Measurement errors when estimating the vertical jump height with flight time using photocell devices: the example of Optojump

AUTHORS: Attia A[1,3], Dhahbi W[2,4], Chaouachi A[2,5], Padulo J[2,6,7], Wong DP[8], Chamari K[9]

[1] Higher Institute of Sports and Physical Education, Manouba University, Tunis, Tunisia
[2] Tunisian Research Laboratory "Sport Performance Optimisation", National Center of Medicine and Science in Sports (CNMSS), Tunis, Tunisia
[3] Research Unit, Analysis and Evaluation of Factors Affecting the Sport Performance, Higher Institute of Sports and Physical Education, Manouba University, Tunis, Tunisia
[4] Université de Tunis El Manar, Faculté des Sciences de Tunis, Tunisia
[5] Sports Performance Research Institute New Zealand (SPRINZ), AUT Millennium Institute, AUT University, Auckland, New Zealand
[6] Faculty of Kinesiology, University of SpLit, SpLit, Croatia
[7] University eCampus, Novedrate, Italy
[8] Sport Science Research Center, Shandong Sport University, Jinan, China
[9] Athlete Health and Performance Research Centre, ASPETAR, Qatar Orthopaedic and Sports Medicine Hospital, Doha, Qatar

Corresponding author:
Wissem Dhahbi
Zaouiet-Elmgueièz, Elhawaria,
Nabeul, 8046, Tunisia
Tel: +216 24 07 07 19
E-mail: wissem.dhahbi@gmail.com

ABSTRACT: Common methods to estimate vertical jump height (VJH) are based on the measurements of flight time (FT) or vertical reaction force. This study aimed to assess the measurement errors when estimating the VJH with flight time using photocell devices in comparison with the gold standard jump height measured by a force plate (FP). The second purpose was to determine the intrinsic reliability of the Optojump photoelectric cells in estimating VJH. For this aim, 20 subjects (age: 22.50±1.24 years) performed maximal vertical jumps in three modalities in randomized order: the squat jump (SJ), counter-movement jump (CMJ), and CMJ with arm swing (CMJarm). Each trial was simultaneously recorded by the FP and Optojump devices. High intra-class correlation coefficients (ICCs) for validity (0.98-0.99) and low limits of agreement (less than 1.4 cm) were found; even a systematic difference in jump height was consistently observed between FT and double integration of force methods (-31% to -27%; $p<0.001$) and a large effect size (Cohen's $d>1.2$). Intra-session reliability of Optojump was excellent, with ICCs ranging from 0.98 to 0.99, low coefficients of variation (3.98%), and low standard errors of measurement (0.8 cm). It was concluded that there was a high correlation between the two methods to estimate the vertical jump height, but the FT method cannot replace the gold standard, due to the large systematic bias. According to our results, the equations of each of the three jump modalities were presented in order to obtain a better estimation of the jump height.

INTRODUCTION

Jump height performance is one of the important functional parameters for most sports [1]. The literature indicates that there are significant differences among vertical jump heights (VJH) estimated by different methods [2]. The VJH has become one of the indirect techniques most frequently used by researchers and coaches to estimate muscle power of the lower limbs [3; 4; 5; 6; 7]. In addition, this measure has been used to evaluate and monitor the effectiveness of training programmes and to determine an athlete's aptitude for sports such as volleyball and basketball [8; 9; 10]. Common methods to estimate vertical jump height are based on the measurements of flight time (FT) or vertical ground reaction force (VGRF) [11; 12].

The assessment of VJH by the VGRF method has been validated in previous studies and is considered as the gold standard for the assessment of VJH performance [2; 13; 14; 15]. On one hand, through measuring the VGRF with a force platform (FP) the VJH can be estimated by various techniques, all based on the double integration of force (DIF) [12; 16; 17]. On the other hand, Quattro-Jump used the DIF method to calculate the jump height. However, it has been observed that VJH is influenced by centre of mass (COM) position before take-off, suggesting that COM displacement can be calculated during the initial position (contact phase). Even if this assessment method has excellent measurement accuracy [15; 18;

19], however, it requires expensive and hardly transportable measurement tools.

The Optojump [20] and contact mats such as "SaltoBras, LABIN" [11] and "Vertec" [8] have been used for measurement of FT. The FT method has been shown to be a reliable field test for assessing VJH in both men and women [12]. Again, the equation of uniform acceleration used to calculate the VJH has been shown to be valid and reliable [18]. The method aiming at assessing VJH through FT, with photoelectric cells (e.g. Optojump), the latter of which consist of 2 parallel bars (one transmitter and one receiver unit) that are positioned at the floor level, allows athlete-surface interaction to be easily accessible because the cells can be placed directly on all sport surfaces (i.e., content validity), except sand. Moreover, the Optojump system has the advantages of being easy to transport, easy to handle, and relatively cost effective [13]. Given these advantages of this measurement device over other measurement methods, the concurrent validity of Optojump to estimate the vertical jump height has been studied.

The intra-session error is free of methodological errors and may be considered as "intrinsic variation", cannot be reduced, and thereby serves as an appropriate baseline for comparisons, remaining independent of other error sources [21]. Intra-session reliability of VJH performance is critically important to ensure that observed differences between testing trials are not due to systematic bias, such as a learning effect, fatigue, or random error due to possible biological or mechanical variations. This variability is usually caused by the emotional state of the subject between the trials and his level of adaptation with the measuring system [21; 22]. Therefore, the aims of this study were:

a. To determine the concurrent validity of the method aiming at assessing vertical jump height through FT, with photoelectric cells (e.g. Optojump) with the gold standard FP (i.e., Quattro-Jump).

b. To determine the intrinsic reliability of the Optojump photoelectric cells in estimating VJH.

MATERIALS AND METHODS
Participants.
Twenty healthy male physically active volunteers participated in this study (age: 22.50 ± 1.24 years; body mass: 75.77 ± 13.22 kg; body height: 177.05 ± 7.04 cm). The participants were physical education students (college athlete), and none of the participants had pathological or traumatic history of the lower limbs. The local ethics committee approved the experimental protocol, and all subjects provided written informed consent before testing. All participants were asked to refrain from strenuous exercise on the day preceding the assessments.

Study design
Each subject performed a minimum of 3 and a maximum of 5 respectively for squat jumps (SJ), counter movement jump (CMJ) and

CMJ with arm-swing (CMJarm) and the highest jump height of each type of jump was used for further analysis. Each trial was simultaneously recorded by the Quattro-Jump and Optojump devices for concurrent validity assessment (i.e., intra-trial concurrent assessment). Two trials were randomly selected to examine the test-retest reliability of the Optojump system. According to this research design, each jump was entered in the calculation as a single case. These tests were performed in randomized order (Latin square design) according to the protocol described by Bosco et al. [23].

Procedures
The participants visited the laboratory twice with an interval of at least 24 hours. The first visit was used as a familiarization session during which the subjects received instructions to correctly perform the three modalities of jump, i.e. they were required to practise between 5 and 10 maximal jumps for each modality of jump. During the second visit, the participants were instructed again on how to perform the jump, after a few minutes of individual warm-up consisting of 5 minutes of gentle jogging and 7 minutes of dynamic active stretching [7 exercises: straight leg march, butt kicks, carioca, high knees, reverse lunge with twist, power shuffle, and jogging with squats). Each stretching exercise consisted of 2 sets of 20 seconds with a rest interval of 10 seconds between sets. The rest interval between stretching exercises was 10 seconds [24]. The participants performed 3-5 repetitions respectively for SJ, CMJ and CMJarm with emphasis on form. After the warm-up, the subjects stood in an upright position in the centre of the force platform with the optical bars of the Optojump positioned. Both devices were synchronized for each jump to evaluate the same jump. During the stance, their feet were shoulder width apart and their toes pointed forward or slightly outward. According to the procedure suggested by Hartmann et al. [25] the subjects performed the jump by bending the knees to a position they felt comfortable (i.e., preferred starting push-off position). A rest interval of 90 seconds was interspersed between jump repetitions, while 5 minutes was allowed between jump trials.

For the SJ, subjects started from the upright standing position with their hands on their hips; they were then instructed to flex their knees and hold a predetermined knee position ($\sim 90°$) for a count of 3 s. At that point, subjects were instructed to jump as high as possible without performing any countermovement phase. For the CMJ, subjects started from the upright standing position with their hands on their hips (i.e., without arm swing); they were then instructed to flex their knees ($\sim 90°$) as quickly as possible and then jump as high as possible in the ensuing concentric phase. For the CMJarm, subjects were instructed to perform a CMJ with arm swing during the execution of the jump (i.e., hands were free to move). For all jumps, it was recommended that at take-off the subjects leave the floor with the toes. Conversely, an incorrect jump was discarded and another jump repetition was repeated [26].

The Optojump photoelectric cells, which consist of two parallel bars (one transmitter and one receiver unit, each measuring

100×4×3 cm, 1.5 kg weight), were placed at the extremities of the force platform without touching it, in a parallel and horizontal position to one another at a distance of 92 cm. The transmitter contains 32 light-emitting diodes, which are positioned 0.3 cm from ground level at 3.125 cm intervals. To enable the comparison of data from both Optojump and force platform systems, the Optojump diodes were positioned at the same height as the force platform surface (approximately 12.2 cm from the ground), so as to record simultaneously FT with the two systems. Optojump bars were connected to a personal computer, and the Microgate software (Optojump software, version 3.01.0001) allowed jump height quantification. The Optojump system measured the FT of vertical jumps at 1000 Hz. In the FT method used by the Optojump tool, the vertical displacement of the COM can be calculated using a uniform acceleration equation [27]. The assumption for this calculation is that the position of the COM is the same at the beginning (take-off) and end (landing) of the jump [12]: $H = g \times t^2/8$ (Equation 1), where H is the VJH (m), t is the FT of the jump (s), and g is the acceleration due to gravity (9.81 m·s^{-2}).

The force platform (Quattro-Jump 9290AD, Kistler, Winterthur, Switzerland) of 92×92×12.5 cm size and 30 kg weight was firmly positioned on the ground to measure VGRFs during jumping (range 0-10 000 N; sampling rate 500 Hz). The force platform was connected to a personal computer, and the Kistler software (QJ software, version 1.0.9.2) allowed VJH quantification. The VJH was calculated using Quattro-Jump software through the DIF method. This DIF method requires the participant to stand still at the beginning and at the end of the jump. So, participants were instructed to "keep standing still at the beginning and at the end of the jump", otherwise the jump performance was automatically rejected by the QJ software.

Statistical analyses
Data analyses were performed using SPSS version 18.0 for Windows. Means and standard deviations (SD) were calculated after verifying the normality of distributions using Kolmogorov-Smirnov statistics. To help protect against type II errors, an estimate of effect size (d), mean differences, and 95% confidence intervals (CIs) were presented [28]. The modified Hopkins scale [29] was used for the interpretation of d; $d < 0.2$ was considered as trivial, between 0.2 and 0.6 as small, between >0.6 and 1.2 as moderate, and >1.2 as large. Paired-sample t-tests were used to detect any systematic difference (also referred to as bias) between tools (validity), test trials (reliability) and compared to the Glatthorn equation [20] (*force plate-jump height (cm) =1.02×Optojump jump height+0.29*). Concurrent (criterion-related) validity of the Optojump system was examined using intra-class correlation coefficients (ICCs) with 95% confidence intervals (CI), Bland-Altman systematic bias ± random errors using the 95% limits of agreement (LOAs) [30], and Pearson correlation coefficient (r) were also used. The relative intra-session reliability of the CMJ, CMJarm and SJ were determined by calculating the ICC$_{[1,3]}$, and the absolute intra-session reliability was expressed in terms of standard error of measurement (SEM) and coefficients of variation (CV) [15; 31]. Heteroscedasticity was assessed using correlation between the absolute residuals and vertical jump scores for each participant. To reduce heteroscedasticity, natural log transformation of raw data was performed when appropriate. Statistical significance was set at $p < 0.05$.

RESULTS
Although the ICC scores calculated for validity were very close to 1 (Table 1), a significant systematic bias was observed between Quattro-Jump and Optojump results ($p < 0.001$). In this regard, the method aiming at assessing vertical jump height through FT, with photoelectric cells (e.g. Optojump) provided lower jump heights for all jump modalities (SJ:-11.66; CMJ:-11.08; CMJarm:-14.49 cm). Therefore, those subjects producing the greatest jump heights as measured by the force platform tended also to achieve the greatest jump heights when the other methods were employed in the FT method (see Figure 1). Heteroscedasticity coefficients for SJ, CMJ and CMJarm were $r = 0.09$, $r = 0.40$ and $r = 0.32$ respectively, showing the presence of heteroscedasticity in CMJ and CMJarm modalities; therefore a logarithmic transformation was applied to the raw data to reduce heteroscedasticity. Thus, the limits of agreement are expressed as ×/÷ 95% limits of agreement within the range of ratios.

TABLE I. Concurrent validity of the method aiming at assessing vertical jump height through flight time, with photoelectric cells (e.g. Optojump) and the gold standard device (Quattro-Jump).

Variable	Optojump (cm)	Quattro-Jump (cm)	Effect size (d)	Systematic bias (95% CI) (cm)	LOA ratio /± (cm)	ICC (95% CI)	Pearson coefficient
SJ	25.95±6.22‡	37.61±6.34	8.85	-11.66 (-12.29 ; -11,04)	±1.33	0.989(0.971 ; 0.995)	0.978‡
CMJ	29.98±6.35‡	41.06±6.76	11.94	-11.08(-11.56 ; -10.61)	×/÷1.06	0.994(0.985 ; 0.998)	0.990‡
CMJarm	36.80±9.46‡	51.29±10.30	5.79	-14.49(-5.74 ; -13.25)	×/÷1.10	0.982(0.954 ; 0.993)	0.968‡

*CI = confidence interval; CMJ = countermovement jump; CMJarm= countermovement jump with arm swing; ICC = intra-class correlation coefficient; LOA = limits of agreement ratios; SJ = squat jump;‡ $p < 0.001$=difference between the two systems.
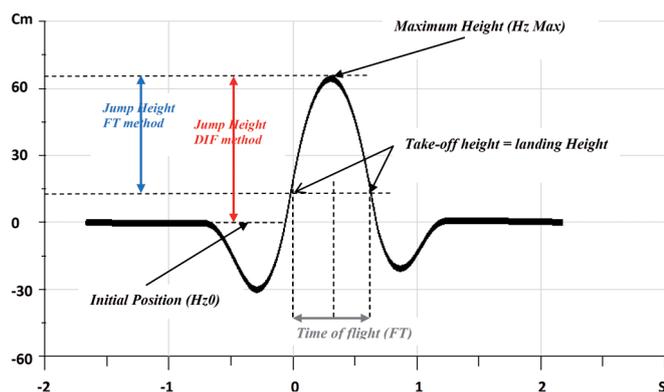
FIG. 1. Comparison of vertical jump height calculation between DIF and FT method devices.

Random error ratios/± were quite low for SJ, CMJ and CMJarm modalities (±1.33 cm, ×/÷1.06 cm and ×/÷1.10 cm, respectively) (Figure 2). Statistical power was 1 for all jump modalities (with a sample size of 20 subjects and a Pearson correlation coefficient of 0.98), and effect sizes were very large (range: 5.79-11.94).

The regression model (Figure 3), developed using the FT (e.g. Optojump) method as the independent variable, explained 96%, 98% and 94% of the variations in VJH calculated by Quattro-Jump for SJ, CMJ and CMJarm respectively. The differences in jump height between the two devices increased with increasing jumping height, as also predicted by the following linear regression equation (see Figure 3).

Table 2 compared the jump height results derived by the equations of the present study and the regression equation of Glatthorn et al. [20]. Systematic bias was observed, and our equations obtained higher jump heights in SJ, CMJ and CMJarm, when compared with Glatthorn et al. [20].

Relative and absolute reliability indices for all jump modalities recorded during trial 1 and trial 2 are summarized in Table III. The pairwise analysis revealed no significant difference between the 2-test trials for SJ, CMJ, and CMJarm ($p=0.88$, $d=0.04$ [trivial], $p=0.35$, $d=0.22$ [small], $p=0.66$, $d=0.10$ [trivial], respectively).

DISCUSSION

The purpose of the present study was to investigate the differences in jump heights gathered from flight time (FT) (Optojump) and a double integration of force (DIF) (Quattro-Jump) devices. Our results indicated that jump heights from the DIF method were significantly greater when compared to the FT method. A systematic difference (bias) was nevertheless observed between the two systems, and the Optojump tool showed the lowest degree of agreement with the reference method, underestimating systematically in the range from -14.49 to -11.08 cm (Table I and Figure 2). Therefore, the major findings of this study were that Optojump photoelectric cells are not valid based on centre of mass; they presented a systematic error and high linearity with the reference device (Quattro-Jump). Indeed, with a significant correlation and high coefficients of determination, it was possible to establish regression equations for predicting the jump height for the three jump modalities by using the Optojump. So, there was a high correlation between the two methods to estimate the vertical jump height (VJH), but the FT method cannot replace the gold standard, despite the strong agreement. These strong results were confirmed by statistical power of 1.0 for all jumps with a correlation coefficient of 0.98; nevertheless they represent excellent intrinsic reliability for the estimation of vertical jump height. In accordance with the results of other studies [8; 11], this study considered the force platform to be the gold standard tool for the estimation of vertical jump height, because in this study the highest values were observed with the DIF.

TABLE 2. Comparison and correlation of theoretical results obtained from equation by Glatthorn et al. and equation of the present article.

Variable	Equation of the present study (cm)	Glatthorn et al. (cm)	Systematic bias (95% CI) (cm)	Pearson coefficient
SJ	37.22±5.79‡	26.81±6.02	10.41(10.30; 10.52)	1**
CMJ	41.20±6.39‡	31.11±6.21	10.09 (10.00; 10.17)	1**
CMJarm	51.25±10.08‡	37.89±9.79	13.27(13.22; 13.49)	1**

Note: *CI = confidence interval; CMJ = countermovement jump; CMJarm= countermovement jump with arm swing; SJ = squat jump.‡ *p*<0.001=difference between the two formulas.** *p*<0.001.

TABLE 3. Relative and absolute intra-session reliability indices of Optojump photoelectric cells for jump height estimation.

Variable	Trial 1 (cm)	Trial 2 (cm)	Effect size (*d*)	ICC (95% CI)	SEM (cm)	CV %
SJ	26.01 ±5.91	25.95 ±6.22	0.04	0.980 (0.951 ; 0.992)	1.16	6.47
CMJ	30.22 ±6.09	29.98 ±6.35	0.22	0.992 (0.980 ; 0.997)	0.79	3.70
CMJarm	36.86 ±9.60	36.80 ±9.46	0.10	0.999 (0.997 ; 1.000)	0.45	1.76

Note: *CI = confidence interval; CMJ = countermovement jump; CMJarm= countermovement jump with arm swing; ICC = intraclass correlation coefficient; SEM = standard error of measurement; SJ = squat jump.

The differences observed between two devices (approximately: SJ: 31%, CMJ: 27% and CMJarm: 28%) was directly proportional to the absolute jump height (Figure 3). These differences can be attributed to several factors. Particularly, the jump height estimated by the FT was significantly lower than that estimated by DIF, which

is comparable to the results reported by Moir [12]. This difference is the distance between the initial height of COM (H_0) and the take-off height (Figure 1). Kistler software calculates the total positive vertical displacement of the COM, from the subject's starting position. In this way, Quattro-Jump (DIF method) was used as the cri-
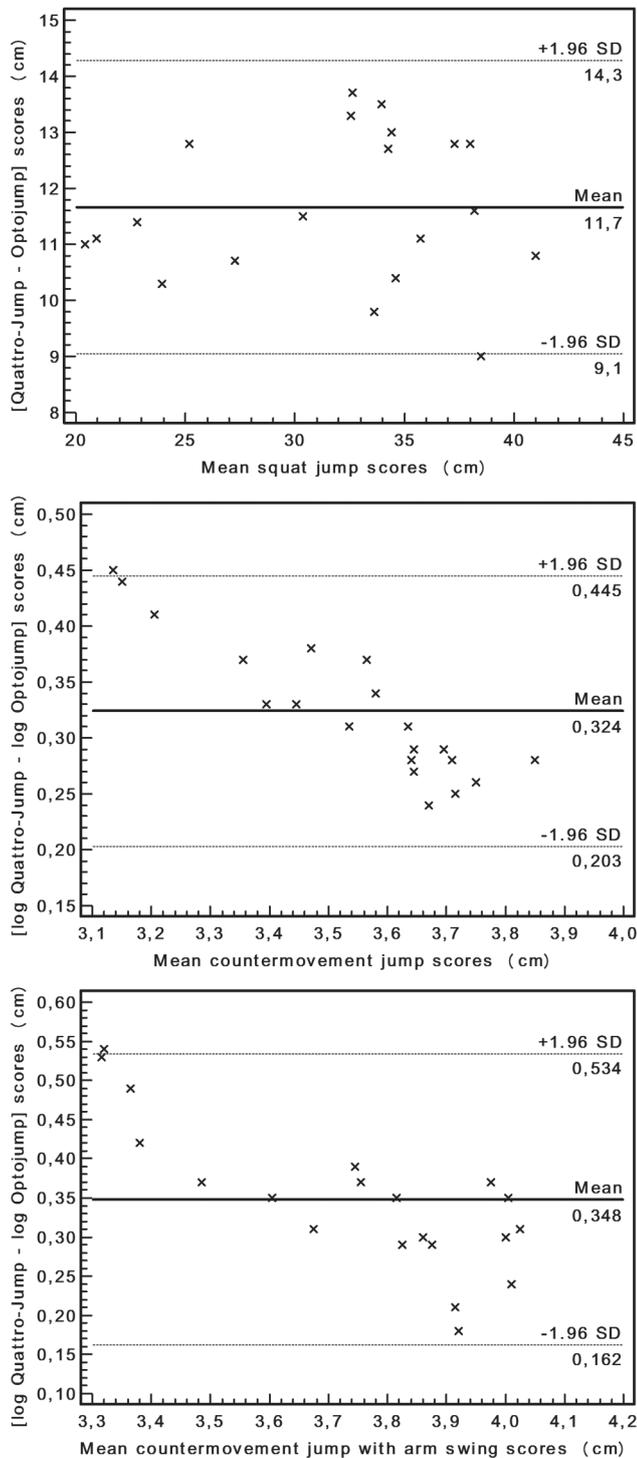
FIG. 2. Bland-Altman plota with limits of agreements between vertical jump heights (SJ, CMJ and CMJarm) measured by Quattro-Jump and Optojump.
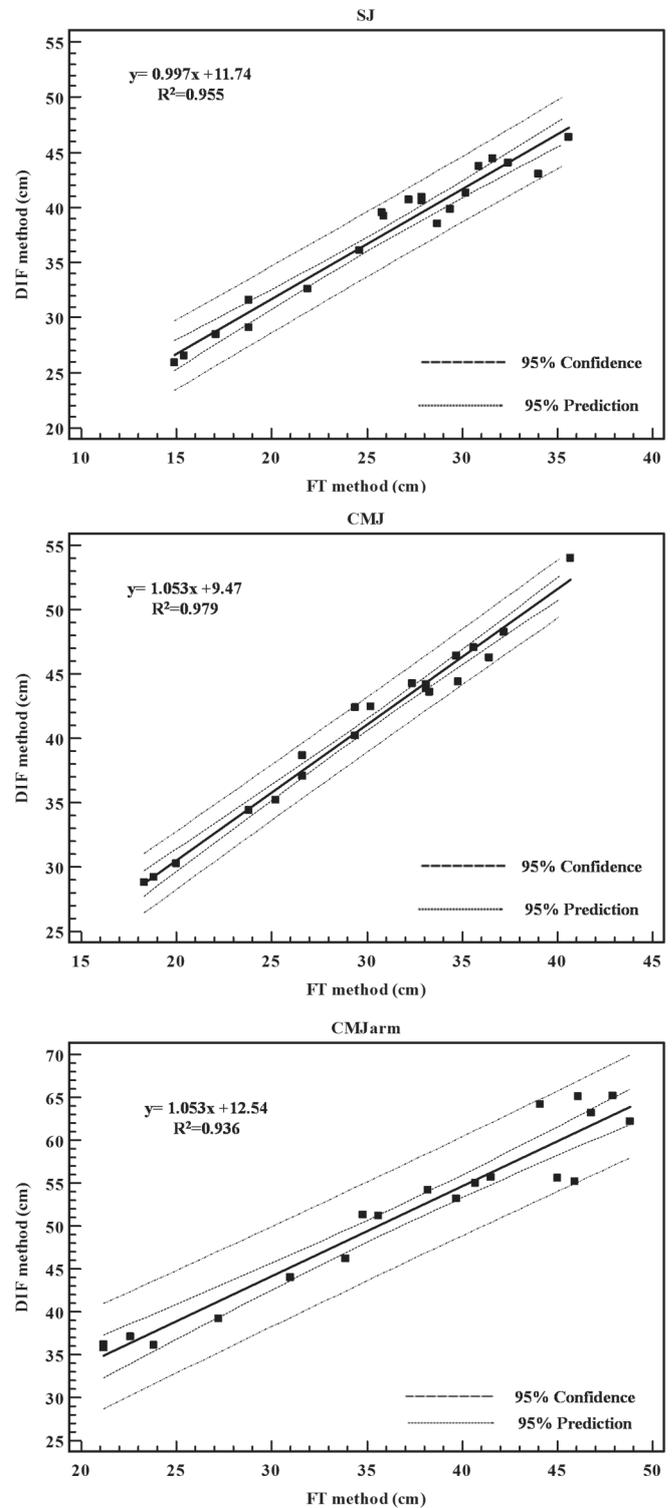
FIG. 3. Pearson correlation of jump heights (SJ, CMJ and CMJarm) between DIF and FT methods. The solid line show the linear regression fit of the two devices and regression analysis equation. Data dots represent individual jump height values.

terion measurement for jump height in this study based on the definition of jump height provided by many authors [11; 12; 32]. According to Moir [12] and Dias et al. [11], methods that consider the COM displacement before take-off obtain greater heights when compared to the methods considering only the FT. All calculation methods have logical validity, depending on the definition of jump height being used [2; 12; 33]. Since there were significant correlations and systematic error among the methods, it was possible to establish prediction equations for the Quattro-Jump performances with Optojump data. The equations obtained presented high coefficients of determination for predicting the jump height for the three jump modalities measured by the FT method (mean: $R^2=$ 0.957±0.022), as seen in Figure 3.

SJ: [(DIF method) jump height = 0.98 × (FT method) jump height +11.74].

CMJ: [(DIF method) jump height = 1.05 × (FT method) jump height +9.47].

CMJarm:[(DIF method) jump height = 1.05 × (FT method) jump height +12.54].

One has to bear in mind the critics quoted by Glatthorn et al. [20] that can give a small under-estimate of the jump height by Optojump (i.e., the differences between tools in their position or detection threshold, or both). For example, the misalignment of the photoelectric "sector" with the force platform surface plane, a small non-horizontal direction – even if care is taken to avoid it – of the Optojump rays, and the sensitivity of photoelectric cells (Optojump) vs. piezoelectric sensor (Quattro-Jump) signals could all contribute to the observed differences. The possible difference in sampling rate between methods aiming at assessing vertical jump height through FT, with photoelectric cells (e.g. Optojump) and FP systems, could not have played a role in the recorded differences as both had the same sampling rates (1000 Hz). Kibele [34] and Moir [12] suggested that the differences in their respective studies may be linked to the changes in the subject's posture during flight (between take-off and landing). This limitation in the ability to make a valid estimate of vertical jump height is frequently cited in the literature using FT because the height of the subject's COM at take-off needs to be the same as at landing, and this is quite difficult to control.

The values illustrated in Table II show that there was a significant difference of the jump height results calculated by the formula of Glatthorn et al. [20] and that of the present study. Additionally, there was a high systematic error (range: 10.09-13.27 cm) with a positive linear correlation in both studies. Despite the significant differences in jump height between the 2 devices, there was a significant correlation and a high degree of linearity of the method aiming at assessing vertical jump height through FT, with photoelectric cells (e.g. Optojump) with the method aiming at assessing vertical jump height through DIF, with a force platform (e.g. Quattro-Jump).

The variability between trials reflects the inherent variation in healthy individuals or those with pathology [13]. Inter-trial reliability of vertical jump performance is critically important to ensure that observed differences in jump height between testing trials are not due to systematic bias, such as the learning effect or fatigue, or random error due to possible biological or mechanical variations. The inter-trial ICC of SJ, CMJ and CMJarm heights obtained in the present study using the Optojump (range: 0.99 to 0.98) were in agreement (ICC: 0.95) with those reported by Nuzzo et al. [35] measured with a Myotest accelerometer. The SEM is not affected by inter-subject variability [36] and provides an estimate of measurement error. In addition, if data are homoscedastic, which was the case in the current study (SJ: $r=0.03$; CMJ: $r=-0.02$ and CMJarm: $r=0.13$), SEM analyses may be more useful to establish absolute reliability [37]. In heteroscedastic data, coefficient of variation (CV) analyses are recommended [37]. According to Hopkins (2000) [29], SEM is best expressed as CV (percentage of the mean). In this study, SEM was for SJ, CMJ and CMJarm 4.47, 2.62 and 1.22% respectively, which was below the reference value of 5% suggested as a limit of difference between any two performances for the same test [33; 38]. The test-retest CVs of SJ, CMJ and CMJarm heights obtained in the present study were in the range 1.76-6.47%, which were similar to the findings reported by Nuzzo et al. [35].

Finally, we concluded that although the method aiming at assessing vertical jump height through FT, with photoelectric cells (e.g. Optojump), had logical validity, it presented a systematic error and high linearity with the reference device force platform (e.g. Quattro-Jump), which meant that the FT method cannot replace the gold standard, despite the strong agreement. Indeed, the principle of calculation of Quattro-Jump, based on double integration of the force from the recording of the VGRF, allows one to control the evolution of COM over time. However, the Optojump tool relies on benchmarking time of flight to estimate the jump height. Thus, it is possible to predict vertical jump height by means of the regression equations proposed, with a high degree of determination, allowing Quattro-Jump and Optojump to be employed. Also, the comparison between the jump height results calculated by the equations of this study and that of Glatthorn et al. [20] showed that the latter one underestimated the vertical jump height; the differences were SJ: 31%, CMJ: 27% and CMJarm: 28%.

CONCLUSIONS

Based on this study, the method aiming at assessing vertical jump height through FT, with photoelectric cells (e.g. Optojump) has a strong agreement with the DIF method (gold standard), but is not valid. The Optojump photoelectric cells had an excellent inter-trial reliability for the assessment of vertical jump height. Thus, they can be used with confidence to detect between-group differences in cross-sectional comparisons [39; 20]. The height of the jump has to be defined (before discussing the performances), as it varies according to the benchmarking tool. Considering that measuring the vertical jump height, in most cases, should be done in a practical and objective manner in the field of sports, FP seems to be too costly and impractical and more expensive. Therefore it will be much more

practical to use the method aiming at assessing vertical jump height through FT, with photoelectric cells (e.g. Optojump) to measure the height of the jump. The prediction equations suggested in this study may allow the use of Optojump by coaches to measure the vertical jumping performances, corrected by the linear regression equation specific for each jump modality.

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