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Original Article

Single marker method to estimate center-of-mass velocity during vertical jumps

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Abstract
Problem statement: Center-of-mass (CoM) analysis of takeoff speeds in jumps preceded by run-ups (such as volleyball spike jumps), using a force platform, requires prior information on CoM speed at touchdown. This, however, can only be evaluated through kinematic methods (KIN). To this end, KINs must be evaluated for accuracy and concurrent validity. An example is a double integration of force (DIF) method for jumps in which the initial CoM speed is zero in countermovement jumps with and without arm swing. **Aim:** To evaluate the reliability and accuracy of three methods for calculating takeoff velocity and their concurrent validity during vertical jumps. **Material and methods:** Fifteen female volleyball players performed 10 vertical countermovement jumps (CMJ), and 10 countermovement jumps with arm swing (CMJa). Two methods were used to measure CoM takeoff velocity: (1) numerical DIF and (2) full-body 3D model (KIN). The latter was implemented using two minimalist marker setups between the right anterior and posterior iliac spines (RASI) and (RPSI), respectively.**Results:** KIN and DIF were more reliable in all jumps (ICC: 0.93-0.96) than minimalistic methods (ICC: 0.87-0.93). The standard error of measurement was lower in KIN and DIF (SEM mean= 1.9) than in minimalistic methods (SEM mean= 3.1). KIN was valid regarding DIF in CMJ, with bias equal to zero, no proportional bias (p=0.514), and narrow limits of agreement (LoA) (0.1 m/s). KIN was also valid in CMJa (bias = 0.01 m/s), with no proportional bias (p=0.244), LoA =0.21 m/s. The minimalist RPSI method was valid only in CMJ (bias= -0.12m/s), with no proportional bias (p=0.27), LoA=0.31 m/s. The RASI method showed a bias difference compared to DIF (p=0.001) and was not valid with either jump types. A large displacement of the pelvis may lead to increased errors using a single marker. **Conclusions:** All procedures were reliable and accurate, but minimalist marker setups decreased the values. The KIN method using a Plug-in-Gait model was valid in both jumps. Minimalist marker setups with a single marker at RPSI may be applied only in CMJ. Minimalist marker setups with a single marker may also lead to controversial results depending on the pelvis's jump type and marker position. These possibilities should be considered to calculate takeoff and touchdown velocities during volleyball spike jumps.
Keywords: Reliability; Accuracy; Validity; Countermovement jump; Minimalist marker models.

Introduction

The main methods for evaluating the performance of jumps starting from static positions and using a force platform are double integration of force (DIF) and kinematic (KIN) methods, which include an anthropometric model to assess center-of-mass (CoM) position. To analyze CoM takeoff speed in jumps preceded by run-ups (such as volleyball spike jump) using a force platform requires prior information on CoM speed at touchdown. To estimate CoM position and speed, the kinematics method uses an anthropometric model defined from anatomical body landmarks and inertial characteristics of their segments (Cicchella, 2020).

In the kinematic model, each body segment is defined using at least three external markers attached to the skin (Erdmann & Kowalczyk, 2020). Therefore, to track full-body movements with 14 body segments, at least 39 markers are required. Such a time-consuming process can lead to task constraints. In this sense, one strategy is to use a setup with fewer body markers, speeding up data collection by reducing risks of marker blockage or fall during movement (Napier et al., 2020). Minimalist marker setups have already been used for many tasks in studies. A few of them have used skin markers as representative of CoM only at the lower limbs (Chowning et al., 2021), some at the center of the pelvis (Sheppard et al., 2011), and others one at the sacral region (Ranavolo et al., 2008). These are commonly used for human running and gait but rare for jumping (Gill et al., 2017). On the other hand, few markers seem to decrease the accuracy of the kinematic method. Halvorsen *et al.* (2009) estimated the trajectory of the CoM during running with thirteen segments and thirty-six markers. They compared this model with ten other options, the same model, decreasing the number of markers until reaching a

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single marker at the sacrum. The results showed that a model with up to ten markers showed reasonable accuracy compared to the whole-body model, while the worst values occurred when only one marker at the sacrum. In this sense, Vanrenterghem *et al.* (2010) measured the displacement of the CoM inside cutting maneuvers comparing a whole-body model with four models: two partials, using only the lower limb, lower limb together with the trunk, and two using only one marker in the posterior iliac spine and the eighth thoracic vertebra spinous process. These authors reported that using only the lower limb showed low agreement and accuracy than the full-body model but higher than using only one marker at the pelvis. Despite this, the heel has different motor characteristics, and so far, no studies have been reported the reliability, accuracy, and concurrent validity of minimalist kinematics models in jumps. For a marker method to be suitable for vertical jump analysis, it must be the most simple, convenient, and economical for studies with higher numbers of individuals and jumps and when a force platform cannot be used.

To evaluate spike jumps using a single force platform, CoM touchdown velocity should be known, which can only be obtained by a kinematic method (KIN). Thus, a KIN method's accuracy and concurrent validity may be verified using a DIF method in jumps where the initial CoM speed is zero, such as countermovement jumps with and without arm swing. This information can be applied later to jumps where the initial speed is not zero, such as volleyball spike jumps (Fuchs et al., 2019). Although some studies have reported high reliability between DIF and KIN methods, the same methods have shown differences (Aragón et al., 2000; Dias et al., 2011). Recent studies have compared several methods for evaluating vertical jumps, mainly with low-cost equipment (Blosch et al. 2019; Pueo et al.; 2020; Watkins et al., 2020). Most of them have reported high reliability and validity, nonetheless, not tested in minimalist kinematics models.

Given the above, our study aimed: (a) to evaluate the reliability and accuracy of different methods in jump tasks and (b) to determine the concurrent validity of two minimalist kinematic setups. We hypothesized that kinematic models would show reliability, accuracy, and concurrent validity with the gold standard method.

Methods

Participants

Participants were fifteen experienced female players of the first Austrian volleyball league (age: 19.85±3.4 yr, body height: 1.79±0.07 m, body mass: 70.4±7.1 kg, training experience: 8.36±3.89 yr, training per week: 11.6±2.1 h). The participants took part in the experimental protocols on a single day and were healthy, reasonably physically active, and right-handed. No athlete reported injuries or disabilities during the time of the study. The Salzburg University ethics committee approved the research protocol complying with the Declaration of Helsinki, and all participants reviewed and signed informed consent before participation.

Experimental protocol

After a 5-minute warm-up consisting of jogging with self-paced moderate velocity and three submaximal CMJs, each subject performed ten CMJs with and without arm movement in randomized order, with a 2-minute recovery interval between trials. The individuals remained stationary on both feet in a parallel position and initiated the jump after a verbal command of "Go" given when the bodyweight components measured by two force platforms were equal. The athletes were instructed to jump as high as possible.

Measurement devices

Thirty-nine reflective markers were placed on bony landmarks, and a Vicon 3-D motion capture system (Vicon Peak, Oxford, UK) was used. Eight cameras (250 Hz) were used to calculate CoM displacement through a Plug-in-Gait model (Vicon, Oxford Metrics, Ltda., UK). Kinematic data were calculated by visual3D™ software, v.5 (C-Motion, Inc., Rockville, MD). Two AMTI™ force platforms (BP-800400, Watertown, MA, USA), mounted side-by-side, registered each leg's vertical ground reaction forces separately at a frequency of 1 kHz (50-Hz, fourth-order, zero-lag Butterworth low-pass filter implemented in the software DASYLab™ 11.0).

Methods for Jump Height Estimation

The methods to estimate jump takeoff velocity comprised impulse-momentum theorem, which allowed calculating CoM takeoff velocity to jump by double numerical integration of force (DIF) (Toft et al., 2019) as a gold standard. Kinematic models to calculate V_{off} were: a) KIN using the Plug-in-Gait model (Fuchs et al., 2019 – b), right posterior iliac spine (RPSI) as a landmark closer to the sacrum, and right anterior iliac spine (RASI) as part of the Plug-in-Gait model (Figure 1). All valid jumps were computed, and averages were chosen because they are similar when using the highest jump (Claudino et al., 2017).

Data analysis and statistics

Descriptive statistics and the Kolmogorov-Smirnov test for normality were applied. As no significant deviation from normal distribution was detected ($p>0.05$), reliability was determined by an intraclass correlation coefficient (ICC1,1). Attempts were considered in pairs, combining the first with the second, the third with the fourth, and so on until the tenth, resulting in five pairs for each athlete. Accuracy was verified by group variability through the standard error of measurement (SEM), calculated by the root mean square error obtained by ANOVA one-way for all attempts (Werner et al., 2019). Concurrent validity among the models was determined by: (a) calculating bias (average difference between the tested and reference procedures); (b) stating bias probability as being equal to zero by t-test (one sample); (c) checking how bias (mean) was close to zero by the Bland-Altman plot analysis (Doğan et al., 2018) and if distribution data were within the agreement limits; (d) assessing proportional bias by linear regression (y = a + bx).

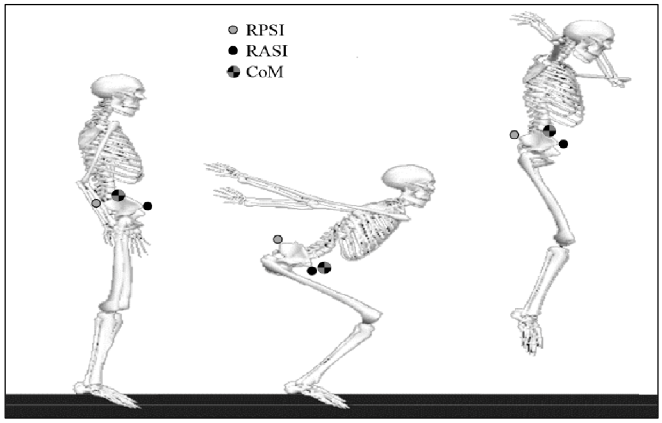

Figure 1. Kinematic models used to calculate jump takeoff velocity: CoM calculated by Plug-in-Gait model, RPSI at right posterior iliac spine and RASI at right anterior iliac spine.

Results

Table 1 shows the averages and standard deviations of takeoff velocity for all methods. The ICC showed that all methods had excellent reliability for CMJ, and only DIF and KIN for CMJa, while RASI and RPSI showed only good reliability. The SEM was greater in CMJa than was in CMJ.

Table 2 shows no significant difference in takeoff speed bias between DIF and KIN ($p \leq 0.05$) for CMJ and CMJa and no difference between DIF and RPSI ($p \leq 0.05$) for CMJ. Figure 2 shows a comparison between methods using the curves of one athlete. Figures 3 to 5 show Bland-Altman plots comparing kinematic methods and the gold standard (DIF).

Table 1. Measures of takeoff velocity in countermovement jump calculated by different methods.

Countermovement jump	Mean (m/s)	S. D.	ICC	*p*	SEM
Without arm swing (CMJ)					
Based on double numerical integration of vertical reaction force (DIF)	2.368	0.150	0.96	0.001	1.7
Based on a kinematic full-body model (KIN)	2.370	0.120	0.95	0.001	1.8
Right anterior iliac spine (RASI)	2.515	0.157	0.91	0.001	3.5
Right posterior iliac spine (RPSI)	2.503	0.180	0.93	0.001	2.4
With arm swing (CMJa)					
Based on double numerical integration of vertical reaction force (DIF)	2.488	0.175	0.96	0.001	2.1
Based on a kinematic full-body model (KIN)	2.432	0.171	0.93	0.001	2.2
Right anterior iliac spine (RASI)	2.662	0.231	0.87	0.001	3.9
Right posterior iliac spine (RPSI)	2.596	0.217	0.89	0.001	2.9

Note: S. D.: Standard deviation; ICC: Intraclass Correlation Coefficient; SEM: Standard error of the mean (%).

Table 2. Bias difference of takeoff velocity in countermovement jumps based on double numerical integration of vertical reaction force between methods.

Countermovement jump	Sig.
Without arm swing (CMJ)	
Based on a kinematic full-body model (KIN)	0.889
Right anterior iliac spine (RASI)	0.001
Right posterior iliac spine (RPSI)	0.538
With arm swing (CMJa)	
Based on a kinematic full-body model (KIN)	0.629
Right anterior iliac spine (RASI)	0.001
Right posterior iliac spine (RPSI)	0.004

Note: Sig: p-value for differences in bias

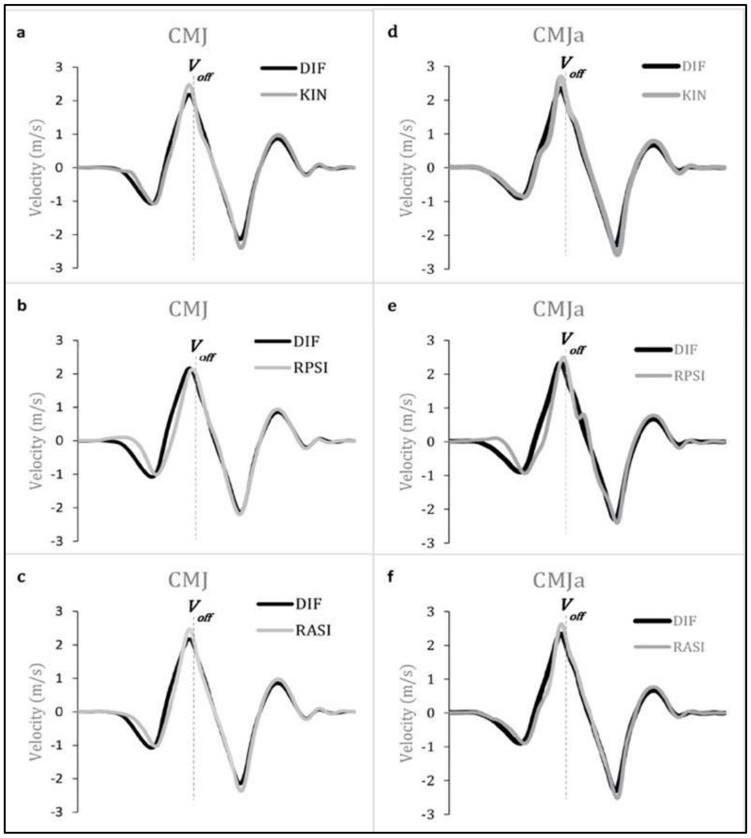

Figure 2. Curves of takeoff velocities in CMJ from one athlete comparing (a) DIF and KIN, (b) DIF and RPSI, (c) DIF and RASI; and of takeoff velocities in CMJa comparing (d) DIF and KIN, (e) DIF and RPSI, (f) DIF and RASI. Dotted lines represent the takeoff moment in jumps.

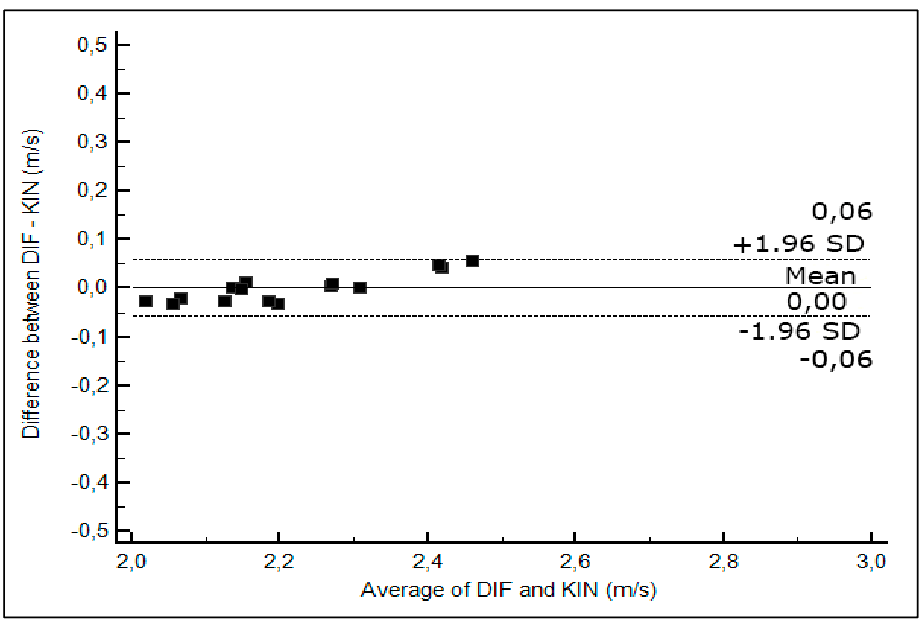

Figure 3. Bland-Altman plot showing the differences between methods (DIF vs. KIN) in CMJ. Note: Mean = bias, DIF = method based on double numerical integration of vertical reaction force, KIN = method based on the kinematic full-body model.

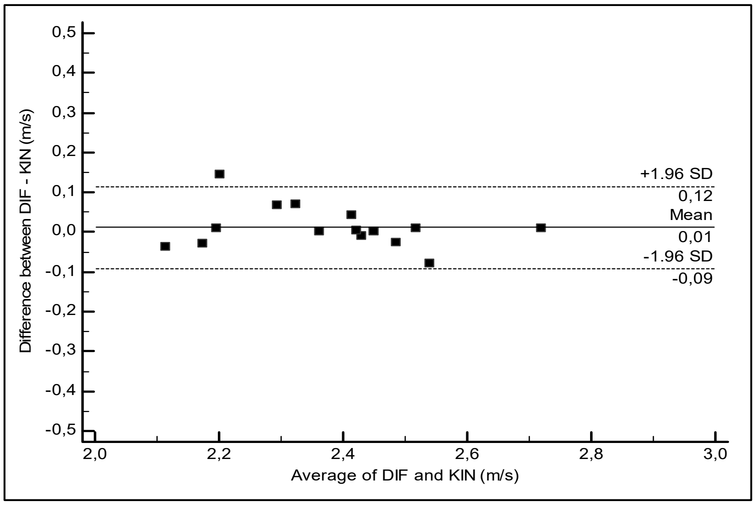

Figure 4. Bland-Altman plot showing the differences between methods (DIF vs. KIN) in CMJa. Note: Mean = bias, DIF = method based on double numerical integration of force, KIN = method based on kinematic full-body model.

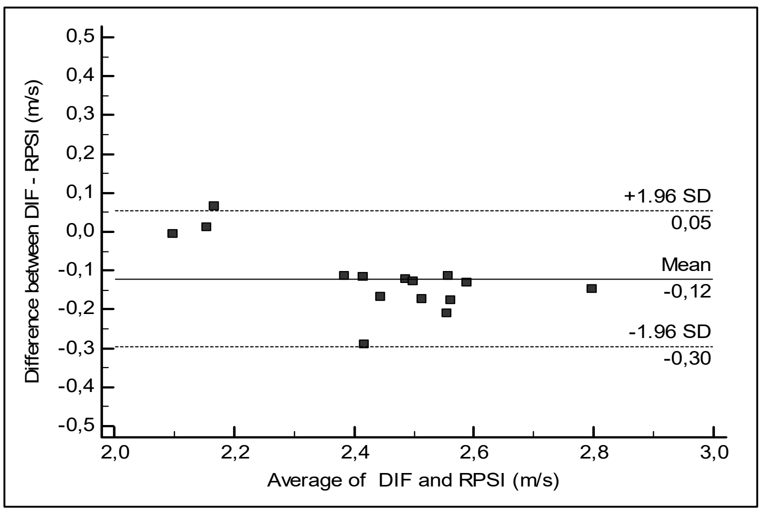

Figure 5. Bland-Altman plot showing the differences between methods (DIF vs. RPSI) in CMJ. Note: Mean = Bias, DIF = method based on double numerical integration of force, RPSI = method with a marker at right posterior iliac spine.

Table 3 shows the result of the bias proportionality assessment through a linear equation. DIF and KIN showed no proportional bias for takeoff velocities in CMJ and CMJa ($p \leq 0.05$). Despite the minimalist marker setup, only RPSI presented no proportional bias, indicating agreement with DIF in CMJ ($p \leq 0.05$).

Table 3. Proportional bias of takeoff velocities among the methods DIF, KIN, RASI, and RPSI.

Countermovement jump	Sig. for takeoff velocity
Without arm swing (CMJ)	
Based on a kinematic full-body model (KIN)	0.514
Right anterior iliac spine (RASI)	0.001
Right posterior iliac spine (RPSI)	0.270
With arm swing (CMJa)	
Based on a full kinematic body-model (KIN)	0.244
Right anterior iliac spine (RASI)	0.001
Right posterior iliac spine RPSI)	0.001

Note: DIF: a method based on double numerical integration of vertical reaction force; KIN = method based on kinematic full-body model. RPSI = method with a marker at right posterior iliac spine.

Discussion

This study aimed to evaluate the reliability and accuracy of different methods available to assess jump tasks and determine the concurrent validity of two minimalist kinematic setups. Although jump height is the main performance criterion in vertical jumps, takeoff speed was the variable of interest in our study because it is more beneficial in jumps with different speeds, such as volleyball spike jumps. However, jump heights can be calculated from takeoff velocities using a simple equation. Some studies have considered KIN as the "gold standard" technique for jump analysis (Rago et al., 2018), even though it disregards body position changes during jump takeoff and landing and rigid segments in the body. Other studies have shown that the use of KIN may lead to calculation errors in jump height (Moir et al., 2008; Street et al., 2001). In the DIF, the force-time curve represents CoM displacement without interference from segment positions. Previous researchers have used the DIF method as a gold standard to validate procedures (Jiménez-Reyes et al. 2017; Ayán-Pérez et al., 2017).

Takeoff speed by the KIN method showed high reliability and precision, corroborating other studies (Aragón et al.; 2000; Słomka et al., 2017). Nevertheless, a minimalistic marker setup decreased reliability and SEM values, as observed in previous studies during running and lateral movements (Napier et al., 2020; Vanrenterghem et al., 2010, respectively). However, our study showed a slight reduction in the reliability of the RASI and RPSI models. A greater precision may be related to the model complexity (number of markers). Our study's single marker setups overestimated takeoff velocity compared to the DIF, as reported in a previous study (Ravanolo et al., 2008). Our results also show that the RASI method had higher takeoff velocities both in CMJ and CMJa, but lower than those from the RPSI in CMJ. At the initial position for the jump, the markers were positioned anteriorly and posteriorly to the CoM in the RASI and RPSI methods, respectively. Therefore, pelvic retroversion during takeoff moved the RASI upwards, increasing the takeoff speed compared to the DIF method. Likewise, the RPSI marker moved downwards in hip retroversion, reducing the increase in takeoff speed. The greater amplitude between trunk and hip joint during CMJa increased speeds in the RASI and RPSI compared to those in the DIF (Argaud et al., 2019).

When compared to the DIF method, KIN showed to be a valid method for CMJ and CMJa. This result disagrees with the findings of Aragón et al. (2000) and Moir et al. (2008), which may be due to model differences. Indeed, the referenced authors used a model wherein head, arms, and trunk (HAT) are taken as a single segment. Such an arrangement could increase errors between CoM positions (and hence takeoff velocity) if compared to the DIF method, as previously reported (Street et al., 2011). On the other hand, our results were like those reported by Palazzi et al. (2013), who used the same model as ours (Plug-in-Gait). In this sense, newer models seem to be more accurate, especially for the trunk segment. Minimalist methods showed controversial results regarding jump types and marker positions at the pelvis. DIF and RPSI were valid for CMJ, with the bias being lower than a single marker at the sacrum (Ranavolo et al., 2008). The same bias values were observed in jumps with direction changes (Vanrenterghem et al., 2010). When comparing different procedures, we must consider the different motor tasks to be performed without expecting similar results.

RASI was not valid with the KIN method for CMJ. As previously stated, the RASI marker showed to be very susceptible to pelvic inversion and retroversion movements. For CMJa, both RASI and RPSI showed proportional bias, which invalidates these procedures. Body trunk stretches faster and earlier in CMJa than in CMJ (Feltner et al., 1999). By speeding up CMJa, the impulse generated increases, and so does the takeoff velocity (Vaverka et al., 2016), without affecting the total time of jumps. The more the torso and hips move, the more the pelvic movement increases, which can overestimate RPSI and RASI velocities compared to the DIF method.

Since the DIF method is a gold standard, the KIN method has an excellent solution in analyzing both jumps. However, minimalist models use a single marker on the pelvis and have decreased reliability and accuracy compared to the DIF. Therefore, they (RPSI) can be used only in CMJ. A single marker for CoM position estimation may present controversial jumps type and marker position on the pelvis.

Conclusion

In conclusion, all procedures were reliable and accurate, but reliability and accuracy decreased when minimalist marker setups were used. The KIN method using a Plug-in-Gait model was valid in both CMJ and CMJa. However, minimalist marker setups with a single marker at RPSI can be applied only in CMJ. The single marker RASI method was not valid to estimate the CoM takeoff velocity during both CMJ and CMJa.

Minimalist setups with a single marker may also lead to controversial results, depending on the pelvis's jump type and marker position. A single marker at RPSI to evaluate CMJ can be used in assessments that do not occur in the laboratory or when force platforms or 3D kinematic systems are unavailable. Future studies in volleyball spike jump may use this methodology to measure the jump performance using force platforms. Since a run precedes spike jumps, the touchdown speed could be calculated using a single marker method.

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