbach's α coefficients near unity. Smartphone-Kinovea showed negligible underestimation of jump height (-0.22 ± 1.15 cm), take-off velocity (-0.01 ± 0.04 m/s) and impulse (-0.56 ± 2.92 Ns), compared to Motion Capture System (*p*<0.01).

Table 1. Pairwise reliability of Motion Capture System and Smartphone-Kinovea methods.

| | Jump height | Take-off velocity | Impulse |
|---|---|---|---|
| ICC (2,1)# | 0.985 (0.982 − 0.988) | 0.985 (0.981 − 0.988) | 0.997 (0.997 − 0.998) |
| ICC (2,1)§ | 0.985 (0.981 − 0.988) | 0.986 (0.982 − 0.988) | 0.997 (0.997 − 0.998) |
| Cronbach's α | 0.993 | 0.993 | 0.999 |
| Mean difference | -0.22* (-0.34 − -0.10) cm | -0.01* (-0.01 − -0.0) m/s | -0.56* (-0.87 − -0.25) Ns |
| SWC | 1.34 (1.25 − 1.45) cm | 1.15 (1.07 − 1.25) m/s | 2.93 (2.72 – 3.17) Ns |
| SEM | 0.81 cm | 0.03 m/s | 2.25 Ns |
| SWC/SEM Ratio | 1.65 | 1.43 | 1.30 |

Data expressed as mean values (95% confidence intervals);
Intra-class correlation coefficient (ICC) showing consistency(#) and
absolute agreement(§) for the comparison between systems; **p*<0.01.

The usefulness of the Smartphone-Kinovea was assessed through the smallest worthwhile change (SWC), as the minimum practically meaningful change in a performance variable due to personal enhancements over the noise of the measure. For jump height, take-off velocity, and impulse, SWC resulted in 1.34 cm, 1.15 m/s, and 2.93 Ns, respectively. The ability to detect changes over the noise of the measure is obtained when SWC > SEM. For the Smartphone-Kinovea method, the SWC/SEM ratio is greater than unity, so the signal-to-noise ratio of practical measurement allows for a meaningful assessment of changes in performance.

Bland-Altman plots showed high level of agreement between Motion Capture System and Smartphone-Kinovea method since the majority of paired measurements fall inside the 95% limits of agreement, depicted in dashed lines in Figure 1 (±1.96·SD of the differences). Likewise, very low mean systematic bias ± random errors are observed for the three variables, jump height: -0.22 ± 2.25 cm, take-off velocity -0.01 ± 0.08 m/s and impulse -0.56 ± 5.73 Ns (*p*<0.01). The difference between the two methods remained constant with increasing jumping height ($r^2$=0.005), take-off velocity ($r^2$=0.005), and impulse ($r^2$=0.001). As a result of the absence of heteroscedasticity of the errors, there is no association between the magnitude of the errors and the mean value [25,39].

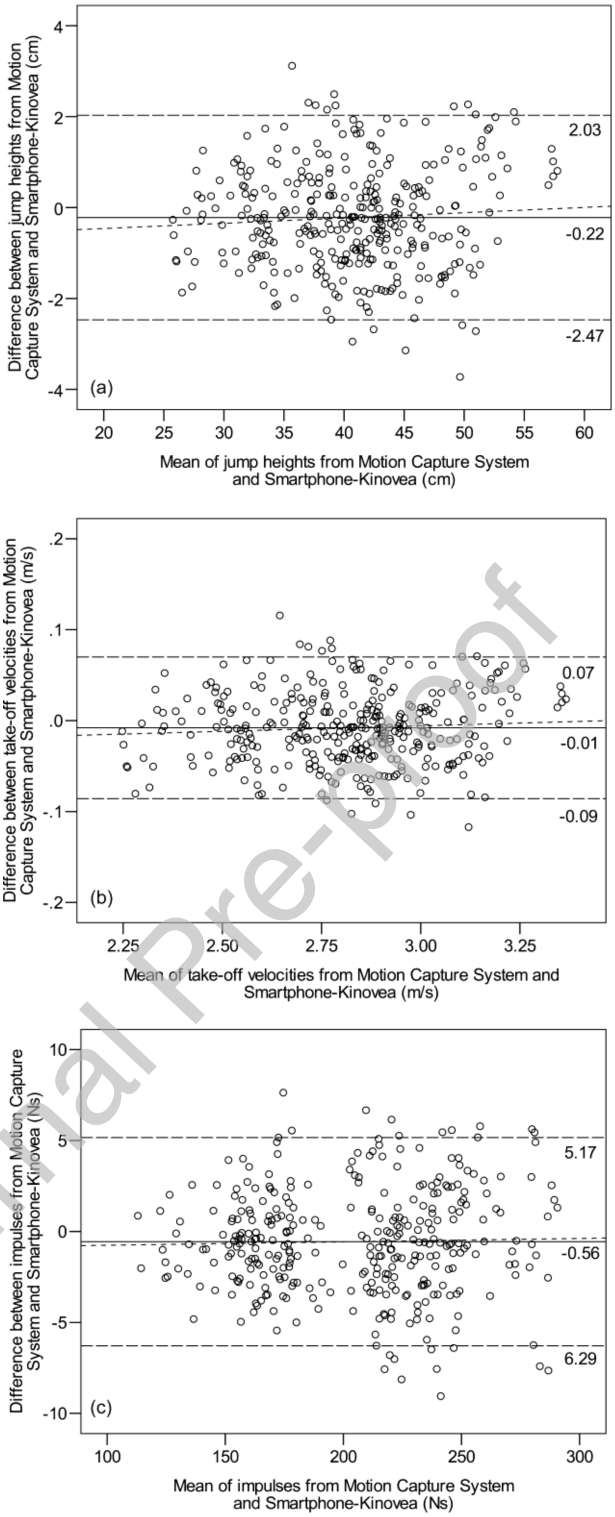

Figure 1. Bland-Altman plots for the measurements of Motion Capture System and Smartphone-Kinovea method. Solid central line represents mean between instruments (systematic bias); upper and lower dashed lines show mean ± 1.96 SD (random error); dotted line shows regression (proportional bias). (a) Jump height: regression $y$=–0.01x+0.60 cm, $r^2$=0.005; (b) Take-off velocity: regression $y$=0.01x–0.04 m/s, $r^2$=0.005; (c) Impulse: regression $y$=0.002x–0.95 Ns, $r^2$=0.0007.

The bivariate Pearson's product moment correlation coefficient showed very high ($r$=0.985 for jump height and $r$=0.986 for take-off velocity, $p$<0.01) and practically perfect (*r*=0.997 for impulse, $p<0.01$) association between Motion Capture System and Smartphone-Kinovea method (Table 2).

Table 2. Results of the Pearson correlation coefficients and simple linear regressions.

| | Jump height | Take-off velocity | Impulse |
|---|---|---|---|
| Pearson's *r* | 0.985* (0.982 − 0.988) | 0.986* (0.982 − 0.988) | 0.997* (0.997 − 0.998) |
| SEE | 1.15 (1.07 − 1.25) cm | 0.040 (0.037 − 0.043) m/s | 2.93 (2.72 − 3.17) Ns |
| Standardized SEE | 0.17 (0.16 − 0.19) | 0.17 (0.15 − 0.19) | 0.07 (0.06 − 0.08) |
| SEE Effect Size | Small | Small | Trivial |
| Slope | 0.997 (0.978 – 1.015) | 0.998 (0.979 – 1.016) | 0.999 (0.992 – 1.007) |
| Intercept | -0.084 (-0.855 – -0.0687) | -0.002 (-0.054 – -0.051) | -0.426 (-2.031 – -1.180) |
| Linear regression $r^2$ | 0.970 (0.964 – 0.976) | 0.972 (0.964 – 0.976) | 0.994 (0.994 – 0.996) |

Data expressed as mean values (95% confidence intervals); $*p<0.01$.

Similarly, the predictions made with the regression lines are very accurate, as given by low standard error of estimates: 1.15 (1.07 – 1.25) cm for jump height, 0.040 (0.037 – 0.043) m/s for take-off velocity and 2.93 (2.72 – 3.17) Ns for impulse, as shown in Figure 2.

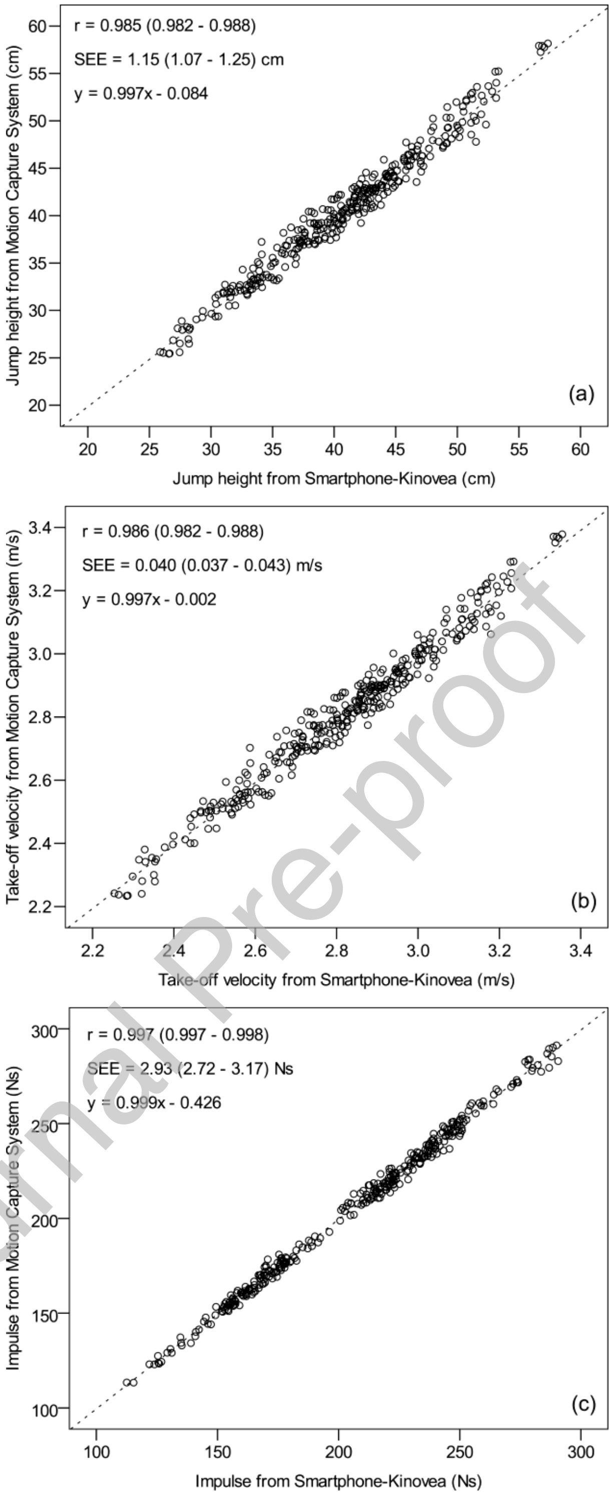

Figure 2. Relationship between measurements derived from Motion Capture System and Smartphone-Kinovea. (a) Jump height; (b) Take-off velocity; (c) Impulse. Pearson's product moment correlation coefficient (*r*) and standard error of estimate (SEE) shown with 95% confidence interval between brackets; *p*<0.01.

## DISCUSSION

In this study, a healthy, active population diverse in gender and physical condition has been used to conduct a validation study between 3D Motion Capture System as criterion and practical, cost-effective Smartphone-Kinovea method to measure jump height derived from body center of gravity displacement.

Method agreement-type studies should involve a minimum of 40 subjects for adequate statistical accuracy [33]. Our study increased this threshold with 112 subjects and 336 jump executions, improving the assessment accuracy of the Smartphone-Kinovea method.

Kinovea is free open-source motion analysis software under GPLv2 license, developed by sport and health professionals, programmers, researchers, and athletes in worldwide non-profit collaboration. In the field of sports, Kinovea has been used as a position-based instrument for measuring coordinates data and perspective [24], lower limb angle [40–42], bar velocity through tracking [43] or drop jump [44]. Similarly, as a time-based instrument, Kinovea has also been used to measure temporal parameters in jump height assessment, such as flight time [45–47]. To the best of our knowledge, this is the first study assessing the validity and reliability of Motion Capture and Smartphone-Kinovea used as a direct measure of excursion of the center of gravity while performing countermovement jumps as the main variable under test.

Several studies have found considerable differences in mean jump heights between position-based instruments, tracking the center of gravity path in the flight phase and time-based instruments, computing jump height with flight time through a basic kinematic equation: 10.33 cm [48], 11.7 cm [49], to name a few. In this study, we used two instruments with direct measure of the excursion of the center of gravity from which to calculate jump height as a simple subtraction between apex and standing positions. Therefore, the reported differences in this study can be used to test if the Smartphone-Kinovea method is a valid and reliable instrument because both golden standard and the instrument under test operate under the position-based principle. Moreover, from a conceptual perspective, jump height can only be defined as the vertical displacement of the center of gravity from a standing position and therefore, instruments tracking this displacement directly in space are the most appropriate [49].

This study has explored basic video technology to generalize the results. Considering that most current smartphones are able to record video frame rates of around 60 fps, the most important feature in a video camera to be a valid and reliable instrument aiming at capturing spatial-derived characteristics is the sensor resolution [22]. Nowadays, most smartphones are able to record videos at resolutions of 1920x1080 pixels, high enough to resolve the excursion of the sacrum marker in a jump execution. The results of the present study have been determined using these two minimum characteristics: 1920x1080 pixels at 60 fps to test the system under the least favorable conditions. It is expected that increases in video resolution to 2048x1080 pixels (2K) or 3840x2160 pixels (4K) would enhance these results as the system would be able to resolve spatial information more precisely. However, an increase in the temporal resolution of the video camera system (120 fps, 240 fps…) may not lead to an improvement in the results as the two key points (standing and the apex of flight phase), which indicate the start and end of the excursion of the center of gravity from which to calculate jump height, are static ($v$=0). Thus, granted that a minimum frame rate of about 60 Hz (16.7 ms) is attained, high-speed video capabilities may not offer additional advantages. This fact opens the possibility to the use of regular consumer video cameras as part of the presented methodology since such consumer segment is focused on high-resolution capabilities with frame rates similar to the ones used in this experiment at affordable prices.

The main finding of this validation study was that the Smartphone-Kinovea method is a valid, reliable, and useful instrument to measure countermovement jump height and derived parameters. Results showed very high consistency and absolute agreement for jump height and take-off velocity (ICC~0.985) and almost perfect agreement for impulse (ICC=0.997). The narrow confidence intervals shown in the three variables also support the agreement between instruments. Our results are in accordance with similar validation studies of jump height test instruments, such as jump mats (0.99 [50], 0.997 [51]), photoelectric cells (ICC=0.994 [52], 0.998 [53]) and smartphone apps (ICC=0.97 [54], 0.96 [46]) but higher than inertial systems (ICC=0.79-0.86 [55]) which relies on the estimation of take-off velocity through integration of the body acceleration. Similarly, Cronbach's α coefficient >0.9 indicated excellent consistency for jump height, take-off velocity, and impulse outcomes.

Bland-Altman plots have also been used to assess the level of agreement between two instruments measuring the same variable [34]. In this study, very low systematic bias was observed across all variables: -0.22 cm, -0.01 m/s, and -0.56 Ns for jump height, take-off velocity, and impulse, respectively. As a consequence, the Smartphone-Kinovea method tends to underestimate measurements relative to the Motion Capture System by a negligible amount. Similar bias was observed in jump height on jump mats -0.11 cm [51] or photoelectric cells: -0.11 cm [53]. Similarly, the random errors depicted by the narrow limits of agreement (2.25 cm, 0.08 m/s, and 5.73 Ns) suggested that the Smartphone-Kinovea method can be regarded as an instrument with an accuracy comparable to jump mats (2.29 cm [51] or photoelectric cells 2.68 cm [53]). The Pearson's product moment of correlation and the regression line of the scattered data revealed lack of association between the systematic mean value and the magnitude of the random errors ($r^2<0.1$) [35]. From a practical perspective, homoscedasticity in the errors means that the amount of random error is stable irrespective of the jump height measured by the Smartphone-Kinovea method. Low and stable random errors play a crucial role when assessing typical small improvements in jump height for high-performance athletes [39].

According to the bivariate Pearson's product moment correlation coefficient between paired outcomes, the Smartphone-Kinovea method provided valid measures of jump height, take-off velocity, and impulse. Very high and practically perfect associations between instruments were observed for the three variables. Our results are in line with jump mats ($r$=0.995 [50], 0.989 [48]), photoelectric cells (0.998 [53]), smartphone apps (0.997 [54])

Finally, the usefulness of the proposed method is assessed by comparing the standard error of measurement, as the uncertainty of the measure and the smallest worthwhile change, as the minimum meaningful change in performance. In our study, the Smartphone-Kinovea method gave very low uncertainty of the jump height (0.81 cm), take-off velocity (0.03 m/s), and impulse (2.25 Ns) measures, with trivial to small effect sizes. On the other hand, the minimum improvement in jump height, take-off velocity, and impulse likely to have a practical impact were 1.34 cm, 1.15 m/s, and 2.93 Ns, respectively. These values were taken as a conservative fraction of the between-subjects SD [56], indicating that measures below these values are not practical. The combination of SEM and SWC gives important information on the usefulness of the Smartphone-Kinovea method by indicating the smallest practical change for the sample and the uncertainty of the measure. In our study sample, the signal (SWC) to noise (SEM) ratio is 1.65 for jump height, 1.43 for take-off velocity, and 1.30 for impulse. The latter means that the Smartphone-Kinovea can be regarded as a sensitive instrument to monitor variations in jump performance over the uncertainty around the measure [32].

In this study, the standardized countermovement jump technique with the hands akimbo was used due to the ease of execution for our study sample. Future studies may use squat jump or other versions of countermovement jump, such as with arm swing, with run and arm swing, or drop jump. However, the difficult execution or physical demands of the latter jump types may refrain researchers from selecting unskilled, broad samples like the one in this study.

## CONCLUSION

This study has shown that the Smartphone-Kinovea method is a valid and reliable instrument to assess vertical jump height through direct tracking of the center of gravity excursion. Sports and health professionals can use this method to monitor changes in jump height due to the low uncertainty of the measure compared to the smallest worthwhile change of an active and diverse in gender and fitness level healthy population. The Smartphone-Kinovea method can be regarded as a trustworthy instrument that provides accurate measures of jump height and derived parameters to assess health status and sports performance at a fraction of the cost of laboratory-based methods.

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