COMPARISON OF THREE DIFFERENT MEASUREMENT SYSTEMS TO ASSESS THE VERTICAL JUMP HEIGHT

COMPARAÇÃO DE TRÊS SISTEMAS DE MEDIÇÃO DIFERENTES PARA AVALIAR A ALTURA DO SALTO VERTICAL

COMPARACIÓN DE TRES SISTEMAS DE MEDICIÓN DIFERENTES PARA EVALUAR LA ALTURA DEL SALTO VERTICAL

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ABSTRACT

Introduction: The numerous instruments used to measure jump height use different technologies and calculations that can provide variable results. Objective: This study compared the countermovement jump (CMJ) height assessed with a wearable 3D inertial measurement unit (IMU), using flight time and the numerical integration method with a force platform and photocells. Methods: Forty CMJs were analysed, starting from an upright standing position with the hands placed on the waist. Twenty healthy volunteers completed 2 CMJs, which were simultaneously assessed using an IMU placed on the subject's sacrum, a force platform (considered the gold standard method) and photocells. The maximum height of each CMJ was measured. Results: The results showed a significant overestimation ($p<0.001$) in jump height for the IMU using the numerical integration method when compared to the force platform (+7 cm). Excellent intraclass correlation coefficients (ICCs) were obtained with the flight time equations for the different types of measurement equipment. Fair to good ICCs were obtained with the IMU using the numerical integration method and force platform. Conclusion: In conclusion, the jump height obtained with the IMU using the numerical integration method showed the poorest agreement compared to the force platform. ***Level of evidence III; Prospective comparative study.***

Keywords: Biomechanics; Instrumentation; Acceleration.

RESUMO

Introdução: Os numerosos instrumentos usados para medir a altura de salto empregam diferentes tecnologias e cálculos que podem fornecer resultados variáveis. Objetivo: Este estudo comparou a altura de salto contramovimento (SCM) com uma unidade de medida inercial 3D (UMI) portátil, usando o tempo de voo e o método de integração numérica, com plataforma de força e fotocélulas. Métodos: Quarenta SCMs foram analisados a partir da posição ortostática com as mãos na cintura. Vinte voluntários saudáveis concluíram 2 SCMs que foram avaliados simultaneamente com uma UMI colocada no sacro do indivíduo, uma plataforma de força (considerado o método de referência) e fotocélulas. A altura máxima de cada SCM foi medida. Resultados: Os resultados mostraram uma superestimação significativa (p < 0,001) da altura do salto para a UMI com o método de integração numérica, em comparação com a plataforma de força (+7 cm). Foram obtidos excelentes coeficientes de correlação intraclasse (ICCs) com as equações de tempo de voo entre os equipamentos de medição. Foram obtidos resultados de regulares a bons de ICC com a UMI pelo método de integração numérica e a plataforma de força. Conclusão: A altura de salto obtida com a UMI com o método de integração numérica mostrou a pior concordância em comparação com a plataforma de força. ***Nível de evidência III; Estudo prospectivo comparativo.***

Descritores: Biomecânica; Instrumentação; Aceleração.

RESUMEN

Introducción: Los numerosos instrumentos usados para medir la altura del salto emplean diferentes tecnologías y cálculos que pueden suministrar resultados variables. Objetivo: Este estudio comparó la altura del salto contramovimiento (SCM) con una un sistema inercial 3D (IMU) portátil, usando el tiempo de vuelo y el método de integración numérica, con plataforma de fuerza y fotocélulas. Métodos: Cuarenta SCMs fueron analizados a partir de la posición ortostática con las manos en la cintura. Veinte voluntarios saludables concluyeron dos SCMs que fueron evaluados simultáneamente con un IMU colocada en el sacro del individuo, una plataforma de fuerza (considerado el método de referencia) y fotocélulas. Fue medida la altura máxima de cada SCM. Resultados: Los resultados mostraron una sobreestimación significativa (p <0,001) de la altura del salto para la IMU con el método de integración numérica, en comparación con la plataforma de fuerza (+7 cm). Fueron obtenidos excelentes coeficientes de correlación intraclase (ICCs) con las ecuaciones de tiempo de vuelo entre los equipamientos de medición. Fueron obtenidos resultados de regulares a buenos de ICC con la IMU por el método de integración numérica y la plataforma de fuerza. Conclusión: La altura de salto obtenida con la IMU con el método de integración numérica mostró la peor concordancia en comparación con la plataforma de fuerza. ***Nivel de evidencia III; Estudio prospectivo comparativo.***

Descriptores: *Biomecánica; Instrumentos; Aceleración.*

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INTRODUCTION

Vertical jump performance is commonly used in the literature to assess strength and power; as such, it is important to ensure that the evaluation of vertical jump height is characterised by adequate validity and agreement.[1,2] The numerous instruments used to measure jump height use different technologies and calculations that can provide variable results.[1,2] To assess jump performance, many different protocols and devices have been used, such as contact mats, high speed video, belt mats, accelerometers, inertial measurement units (IMU), or force platforms.[1-8]

Usually, the use of 3D motion analysis systems[9] and a force platform is considered as the 'gold standard' for the assessment of vertical jump performance;[1,6] the 'gold standard' is accurate, because the initial conditions of the free-fall equation (take-off height and velocity) can be obtained from the instantaneous vertical acceleration of the centre of mass,[10,11] but requires an equipped laboratory, long test procedures, and a high acquisition cost, preventing its use on playing fields or other 'non-structured' environments[12] Using a force platform to measure the vertical ground reaction force, the jump height can be estimated by various techniques that are based on the velocity at the instant of take-off.[7]

On the other hand, measurement of flight time (FT) is a common methodology to estimate vertical jump height, by an equation of uniform acceleration. Although this estimation of jump height relies on the assumption that the height of the centre of mass at take-off and landing coincides[13] but this does not occur frequently.[11,14,15] However, FT measurement has some advantages, such as that it requires only cheap devices and is an easily accessible and simple method for physical trainers and sport scientists.[5,16]

Recently, sensors that have an integrated accelerometer and gyroscope, named IMU sensors were developed and may serve as a means for more robust field-based testing. However, most accelerometers and IMUs have been developed and have been used as a mean for calculated parameters of gait or daily living activity classification.[17,18]

Accelerometers and IMUs are extremely small, portable, easy to handle, and relatively cheap and can be placed on the sacrum to estimate jump height using two methods based on the estimation of two different parameters: FT and the vertical velocity at take-off, the latter called the numerical integration method, as the velocity is obtain by integrating the acceleration measured along the vertical axis of the IMU. Although it should be noted that trunk movements interfere with jump height, this limitation can be compensated using a gyroscope[19] and provided that an accurate detection of the take-off and landing is obtained[20] to calculate the jump height. Therefore, trunk correction is possible with IMU devices but not with accelerometers.

Regarding to the FT method, some studies compared the jump height obtained using the FT calculi of an accelerometer with stereophotogrammetry, force platform, or optical mats,[6,8,12,19,21,22] with controversial results. Some studies reported that accelerometer devices overestimated the jump height when compared to photocells[6,8] whereas other studies obtained good reliability by varying the algorithms used[19,22] or by placing an accelerometer on each ankle.[12] On the other hand, Nuzzo et al.[23] reported that the accelerometer showed the best intrasession and intersession reliability compared to systems using FT calculi.

With respect to the numerical integration method, the jump height obtained through both methodologies an accelerometer sensor was validated with the photocell mat.[5] Both of the methodologies used with an accelerometer overestimated the jump height, but FT showed more validity than the numerical integration method. A recent study compared the jump height obtained with a force platform and obtained from an accelerometer sensor through FT and the numerical integration method.[20] In this study, a comparison was made between the specific software of the accelerometer and a new threshold to detect the take-off and landing. The new algorithms improved the accuracy for FT but did not enhance the use of numerical integration of the acceleration, note that these previous studies used accelerometers without gyroscopes to estimate the jump height.

Although the numerical integration method using the accelerometer sensor and force plate has been studied, additional research with other algorithms is necessary to improve the detection of take-off and landing or to reduce the trunk movements' interference with IMU sensors. Thus, the aim of this study was to compare the CMJ height assessed using an IMU, with a force platform and photocells with their proprietary software to measure vertical jump height through two different procedures: FT and the numerical integration method. The FreePower IMUs improved take-off and landing measurements with the use of a gyroscope to reduce trunk movement interference.[19] Therefore, our hypothesis, according to previous literature, is that IMU will show a good agreement using the FT method and the numerical integration method factoring in trunk movement corrections algorithm using the gyroscope.

MATERIAL AND METHODS

Twenty healthy volunteers (age: 23.4±2.9 years; height: 1.79±0.06 m, and body mass: 75.2± 9.40 kg) participated in the study. All volunteers were normally physically active, i.e., they performed more than 2 sessions of 2-6 exercises per week. They gave their written informed consent before the jump testing. The present study complies with the 1995 Helsinki declaration and the relevant University Ethics Committee approved the experimental protocol (137/CEIH/2016).

At the beginning of the experimental session, the participants did a standard warm-up: 4 minutes of jogging; 3 minutes of static stretching and lower extremity exercises, and 3 minutes of submaximal vertical jumps for familiarization with the testing area. After this, each participant performed 2 countermovement jumps (CMJs), starting from an upright standing position with their hands placed on the waist. There were at least 30 seconds of rest between each jump. It was recommended that on take-off, participants leave the floor with the knees and ankles extended and land in a similarly extended position. All of the measurements were taken simultaneously.

A force platform (Kistler 9269AA6, Kistler Instruments AG, Winterthur, Switzerland) was firmly positioned on the ground to measure vertical reaction forces during jumping (range 0–5 kN; sampling rate 200 Hz). The plate was connected to a personal computer, and the proprietary software MARS v.1.0.9.2 (S2P Ltd, Ljubljana, Slovenia) automatically calculated the jump height. The force platform estimated the jump height using two different equations. The first was based on jump FT, specifically the time interval when the vertical force was equal to zero (from take-off to landing). The jump height was estimated by the equation of uniform acceleration during free-fall motions and this procedure was called FT. The second equation to obtain the jump height, called the numerical integration method, used the vertical ground reaction force that the participants applied to the force platform, to estimate the take-off velocity as calculated from the force impulse using the commercial software from Kistler (MARS v.1.0.3); this method, where jump parameters are derived from GRFs are often used as a "gold-standard" or reference criterion.[1,2]

The SportJump System Pro (SportJump System Pro; DSD Inc., León, Spain) is a photocell mat with a photoelectric circuit based on laser beams. It had a testing area of 95 x 93 cm (the width of 95 cm could be varied) and a temporal resolution of 0.001 seconds. It consisted of 2 parallel bars, 1 laser transmitter module with 32 laser lights longitudinally placed 3 cm apart, and 1 photosensitive receiver module with 32 laser receivers placed in front of the laser lights. To investigate its validity, we attempted to position SportJump System Pro diodes at the same height as the force platform surface plane in order to simultaneously record the FT of the 2 systems.[16] The hardware was connected to a personal computer and the SportJump-v2.0 software (SportJump-v2.0; DSD Inc., León, Spain) measured the jump height through FT by the equation of uniform acceleration during free-fall motions.

At the same time, an IMU (FreePower, Sensorize, Rome, Italy) was positioned on the participant's lower back at the level of L5 using an elastic belt. The IMU contained a 3D accelerometer ($\pm$ 6 g of full range) and a 3D gyroscope ($\pm 500^{o} \cdot s^{-1}$ of full range), providing 3D linear acceleration and 3D angular velocity with respect to a local sensor-embedded reference system, coinciding with the geometrical axes of the IMU. This sensor, which was used in previous studies,[19,24] sent the data via Bluetooth at 100 Hz to a computer installed with proprietary software (FreePower Jump Next, Sensorize, Rome, Italy) that automatically estimated the jump height. Jump height was obtained using the free-fall motion equation (Equation 1). Firstly computing jump FT to obtain the jump height, and secondly using vertical velocity at take-off according to the numerial integration method.

$$H_{(t)} = H_0 + \upsilon_0 \cdot t - 1/2\, g \cdot t^2 \quad \text{(Equation 1)}$$

$H_{(t)}$: jump height, H_0: take-off height, υ_0: the take-off velocity, t: flight time duration, g: 9.81 m/s.[2]

To obtain the absolute vertical acceleration, the IMU sensor compensated for the bending of the trunk, and eliminated the contribution of gravity from the acceleration component along the global vertical axis, Picerno et al.,[19] used the equations 2 and 3 respectively:

$$a_Z(t) = a_{x`}(t) \cdot \sin \beta\,(t) + a_{z`}(t) \cdot \cos \beta\,(t) \quad \text{(Equation 2)}$$

$$a_v(t) = a_Z(t) - g \quad \text{(Equation 3)}$$

$a_Z(t)$ is the absolute vertical acceleration compensated for the β (t) is the trunk bending, and the total acceleration projected on the vertical and anterior-posterior axes ($a_{x`}(t)$, $a_{z`}(t)$) (Equation 2). a_v is the vertical acceleration, and FT was determined as the interval in wich a_v was found equal to or lower than the gravitacional acceleration (Equation 3). The global reference system of the IMU sensor was defined as follows: the Z-axis is determined by gravity; the X-axis lies on the participant's sagittal plane and is perpendicular to gravity; and the Y-axis is defined as orthogonal to the ZX plane.

Statistical analysis

The Shapiro-Wilk test was performed to verify the normal distribution of the estimated parameters. A one-way ANOVA with repeated measurement was performed between the measurement systems. To determine the relative agreement of the different measurement instruments in estimating the jump height, the intra-class correlation coefficient (ICC) was calculated using SPSS 21.0 software (SPSS Inc., Chicago, IL, USA). According to Fleiss' classifications,[25] excellent agreement is when ICC>0.75, fair to good agreement when 0.40<ICC<0.75, and poor agreement when ICC<0.40. The Bland-Altman method allowed the determination of systematic bias ($\pm$ random error) between systems, and the lower and upper LoA[26] were calculated via MedCalc v.12.1.4.0 software (MedCalc Software, Belgium). Statistical significance was set at p<0.05.

RESULTS

Table 1 showed the jump height recorded by each measurement equipment and methodology.

The ANOVA analysis showed a significant increase in the jump height assessed by the IMU based on the numerical integration method equation compared to the rest of the measurement systems and methodologies (p<0.001) (Table 1). No significant difference in the jump height obtained with the FT methodology was found among the three measurement systems or between the force platform calculation by the numerical integration method. (Table 1)

Table 2 showed the concurrent validity, using ICC, and the systematic bias, using the Bland-Altman method, among systems. Excellent ICC agreement was found among all measurement systems when using the FT method to estimate the jump height. Moreover, the photocells showed an excellent ICC when compared to the gold standard method. A fair to good agreement was obtained between the IMU based on the numerical integration method compared to the rest of the equipment and methodologies. Moreover, the IMU based on FT showed a fair to good ICC when compared to the gold standard method.

Table 1. CMJ height obtained from the different measurement systems (rows) and methodologies (columns). n= 40 jumps (2 per subject).

Measurement System	Flight time (meters) Mean + SD	Numerical Integration (meters) Mean + SD
Force Platform	0.37± 0.05	0.37± 0.06
Photocells	0.35 ± 0.05	N/A
IMU	0.37± 0.05	0.44 ± 0.06

SD: Standard Deviation.

Table 2. Concurrent validity and systematic bias between systems and methods.

Pair comparison	ICC (95% CI)	Bias (m)	Random error (m)	Upper LoA (m)	Lower LoA (m)
FP_NI –Photocells	0.82	0.02	± 0.04	0.10	-0.06
FP_NI - IMU_FT	0.74	< 0.001	± 0.056	0.11	-0.11
FP_NI - IMU_NI	0.47	-0.07	± 0.060	0.05	-0.19
FP_NI - FP_FT	0.86	0.003	± 0.04	0.08	-0.08
FP_FT – Photocells	0.96	0.019	± 0.005	0.029	0.008
FP_FT - IMU_FT	0.93	-0.003	± 0.033	0.06	-0.07
FP_FT - IMU_NI	0.60	-0.07	± 0.04	0.006	-0.15
Photocells - IMU_FT	0.88	-0.02	± 0.034	0.047	-0.087
Photocells - IMU_NI	0.47	-0.09	± 0.042	-0.008	-0.17
IMU_FT - IMU_NI	0.66	-0.07	± 0.034	-0.004	-0.14

FP: Foce Plate; FT: flight time; NI: numerical integration.

DISCUSSION

In this study, CMJ height was estimated using different methodologies and instruments. According to the previous hypothesis, there were no significant differences in jump height obtained when using the FT method. The results indicated that the highest level of correlation was between the instruments based on FT; the photocells' bias underestimated CMJ by 2 cm with respect to the force platform and IMU. Our results corroborated previous studies that found that photoelectric cells underestimated jump height by around 1 cm with respect to the force platform.[2,16]

In accordance with our findings, some studies showed excellent concurrent validity when they compared a triaxial IMU with photocell for the assessment of jump height using FT equations.[5,6,12] Previous studies obtained excellent ICC between IMU and the force platform using FT[6,21]. Although the above studies showed excellent ICCs, Castagna et al.[6] reported an overestimation of jump height when using a Myotest accelerometer due to the inaccuracy in the detection of the instant of take-off. In the present study, we used a Sensorize IMU (accelerometer plus gyroscope) that used a trunk correction, following the study of Picerno et al.,[19] to improve FT recognition, which may be the reason why no significant differences were obtained between the IMU using FT and the rest of the FT methods.

However, when we compared the IMU using the numerical integration method with the rest of the equipment and methodologies, the results showed that the trunk correction algorithm doesn't solve the problem when using the numerical integration approach. Other authors have also obtained greater jumping heights when comparing an IMU using the numerical integration method with a photocell system[5] or a linear position transducer plus force plate[8] and showed poor concurrent validity and insufficient agreement between IMUs using the numerical integration method and photocell mats.[5]

In the present study, the use of the IMU with numerical integration of the acceleration showed a significant overestimation (+7 cm with respect to force platform and +9 cm with respect to photocells). That could be explained by the fact that IMUs use the vertical velocity method in the take-off,[5] although the IMU was able to precisely detect the take-off and landing when calculating the jump height through FT.[5,11] Besides, the numerical integration process to estimate the vertical velocity and the displacement is affected by errors that are accumulating during the numerical integration calculi.[27] These would explain the good results obtained in our study when the IMUs used FT to calculate the jump height. In fact, a recent study compared the jump height obtained through the numerical integration method and FT with an accelerometer compared to a force platform[20] and concluded that accelerometer showed a decrease in the systematic bias, but no random error compared to the force platform.

The main limitations of the present study were the collection frequency was different between the equipment used and that no other jump styles were studied. As a practical application, the use of the photocells and IMU systems provided a good agreement using the FT method compared to the gold standard. Use of the numerical integration method for the commercial IMU did not guarantee correct agreement when obtaining the vertical height of the CMJ. In field conditions, only the FT methods of commercial portable systems (photocells and IMUs) provided a good measure of vertical jump.

CONCLUSIONS

The use of the IMU with the numerical integration method to calculate CMJ height showed the poorest correlation compared to the gold standard method and the photocells. All measurement systems showed good agreement when comparing the CMJ height using the FT methodology.

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