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On the estimation of centre of gravity height in vertical jumping

Introduction

Vertical jumps such as counter movement jump from upright standing position (CMJ), squat jump from resting squat position (SJ) and drop jump from different drop heights (DJ) represent one of the most applied test methods to mirror jumping abilities in game sports (Kollath, Merheim, & Jedrusiak-Jung, 2015; Faude, Schlumberger, Fritsche, Treff, & Meyer, 2010; Vetter & Ferrauti, 2006), athletics, gymnastics (Battaglia et al., 2014) or in fitness testing (Schiltz et al., 2009; Ulbricht, Fernandez-Fernandez, & Ferrauti, 2015). In the past, vertical jumping tests were executed as jump and reach tests (Bui, Farinas, Fortin, Comtois, & Leone, 2015). After the introduction of electrical powered contact pads in the 1960s the maximum height in jumping exercises was mostly calculated from flight time between take off and drop down registered by contact pads (Kollath et al., 2015) or light bar arrays (Erculj, Blas, & Bracic, 2010; Battaglia et al., 2014). The rapid progress in the field of force sensor technology and electronic measurement data processing nowadays enabled a fast and accurate estimation of the maximum jumping height based on integration of vertical ground reaction force. Unfortunately, available and not very expensive modern measurement tools are not used everywhere when top level athletes are tested. Many successful athletes and teams such as the German Football Association (Faude et al., 2010; Kollath et al., 2015), the German Tennis Federation (Ulbricht et al., 2015), the German Volleyball Federation (Vetter & Ferrauti, 2006) and national Basketball teams in several countries (Schiltz et al., 2009; Erculj et al., 2010) still use the flight time method to test the performance in vertical jumping, although systematic error sources and the low precision of test results based on flight time measurement are well known and indisputable. Currently there is no reliable data that allows a comparison of the different methods for jumping height determination.

The purpose of this study was to demonstrate the large errors using the flight time method (FT) and the impulse method based on the energy conservation law (IMP) for estimation of the height of the center of gravity (CG) in vertical jumping and to encourage practitioners to use the vertical ground reaction force to evaluate the performance in vertical jumping. Besides this a new method will be presented to calculate jumping height in SJ and DJ, where the initial conditions at the beginning of acceleration and of touch down, respectively, are difficult to estimate. The initial conditions at touch down of drop jumps, for instance, cannot be calculated from the height of fall (drop height), since the jumpers are not able to start the fall exactly from the height of the platform at the beginning of fall down.

Material and methods

Participants and experimental setup for kinematic analysis

During this study 15 well trained men (age 29.0 ± 4.7 years, body height 1.82 ± 0.11 m, weight 78.8 ± 8 kg) were asked to perform vertical jumps of different types (CMJ, SJ and DJ). After preparation with 47 infrared (IR) reflex markers (plug in gait model according to Davis, Õunpuu, Tyburski, & Gage, 1991), the subjects performed four maximal jumps of each type starting and finishing at a resting upright position. There were no restrictions relating to prelude or arm movement. The trials were accepted as valid if the vertical force showed a constant baseline at body weight of the subjects over 1–2 s both before the initial movement in the CMJ and before the take off in the SJ and at the end of the jumps after drop down. The highest jump of each type and of each subject was used for comparison and statistical analysis.

The motion kinematics of the body limbs were analysed with an automatic marker tracking System (Vicon, Oxford, UK) based on 10 synchronized IR cameras (type T20S) with 2 Megapixel resolution. To evaluate the computed maximum jumping heights measured by the different methods, the maximum CG height calculated from kinematic data was chosen as golden standard. For this purpose, the CG of each subject was calculated from three-dimensional (3D) limb coordinates according to Zatsiorsky (2002).

Estimation of CG height based on ground reaction force

In addition to 3D kinematic analysis, the 3D ground reaction force was recorded with a 40 × 60 cm force plate (type 9281E, Kistler Instruments GmbH Winterthur, SUI). For the evaluation and analysis of drop jumps, a second force plate was mounted on a base with a variable height to register the 3D ground reaction force at take off to the drop (60 × 90 cm force

Table 1 Names of the variables used for calculations described in the text	
CG	Center of gravity
h_0	Height of CG at the beginning of the jump
h_{max}	Maximum height of CG (flight height)
z_0	Height of CG at the beginning of drop jumps (drop height)
h_{End}	Height of CG at the end of the jump (at upright standing)
$v_{z,0}$	Vertical velocity of CG at the beginning of the movement
$v_{z,TO}$	Vertical velocity of CG at take off
$v_{z,End}$	Vertical velocity of CG at the end of the jump
t_0	Time at start of integration
t_{End}	Time at end of integration
t_{TP}	Time at lower turning point
t_{TO}	Time at take off
t_{rise}	Rise time
t_{fall}	Time of free fall
t_{flight}	Time of flight
g	Gravitational constant
m	Mass
F_Z	Vertical ground reaction force
F_G	Weight force

plate, type 9287C, Kistler Instruments GmbH Winterthur, SUI).

The signals of both force plates were recorded at a sample frequency of 2000 Hz together with IR camera pulse so that kinematics and force data could be synchronized at the first frame of Vicon data.

Comparison of three different methods to evaluate the maximum jump height

Three methods for the estimation of maximum jumping height were compared to the results of 3D kinematic analysis (for abbreviations see **Table 1**):

1. Flight time method: based on the time t_{flight} between take off and drop down:

$$h_{max} = \frac{g \cdot t_{flight}^2}{8} \quad (1)$$

2. Impulse method: based on the take off velocity $v_{z,TO}$ calculated from $F_z(t)$:

$$v_{z,TO} = \frac{1}{m}\int_{t_0}^{t_{TO}} (F_z - F_G)\, dt + v_{z,0} \quad (2)$$

$$h_{max} = \frac{v_{z,TO}^2}{2g} \quad (3)$$

3. $h(t)$ Calculated with a double integration of $F_z(t)$:

$$v_z(t) = \frac{1}{m}\int_{t_0}^{t_{TO}} (F_z - F_G)\, dt + v_{z,0} \quad (4)$$

$$h(t) = \int_{t_0}^{t_{TO}} v_z dt + h_0 \quad (5)$$

Example of the calculation and statistical analysis

In the following, the calculation procedures to determine the maximum CG height according to the three methods mentioned above, are demonstrated using an example of a counter movement jump. The registered time course of the vertical ground reaction force is the starting point of every calculation. The flight time t_{flight} is defined between take off (force decline to zero) after support phase and touch down (force rise from zero) after the flight phase. The physical basis for the flight time method is the equation of motion for vertical throws. According to this law the calculation based on the following equations, assuming that rise time and the time of the free fall after maximum CG height is equal:

$$t_{rise} = t_{fall} = 0.5 \cdot t_{flight} \quad (6)$$

$$z(t_{fall}) = -\frac{g}{2} \cdot t_{fall}^2 + v_0 \cdot t_{fall} + z_0 \quad (\text{with } v_0 = 0\,\mathrm{ms}^{-1} \text{ and } z_0 = 0\,\mathrm{m}) \quad (7)$$

$$h_{max} = \left| -\frac{g}{2} \cdot \left(\frac{t_{flight}}{2}\right)^2 \right| = \left| \frac{-g \cdot t_{flight}^2}{8} \right| \quad (8)$$

With measured $t_{flight} = 0.566$ s it arises as a result for jumping height:

$$h_{max} = \left| \frac{-g \cdot t_{flight}^2}{8} \right| = \left| \frac{-9.81\,\mathrm{ms}^{-2} \cdot (0.566\,\mathrm{s})^2}{8} \right| = 0.393\,\mathrm{m} \quad (9)$$

The impulse method is based on the law of conservation of energy, according to which the potential energy at the maximum height during the flight phase is identical to the kinetic energy of the jumper at take off:

$$m \cdot g \cdot h_{max} = \frac{m}{2} \cdot v_{z,TO}^2 \quad (10)$$

One can calculate the height of the CG after leaving the ground when the take off velocity $v_{z,TO}$ is known:

$$h_{max} = \frac{v_{z,TO}^2}{2g} \quad (11)$$

The maximum CG height can be calculated by integrating the vertical ground reaction force $F_z(t)$ up to the time of take off assuming that the initial velocity at the beginning of the CMJ at resting upright stand is zero ($v_{z,0} = 0\,\mathrm{ms}^{-1}$).

With the calculated $v_{z,TO} = 2.72\,\mathrm{ms}^{-1}$ the maximum CG height totals 0.377 m.

The maximum CG height can also be estimated by calculating the CG trajectory using a double integration of vertical force time course (Eqs. (4) and (5)). This method provides the entire velocity time profile of the CG motion as an intermediate result. Starting from $v_z(t)$ the CG path can be calculated relative to the initial position at upright standing. To this end it is useful to set the starting point to zero ($h_0 = 0$ m) (**Figs. 1 and 2**).

$$v_{z,TO} = 2.72\,\mathrm{ms}^{-1}$$
$$h_{max} = 0.564\,\mathrm{m}$$

Finally, the calculated maximum CG heights h_{max} of the example jump estimated by different methods can be compared:

- FT: $h_{max} = 0.393$ m
- IMP: $h_{max} = 0.377$ m

- INT: $h_{max} = 0.564$ m
- 3D kinematic analysis: $h_{max} = 0.568$ m

For statistical analysis, mean differences were tested using the paired-sample t-test with Bonferroni correction. Alpha was set at $p \leq 0.01$ for all analyses.

Determination of the initial values for squat and drop jumps

For the CMJ, it can be shown that the double integration of the ground reaction force is the most effective method to determine the maximum CG height of jumping exercises. However, this method includes a process-related problem. Only changes of variables can be determined by means of integration. The true value can only be calculated explicitly on the basis of the integral with consideration of the initial value. For vertical jumps, these initial values are the vertical CG velocity and the CG height at the beginning of the integration. The start of the integration is usually set to a point of time t_0 shortly before the jump starts. As already described, the initial values for a CMJ, starting from a stationary and well-defined position (upright standing), are sufficiently defined: $v_{z,0} = 0\,\text{ms}^{-1}$ and $z_0 = 0$ m.

The definition of the CG height in the upright standing position as zero is very useful for further interpretation of the calculated results. In most cases the focus of jumping tests is more directed on the difference of the CG height to the baseline at upright standing than on the total maximum CG height in relation to the ground. The double integration delivers directly amplitude and velocity of the prelude motion of a CMJ, by setting the upright standing as baseline. The CG position in upright standing is an individual constant depending on the anthropometry of the subject. If the total CG flight height is requested, the real initial CG height can be easily set as a constant value.

Unlike with the CMJ, determining the initial height and initial velocity of SJ and DJ is a greater issue. The DJ will be considered first. The approximation inferred from the drop height based on the energy conservation law on the impact velocity

Abstract · Zusammenfassung

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Abstract

The purpose of this study was to compare three different methods for the estimation of vertical jump height and to reveal errors in maximum height of the centre of gravity (CG) that emerged. Additionally, the problem of initial values, which are difficult to estimate for squat jumps and drop jumps, was addressed by suggesting a new method for the calculation of CG height of squat and drop jumps. To evaluate and compare the methods used to examine the vertical jump performance, 15 men performed four maximal vertical jumps of three different types: counter movement jump (CMJ), squat jump (SJ) and drop jump (DJ). Kinematic data and the vertical ground reaction force were recorded. Three methods were used for the evaluation of the jumps: flight time method (FT), impulse method based on the energy conservation law (IMP) and the double numerical integration of the ground reaction force (INT). The maximum CG height calculated from three-dimensional (3D) kinematics using automatic infrared (IR) marker tracking (Vicon [Oxford, UK], Plug in Gait model, Davis et al., 1991) was used as reference (golden standard). The results of the 3D kinematic analysis and the double integration of the vertical reaction force did not show significant differences. The jump heights determined by IMP and by FT were too low in relation to the real jump height due to the absence of the CG height at take off. Besides this, the flight time can be manipulated by the jumper, meaning that the flight time method is not suitable for CG height estimation of vertical jumps in scientific studies.

Keywords

Vertical jump · Maximum height · Ground reaction force · Impulse · Flight time

Zur Bestimmung der Körperschwerpunkthöhe bei Vertikalsprüngen

Zusammenfassung

Ziel dieser Studie war es, drei verschiedene Methoden zur Bestimmung der maximalen Sprunghöhe bei Vertikalsprüngen zu vergleichen und auftretende Fehler bei der Berechnung der maximalen Körperschwerpunkt (KSP)-Höhe aufzudecken. Zudem wird das Problem der Anfangswertbestimmung bei Squat- und Drop-Jumps thematisiert, indem eine neue Methode für die Berechnung der KSP-Höhe bei diesen Sprüngen vorgeschlagen wird. Um die verwendeten Methoden zur Ermittlung der Sprungleistung bei Vertikalsprüngen bewerten und vergleichen zu können, führten 15 männlichen Probanden vier maximal hohe Vertikalsprünge auf drei unterschiedliche Arten aus. Einen Counter-Movement-Jump (CMJ), einen Squat-Jump (SJ) und einen Drop-Jump (DJ). Kinematische Daten und die vertikalen Bodenreaktionskräfte wurden gemessen und für die Auswertung der Sprünge drei verschiedene Methoden verwendet. Das Flugzeitverfahren (FT), das Impulsverfahren (IMP), das auf dem Energieerhaltungssatz basiert und das Verfahren der doppelten numerischen Integration der vertikalen Bodenreaktionskraft (INT). Die maximale KSP-Höhe, die aus den Daten der 3D-Kinematik unter Verwendung eines automatischen Infrarot (IR)-Markertrackings (Vicon [Oxford, UK], Plug in Gait-Modell, Davis et al., 1991) bestimmt wurde, diente als Referenz (Goldstandard). Die Ergebnisse der Analyse der 3D-Kinematik und die doppelte Integration der vertikalen Bodenreaktionskräfte zeigten keine signifikanten Unterschiede. Die Sprunghöhen, die durch IMP und FT ermittelt wurden, waren im Verhältnis zur tatsächlichen Sprunghöhe zu gering, da die KSP-Höhe zu Beginn des Absprungs hier nicht berücksichtigt wird. Außerdem kann die Flugzeit durch den Springer manipuliert werden, so dass geschlussfolgert werden muss, dass die Flugzeitmethode nicht für die Bestimmung der Sprunghöhe bei Vertikalsprüngen in wissenschaftlichen Studien geeignet ist.

Schlüsselwörter

Vertikalsprünge · Maximale Sprunghöhe · Bodenreaktionskraft · Impuls · Flugzeit

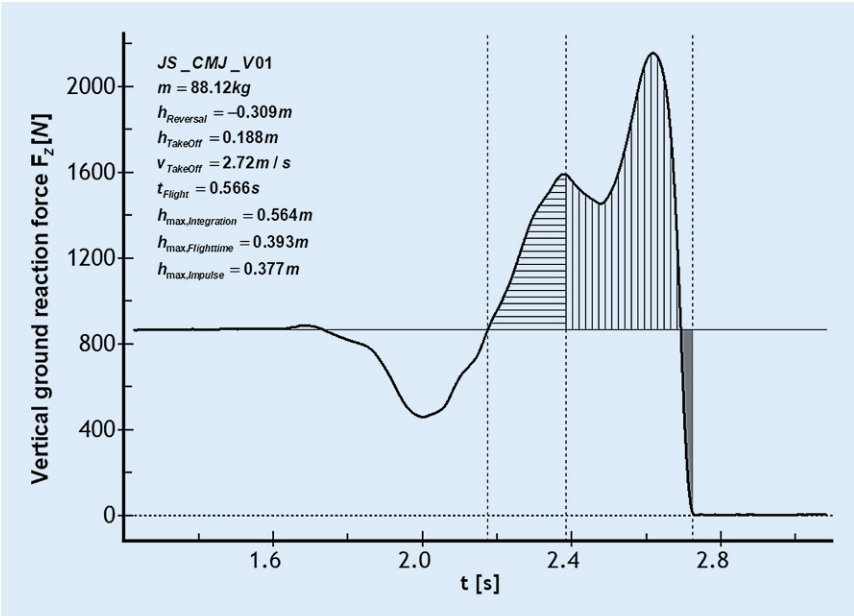

Fig. 1 ▲ Registered time course of the vertical ground reaction force including integration area and jump parameters. *CMJ* counter movement jump

is extremely rough and unsuitable for scientific studies. If the jumper falls from a precisely given platform height, neither the real CG height at the beginning of the free fall nor the CG height and velocity at touch down can be concluded with sufficient accuracy. Even experienced jumpers are not able to drop from the jumping platform to the DJ without lifting or lowering the CG. A difference of only 3 cm in height, which cannot be optically detected by the test manager, will make a difference of about 0.1 ms^{-1} in the impact velocity at a drop height of 0.40 m. That is about 4% of the impact velocity at a usual drop height of 0.4 m. This is not admissible for competitive sports studies.

In addition, there are still non-negligible differences in the CG impact height, which arise as a result of different body positions (especially leg angles) upon landing after free fall. The CG height at touch down not only affects the impact velocity at the drop but also the initial height of the CG at the beginning of the integration t_0, which in DJs is typically set at touch down.

The problems are similar with the squat jump. In a good approximation, one can assume that the initial velocity of the CG is $v_{z,0} = 0\,ms^{-1}$. Kinetic analysis showed that the real values fluctuate around $\pm 0.05\,ms^{-1}$. However, the initial height of the CG would need to be determined by means of a complex kinematic analysis, which would exeed the time frame for routine measurements.

What are the alternatives, for example, in the case of squat and drop jumping, to determine the jump height sufficiently correct without initial values?

On the one hand, this would be a 3D kinematic analysis with automatic marker tracking (e.g., using a Vicon system). The method requires a large amount of time to place the markers on the jumper. The measurements themselves and the evaluation would take less than 1 min per jump with a prepared data processing routine after the measurement.

By integrating the reaction force from the lower turning point (TP), so that only the acceleration force impulse is evaluated, the take off velocity could be determined. The timing of the reversal of movement could be approximated with a synchronized high-speed video camera or approximately with goniometers at the knee and hip joint. Apart from inaccuracies in the estimation of t_{TP}, the method could only determine the CG height using the impulse method, since the initial height of the CG is not known when the jumper is passing the turning point at t_{TP}.

Alternative methods to analyse drop jumps

Double force plate method

Another, very elegant method, which requires a certain deployment of technical equipment, is the use of two force plates (at the top, at leaving to drop and below for the contact phase of the jump). This method is also used by commercial manufacturers for professional fitness test equipment (e.g., MLD system from the company SP-Sport, Trins, AT). **Fig. 3** shows the basic measurement setup for this method. The jumper jumps from a force plate in drop height (z_0) to a second force plate on the ground ($z = 0$ m). In this case, the two force signals are added (**Figs. 4 and 5**) and integrated from the resting upright position on the upper force plate over the entire period up to the end of the flight phase after the drop jump using integration constants $v_{z,0} = 0\,ms^{-1}$ and $z_0 = h_{drop}$. The first integration leads to the time course of the vertical CG velocity $v_z(t)$ and the second integration calculates the CG height $z(t)$.

Backward integration

The best alternative method to compensate the effort to obtain the initial values for drop jumps or squat jumps with a fast measurement method is a "backward integration" of $F_z(t)$. Here one does not assume the initial values at the beginning of integration, but rather from the final values after a vertical jump. A precondition for the application of this method is that the subject is instructed before the SJ or DJ to remain rigidly in the upright position for at least 1 s after the jump. If he moves neither head nor arms in this situation, good conditions should be given to fix the final values for the integration from behind with $v_{z,End} = 0\,ms^{-1}$ and $z_{End} = 0$ m. The measurement period for this procedure must be long enough (6–8 s) so that the subject can take the required basic position after landing from the jump. In the evaluation of the vertical reaction force, integration during resting standing after the DJ needs to be started.

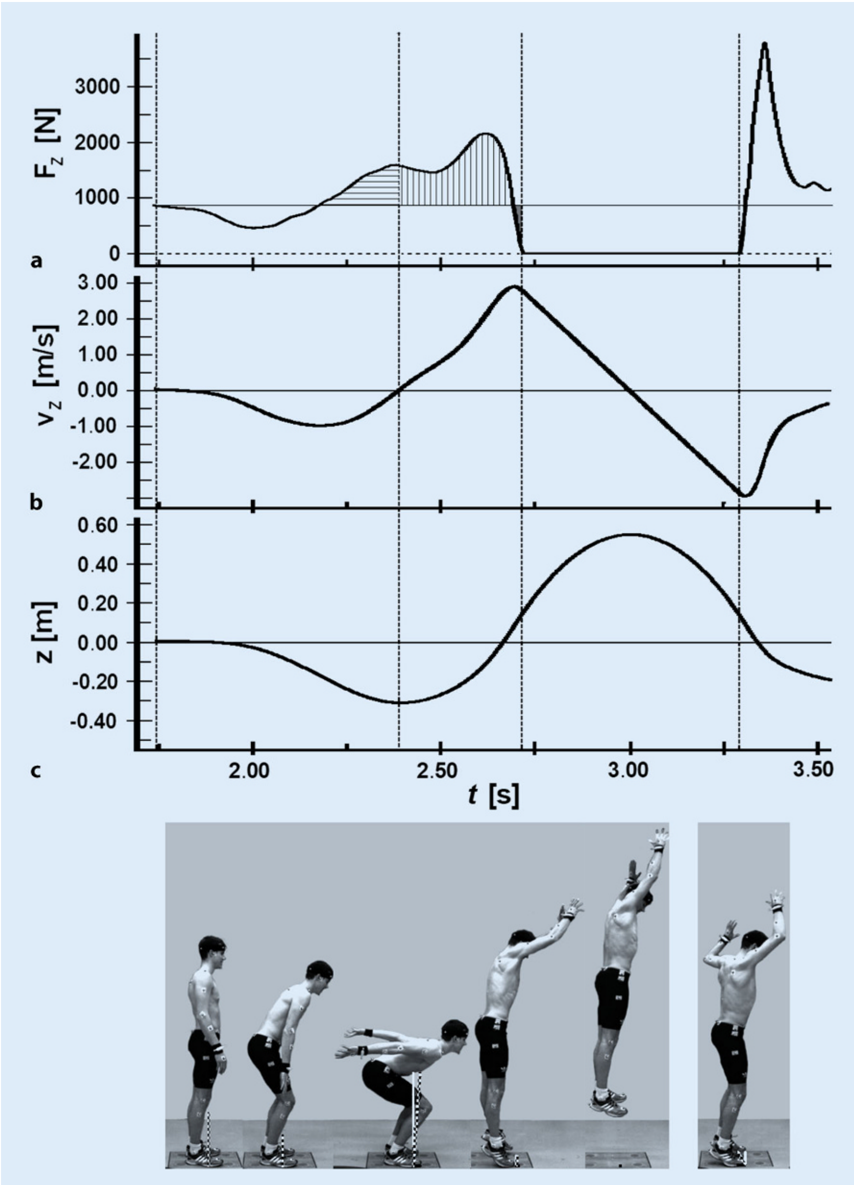

Fig. 2 ▲ Registered time course of the vertical ground reaction force (**a**), calculated vertical centre of gravity velocity (**b**) and CG height (**c**), with photographs of essential phases of a counter movement jump including the ground reaction force vectors

From this time on, the weight force line remains remarkably constant.

Formally, according to the equations:

$$v_z(t) = \frac{1}{m}\int_{t_{\mathrm{End}}}^{t_0} (F_z - F_G)\,dt + v_{z,\mathrm{End}} \qquad (12)$$

and

$$z(t) = \int_{t_{\mathrm{End}}}^{t_0} v_z dt + z_{\mathrm{End}} \qquad (13)$$

The time courses of the CG velocity and the CG height are obtained as already mentioned (see **Fig. 6**). The numerical integration has to take place as long as the CG velocity is zero at a point in time before the beginning of the contact. At this time, the CG has reached its highest position before the free fall (upper turning point at the beginning of the drop, see **Fig. 6**).

Analogously to the procedure described above for DJ, the backward integration was also used for the SJ, in which the determination of the initial values is similarly complicated. Here, in the second step of integration, one obtains the initial height from which the squat jump was started (**Fig. 7**).

Results

The maximum height of the CG during flight was obtained from three different calculations and compared to the 3D kinematic data that have been chosen as golden standard. Regarding the means, large differences were found between the investigated methods for estimation of maximum jumping heights. From the vertical reaction forces, the CG height of the jumps was determined by the flight time method, the impulse method, and by means of double integration. In **Fig. 8**, the means of the CG flight height and the standard deviation calculated with the aforementioned methods are listed with respect to the CG height at upright standing (starting position). The results of the complex 3D kinematic analysis and the double integration of the vertical ground reaction forces did not reveal any significant differences. Otherwise, the jump heights determined by means of impulse and flight time method are too low in relation to the real jump height due to the absence of the CG height at take off. The significantly lower results of the flight time and impulse methods are caused by a significant higher CG position at take off compared to upright standing. The flight time method is based on the assumption of a symmetric CG trajectory in upward and downward phase. These requirements were not fulfilled in any type of vertical jump. For example, the mean CG height at take off during CMJ was 19.3 ± 1.9 cm. The mean CG height at drop down after flight phase was registered as only 9.1 ± 0.04 cm.

Consequently, the double integration of vertical ground reaction force is the most reliable method to calculate jump height performance in vertical jump testing.

Discussion

The principal purpose of the present study was to demonstrate the significance of the method for the estimated CG heights in vertical jumping. In addition, a new method for the analysis of SJ

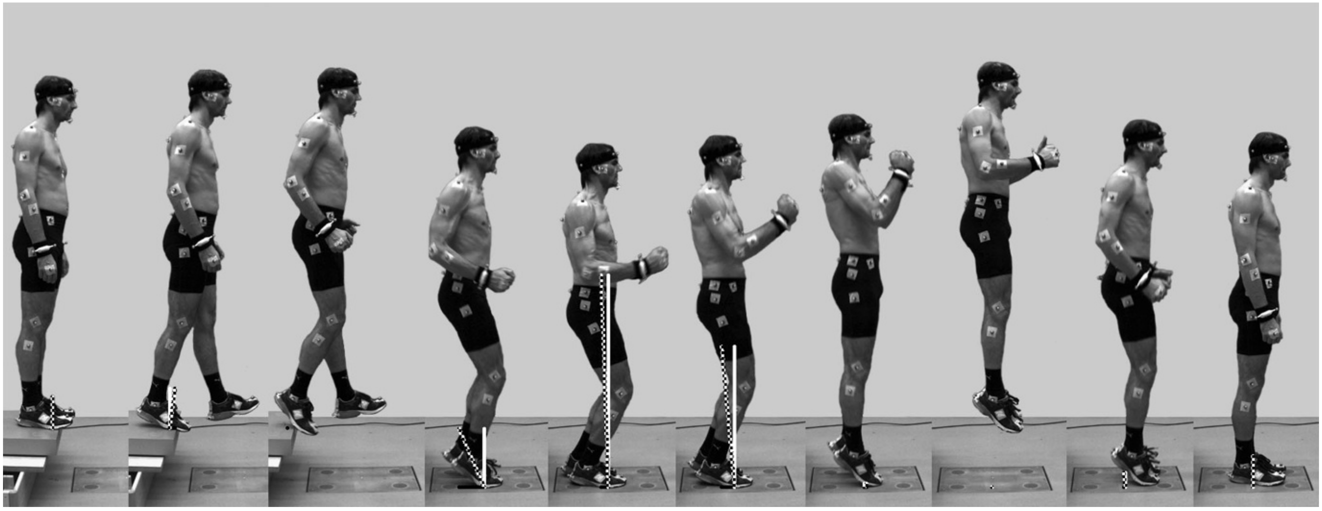

Fig. 3 ▲ Drop jump measured with two force plates. One at the top, at leaving to drop and another below for the support phase of the jump, including the ground reaction force vectors

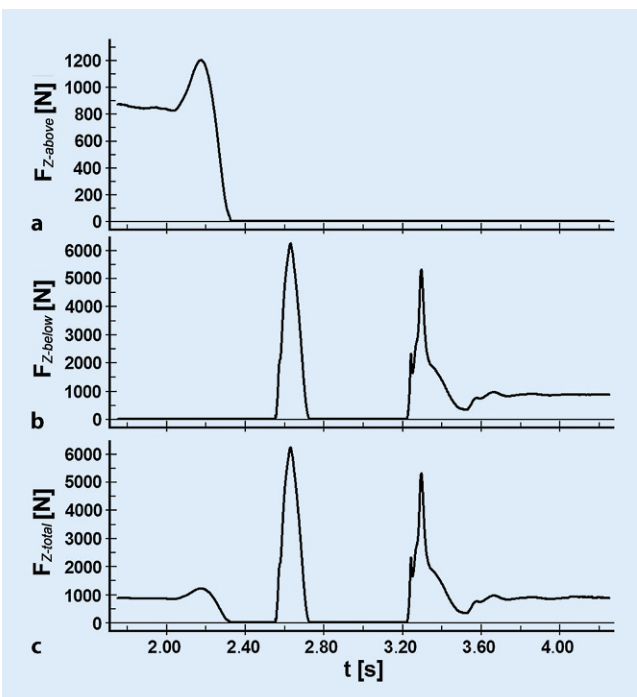

Fig. 4 ▲ Time courses of the vertical ground reaction force during a drop jump measured with two force plates: upper plate (step to drop, **a**), lower plate (support phase, **b**) and sum up force (**c**)

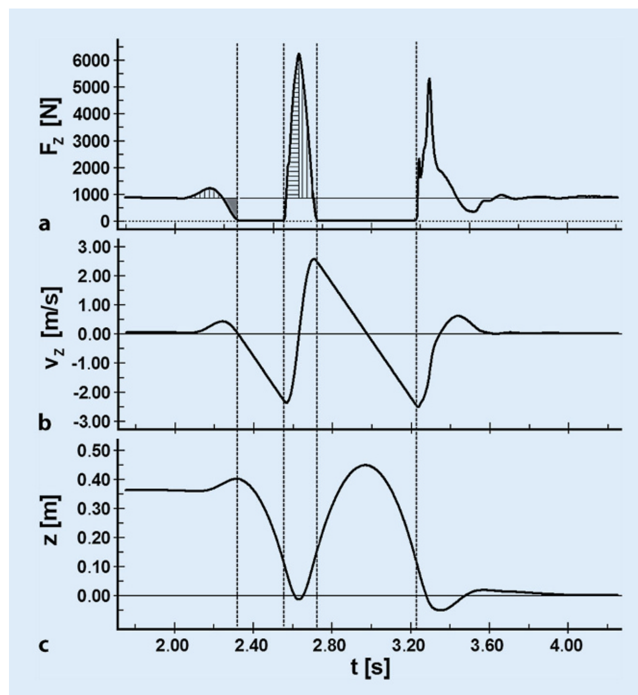

Fig. 5 ▲ Integration of the sum up force of the upper and lower force plate signals registered during a drop jump (**a**) lead to centre of gravity (CG) velocity (**b**) and CG height (**c**)

and DJ, where the initial conditions are difficult to define and a fast procedure to estimate accurate jump parameters is still lacking, should be presented.

As already mentioned, the development of the available technical equipment in sports biomechanics has a decisive influence on the accuracy for the estimation of CG height in vertical jumping. From the beginning on in the evaluation of vertical jumps, flight height used to be the most important parameter and it was always important to obtain the result as quickly as possible. Initially, jump and reach tests were established (e.g., Bui et al., 2015), in which the difference between the reaching height of upright standing and the maximum reaching height was measured according to a CMJ.

The first electronic devices to determine jump height in biomechanics labs were simple contact mats or optoelectronic devices, which were connected with a time measurement processor. The flight time method was originally established correspondingly quick in order to estimate the height of the vertical jumps. The physical basis for this is the equation of motion for the vertical throw.

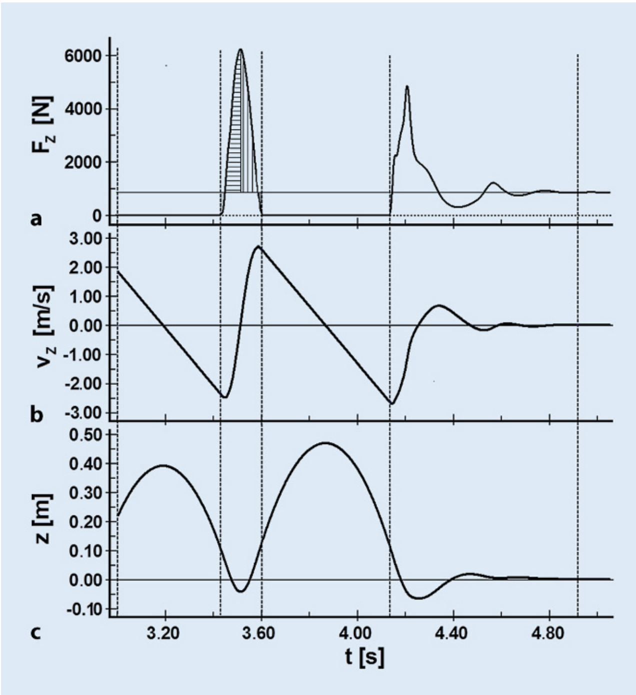

Fig. 6 ▲ Result of a double backward integration of the vertical ground reaction force during a drop jump. For this purpose, the athlete must pause in a resting upright standing position after drop down at the end of the flight phase to make sure that the end position is at zero velocity ($v_{z,End} = 0\ \mathrm{ms}^{-1}$) in upright standing ($z_{End} = 0$ m); see (**b**) and (**c**) at right time mark

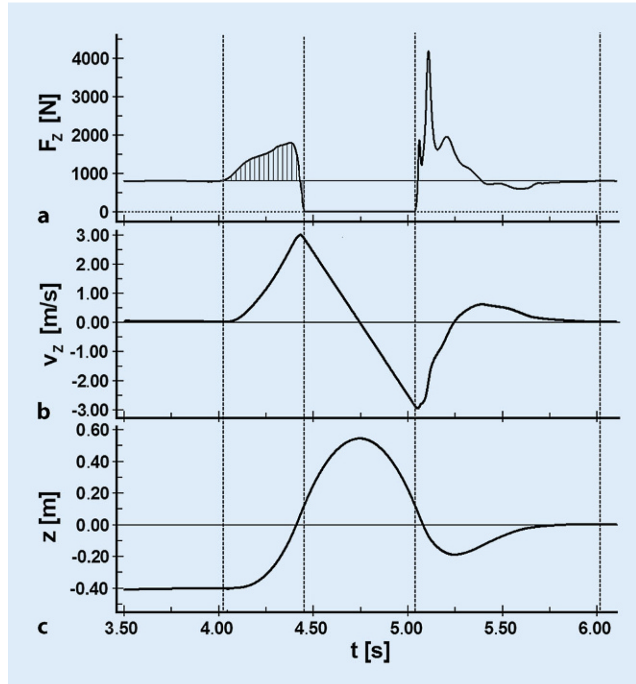

Fig. 7 ▲ Result of a double backward integration of the vertical ground reaction force during a squat jump. For this purpose, the athlete must pause in a resting upright standing position after drop down at the end of the flight phase to make sure that the end position is at zero velocity ($v_{z,End} = 0\ \mathrm{ms}^{-1}$) in upright standing ($z_{End} = 0$ m); see (**b**) and (**c**) at right time mark

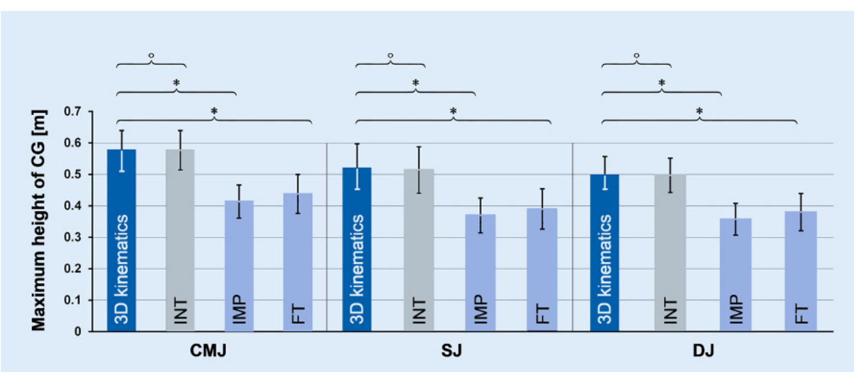

Fig. 8 ▲ Comparison of centre of gravity heights depending on the method of determination at different vertical jumps. Mean and standard deviation and results of students t-test with Bonferroni correction (o—no significant difference, *—significant difference for $p \leq 0.01$, $n = 15$). *INT* integration method, *IMP* impulse method, *FT* flight time method

The application of this equation presupposes that the CG height at take off is identical to the CG height at landing, meaning that rising and fall time are equal. Our data show that this is usually not the case.

The calculation of jump height using the flight time method has three weak points, making this method unusable for scientific research and the use of this method in the field must also be questioned. First, the height at take off is not included in the calculation of the flight height, which has meant, for example, that the jumping heights calculated with flight time method were significantly lower than the flight heights determined with the jump and reach test or with kinematic analysis of the CG trajectory. Second, the symmetry criterion in the upward and downward phase in vertical jumps is not entirely satisfied. ◘ Fig. 2 shows that the take off height is obviously higher compared to the drop down height, so that the assumption $t_{rise} = t_{fall}$ is only a very rough approximation. Due to the lower landing position compared to take off, the flight time is artificially extended, which leads to slightly greater jump heights being determined with the flight time method compared to the impulse method. Although these data are closer to real CG heights, this cannot be considered an indication of a higher measurement accuracy of the flight time method. The most important fact is the third, i.e., that the flight time could be manipulated through the landing position during the jump so that the results do not necessarily reflect the real performance of the jumper.

Jump tests using the flight time method are still used even in some top-level associations despite the known weaknesses (Schiltz et al., 2009; Erkulj et al., 2010; Faude et al., 2010; Ulbricht et al., 2015). The measurement technique has even been refined and made more comfortable for the user, for example, by optoelectronic detection of ground contact by means of light barrier arrays. However, the process-related weaknesses of jump height measurement according to the flight time method is completely unaffected by technical advances in contact or flight time measurement. From a scientific point of view, it does not appear to be a real advance to add a mean CG height at take off in order to correct the excessively low maximum CG heights of vertical jump analysis based on the flight time method (Aragón-Vargas, 2000; Moir, 2008).

Force plates have been established in many academies for biomechanical analysis, and these were also routinely used for the determination of the CG height in vertical jumps. With the software of many manufacturers of force plates, the flight height could be determined from the time curve of the vertical ground reaction force $F_Z(t)$ initially on the basis of the impulse balance according to the law of conservation of energy (impulse method).

However, the take off height of the jumper upon leaving the ground is also not taken into account, which is reflected in excessively low maximum CG heights, due to the extension in the ankle joint and raising of the flywheel masses (arms). The CG is shifted at the take off position compared to upright standing (reference height) depending on the body height and foot length of the jumper by 10–20 cm.

If a force plate is available for jump force analysis, then the CG path should be calculated by a double integration of the vertical force. With this method, which also provides an intermediate result, the entire velocity time profile of the CG motion, as well as a number of further biomechanical parameters can be determined in order to judge the technique during vertical jumps. In addition to the maximum height, for example, the maximum prelude depth and velocity, the take off height and the braking and accelerating force impacts could be measured. The evaluation is carried out in two steps according to Eqs. (4) and (5). **Figs. 1 and 2** show the measurement data trace of the vertical ground reaction force $F_Z(t)$ as well as the integrated CG velocity $v_Z(t)$ and the CG height $h_Z(t)$ for a CMJ example jump.

This method is not affected by differences in the position of the CG at take off or landing. In the case of a CMJ, determination of the initial values $v_{Z,0} = 0\,\mathrm{ms}^{-1}$ and $z_0 = 0\,\mathrm{m}$ is useful, since the jump starts from a resting upright position in which the CG height can be used as a reference line ($z_0 = 0\,\mathrm{m}$) without calculating the CG position using the mass distribution of the jumper in the starting position. The evaluation of CMJ by means of a force plate also makes it easy for non-professional test managers to reach high measurement precision.

The calculated flight altitudes were evaluated based on the results of 3D kinematic analysis (Vicon). The measuring accuracy of automatic infrared trackers is far below 1 mm. Nevertheless, the determination of the body's center of gravity with kinematic methods has its limits.

Inaccuracies are mainly caused by marker displacements on the skin and by partial mass movements under the skin (wobbling masses; Günther, Sholukha, Kessler, Wank, & Blickhan, 2003). In addition, the model of mass distribution used for CG calculation (Zatsiorsky, 2002) does not reflect the true distribution of body mass over the various body segments of the subjects.

To conclude, the most serious and most convenient method for jump analysis is the evaluation of the vertical ground reaction force by means of double integration. The use of this method should be seen as the standard procedure. Based on current results, , there is no sound justification today to continue applying flight time- or impulse-based methods to analyze jumping heights in testing procedures in high performance sports!

The results of this study demonstrate that only an integration of vertical ground reaction force will lead immediately to reliable maximum heights in vertical jumping. This could be shown for CMJ as well as for SJ and for DJ.

Velocity and CG position parameters can be detected with high accuracy. There is no possibility of manipulation by the subject. The problem of the missing initial values during the DJ or the SJ can be solved precisely by the integration from final conditions ($v_{Z,\mathrm{End}} = 0\,\mathrm{ms}^{-1}$ and $z_{\mathrm{End}} = 0\,\mathrm{m}$), provided that the reaction force has been recorded up to the resting standing in the final position. A precondition for the application of this method is that the subject is instructed before the SJ or DJ to remain rigidly in the upright position for at least 1 s after the jump. If he moves neither head nor arms in this situation, good conditions should be given to fix the final values for the integration from behind with $v_{z,\mathrm{End}} = 0\,\mathrm{ms}^{-1}$ and $z_{\mathrm{End}} = 0\,\mathrm{m}$. In the evaluation of the vertical reaction force, integration after resting stand after the SJ or DJ must be started. From this time on, the weight force line remains remarkably constant.

A precondition for the application of the method described on the basis of the backward integration is a correctly calibrated force plate and a carefully determined weight force of the subject. The further the weight force or mass of the subject used in the calculation deviates from the real value, the greater the drift in the integration of the ground reaction force. The drift error increases with integration time. For this reason, integration starts with the backward integration at the end of the jump, which should be set directly where $F_Z = F_G = \mathrm{const.}$

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Compliance with ethical guidelines

Conflict of interest V. Wank declares that he has no competing interests.

No studies with human participants or animals were performed by any of the authors for this article. All studies performed were in accordance with the ethical standards indicated in each case.

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