Possibilities and Limitations in the Biomechanical Analysis of Countermovement Jumps: A Methodological Study

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Possibilities and limitations in the biomechanical analysis of countermovement jump performance were examined using force plate data. Four male and 4 female sport students participated in the study. Software designed to test jumping performance was used to evaluate recordings from a force plate and to compute net velocity and net displacement measures for the center of gravity. In parallel, a film analysis incorporating Dempster’s center of gravity model was used for a comparison. Validity of the computed kinetic measures was evaluated with a general analysis of the major error sources including the data acquisition and numerical computations. Numerical integration procedures were found to be a reasonable tool for calculating net velocity and net displacement parameters for a more detailed analysis of athletic jumping performance. On the other hand, it appeared that Dempster-like center of gravity models can cause errors that disqualify their use as validation criteria for kinetic parameters.

Key Words: jumping performance, film analysis, center of gravity model

Since the work of Asmussen and Bonde-Petersen (1974) and Komi and Bosco (1978), a large body of literature has been published on biomechanical aspects of jumping performance. However, few articles have addressed a methodological point concerning standard routines used in laboratory testing of high-performance athletes as well as recreational athletes and nonathletes.

The introduction of microcomputers in biomechanical testing has opened up many new ways to judge athletic jumping performance “on-line” on the basis of force plate data only. One of those methods concerns numerical integration for calculating net velocity and net displacement curves for the center of gravity (CG). From the standpoint of elementary physics, this problem appears to be directly related to Newton’s laws. However, in a jumping analysis things are somewhat different. Based on force plate data, there is no continuous function with a definite double integral. Therefore, simple calculus cannot solve the problem. Force plate recordings do not supply a function for the force curve at all; they only provide a data array of possibly biased discrete force values originating from an analog-to-digital (AD) converter. The possible sources of error originate from the force plate electronics, the AD conversion, and the software-based computations. The latter include round-off errors; errors in defining time markers, maxima, and minima; and errors involved in numerical integration of the force record when net velocity and net
displacement data are calculated. In the past, these sources of error have led to an uncertainty about whether to use net velocity and net displacement measures derived from force records. To resolve that issue, a film analysis incorporating CG models has been used in many studies. However, it has not been clarified whether a CG model can actually serve as a precise validation criterion for net displacement and net velocity calculations.

The goal of the present study was to support the use of force plate data for the calculation of net velocity and net displacement parameters as measures of performance in standard testing routines that go beyond the registration of jumping height only. It was thought that the outcome of the study would provide guidelines for researchers developing standard testing routines for athletic jumping performance.

To validate the net velocity and net displacement parameters, it was useful to specify the major error sources and to estimate their possible effects on numerical data evaluation. As a comparison, Dempster’s center of gravity model (Dempster, 1955) was used to calculate CG displacements from cine data. The Dempster model was chosen because it appears in numerous studies in which jumping behavior was analyzed (Bobbert et al., 1986; Komi & Bosco, 1978; Lamb & Stothart, 1978; Luhtanen & Komi, 1978).

Methods

Four male (age 21.5 ± 1.3 years, height 181 ± 6.2 cm, weight 73.0 ± 5.6 kp) and 4 female (age 22.0 ± 2.4 years, height 170 ± 9.5 cm, weight 64.0 ± 12.3 kp) sport students performed countermovement jumps (CMJ) on a force plate (Kistler Type 9281). After verbal instruction, subjects warmed up and performed several testing trials in order to become accustomed to the required task. Subsequently, the subjects indicated when they were ready to perform the jump that would be used for the film analysis. Only one jump per person was recorded, with a speed of 200 frames per second (Locam Highspeed Camera) and a shutter factor of 1/600 s. The optical axis of the camera was perpendicular to the plane of motion with the camera standpoint 10 m apart from the force plate. High-voltage spotlights were used for lighting in the plane of motion. All frames were digitized with 10 landmarks in order to calculate the ankle, knee, and hip angles as well as the CG coordinates based on the Dempster model (Dempster, 1955) with corrected values according to Miller and Nelson (1973). The landmarks were placed above the ankle, knee, hip, wrist, elbow, and shoulder joints (as described by Barham, 1978) as well as above the heel, the fifth metatarsophalangeal joint, the tip of the little finger (phalanx distalis), and the center of the ear. Prior to the CG computations, a fourth-order Butterworth filter was used for data smoothing (Schweizer, 1987). The cutoff frequencies, based on my experience with jumps, were chosen to be 15 Hz for the leg landmarks and 5 Hz for all other markers (Schweizer, 1987). A higher cutoff frequency was used for the leg landmarks in respect to the landing impact after the airborne phase (Bobbert et al., 1986; Bobbert, Huijing, & Ingen Schenau, 1987). For the more proximal landmarks that were not affected as much by the landing impact, a cutoff frequency of 5 Hz was chosen according to Hubley and Wells (1983).

For the descriptive statistics, the different CG locations as well as ankle, knee, and hip angles were determined at the onset of the movement, for the inflection point of the countermovement, at the takeoff, in the apex of the airborne phase, and at the landing. Cine data for the takeoff and landing were determined by a force threshold circuit (5 N) operating a light source in the plane of motion. A threshold circuit was used to identify consecutive frames with the force plate still loaded (light source on) in one frame and unloaded (light source off) in the next. To reduce the absolute error, the mean of the CG heights and the joint angles in those two frames was used.
Software Analysis of the Force Recordings

All jumps were performed according to the guidelines given by Komi and Bosco (1978). To ensure that the jumps were performed primarily by the leg extensor muscles, the subjects were asked to keep their hands on their hips throughout the movement. After verbal instruction prior to the jumps, subjects waited in an upright starting position for the starting command. Shortly before the starting command, the computer-based data acquisition was initialized by a keystroke. A delay of at least 300 ms was necessary to provide a constant force signal corresponding to body weight prior to the onset of movement. Even small force variations during that time period are detected by the software program and reported to the experimenter by an acoustic signal in order to repeat the trial. All further computations proceeded automatically.

The vertical ground reaction force from the force plate was recorded by 1,000 N/V and digitized by computer (IBM PC/AT compatible) with a frequency of 1000 Hz and a resolution of 12 bits (DT2821, DATA Translation, USA). A major problem here concerns the optimal resolution for the expected range of force recordings. For CMJs (and also for squat jumps), optimal resolution can be determined according to the subjects’ body weight prior to testing. In my experience, maximal force values during propulsion for CMJs do not reach beyond 3 to 3.5 times body weight. On that basis, suitable amplification values for the AD-converter are chosen by the software program prior to data acquisition.

For the airborne phase between takeoff and landing, a constant force signal is present. The difference between that constant force level and the one before the onset of the countermovement gives the actual value for body weight. Therefore, for each trial a specific body weight was calculated. This procedure takes care of possible force shifts in the piezoelectronics. With a precise body weight, several parameters for the testing of jumping performance can be calculated (Figure 1). These describe the characteristics of the force record as well as those of the net velocity and net displacement curves.

Displacement measures are particularly interesting for jumping techniques with movement reversals. In this regard, the amplitude of the countermovement is given by the CG displacement from upright standing to the inflection point of the movement. Based on the force plate data, the time to reach the inflection point is given by the area A2 above the body weight being equivalent to area A1 below the body weight (Figure 1). Between the intersection of the body weight line with the force curve and the inflection point of the movement, body mass slows down in the downward direction. The extensor tendomuscular system, envisioned as one entity, is stretched in that phase with the force above body weight and the direction of the movement still downward. Therefore, this phase may be called the “stretching time,” and the displacement of the CG during that phase may be called “stretching distance.” Both parameters are useful for a quantitative estimate of the stretch–shortening behavior within the extensor tendomuscular system. They can be easily calculated on the basis of force plate data only and therefore extend the usual scope of a routine jump analysis (without cine data) that is quite often limited to jumping height only.

The Possible Sources of Error

One of the possible sources of error lies in calibration of the force signal and its conversion into digits. The effect of a calibration error is a constant factor in all measures of the force record. However, this error does not cause any problems in calculating net velocity and net displacement curves. The net velocity \( v(t) \) at time \( t \) is calculated by means of the impulse corresponding to the area \( A(t) \) underneath the force–time curve divided by the
Jumping Height: 31.1 cm (flight time) — 31.2 cm (Impulse)
Maximal Amplitude of Countermovement: –0.266 m
Maximal Velocity of Countermovement: –1.203 m/s
Stretching Distance: –0.106 m
Stretching Time: 134 ms
Total Movement Time: 688 ms
Time for Upward Movement: 248 ms
Fmax: 1228 N

Figure 1 — Computer screen copy for a countermovement jump. The parameters for the jumping performance are jumping height calculated by flight time and by takeoff impulse (for correct performance, both measures for jumping height should differ by no more than 5%), maximal amplitude of countermovement, maximal velocity of countermovement, stretching distance (displacement of center of gravity during downward movement while force level is above body weight), stretching time (time during downward movement while force level is above body weight), total movement time, time for upward movement, and Fmax (maximal force amplitude above body weight). Stretching distance and stretching time refer to the extensor tendomuscular system envisioned as one entity. (The different scales for ground reaction force, velocity, and displacement values have been omitted.)

Name: TRA-M
Body mass: 78.7 kg

mass \[ v(t) = A(t)/m \]. Since the calibration error is involved in both the integral \( A \) as well as the body mass \( m \), it can be eliminated in the numerator and in the denominator.

The error involved in the AD conversion process is random such that for a distinct analog voltage from the Kistler force plate, a digital value with a resolution of 4,096 digits (12 bits) is assigned for the given force range. Therefore, this error should not play any systematic role for the calculation of force, net velocity, and net displacement measures.

Net velocity and net displacement curves are computed in the software program by a numerical integration algorithm (trapezoidal rule) based on calculated body weight as given by the difference between the force levels prior to the countermovement and during the airborne phase. My experience has been that this body weight value does not vary significantly (less than 1%) between trials. However, the variation is slightly higher in squat jumps than in countermovement jumps. This is due to a more variable force record in squat jumps during the stance phase prior to the jump.
The trapezoidal rule was used because of its convenience within an integration algorithm. Because of the chosen AD conversion frequency, there is a large data array. Higher order integration procedures such as the Simpson rule do not improve the precision of the calculated parameters significantly.

The following equation relates to the mathematical background for the trapezoidal rule with \(m\) subintervals and gives an estimate for the error term involved (after the brackets).

\[
\int_{a}^{b} f(x) \, dx \approx \frac{h}{2} \left[ f(a) + f(b) + 2 \sum_{j=1}^{m-1} f(x_j) \right] - \frac{(b-a)h^2}{12} f'(\mu)
\]

for some \(\mu \in [a,b]\) with \(h = (b-a)/m\) and \(x_j = a + jh\), for each \(j = 0, 1, \ldots, m\).

The error term for the trapezoidal rule depends on the AD conversion frequency \((F = h^{-1})\), the endpoints of the data array \(a\) and \(b\), and the second derivative of a fictitious function \(f\) that is supposed to represent the force–time curve. If the derivative \(f'\) does not take any extreme changes between \(a\) and \(b\), \(f''(\mu)\) will not be large. Therefore, the error term is dominated by the value \(h^2\). For the AD conversion frequency of 1000 Hz, \(h^2\) is equal to 10^{-6}.

The different time markers for the onset of the movement and also for takeoff and landing are automatically determined by the software. A simulation of possible errors in those time markers provides insight into any erroneous follow-up effects. It can be shown that slight misplacements of 5 to 10 ms for the onset of the force–time curve do not change velocity or displacement parameters by more than 0.1%. However, more care must be taken for the takeoff and the landing because of a higher rate of change in the force values at those times. Nevertheless, misplacements for the takeoff up to 2 or 3 ms do not change the velocity or displacement parameters by more than 2%. Therefore, they are not considered to play an important role.

**Jumping Height Estimates**

Only a few authors (Frick, Schmidtbleicher, & Wörn, 1991; Hennig & Steinmann-Milani, 1990; Lamb & Stothard, 1978; Virmavirta, Avela, & Komi, 1995) have comparatively analyzed different methods of estimating true jumping height. In the present study, I used the Dempster model in the film analysis method (FAM), the flight time method (FTM), and the takeoff impulse via numerical integration of the force record (NIM).

For the FAM, the jumping height \(H_{FAM}\) is given by the difference between the CG heights at takeoff and the apex of the airborne phase. For the FTM it is assumed that \((\frac{1}{2} \cdot \text{flight time})\) is equal to the time for the rise of the CG within the airborne phase. This assumption holds true only for equivalent CG heights at the takeoff and landing. Only for that case, the jumping height \(H_{FTM}\) can be estimated by the formula \(H_{FTM} = \frac{1}{2} \cdot g \cdot (\frac{1}{2} \cdot t_{flight})^2\), with \(t_{flight}\) being evaluated by the software program and based on the force plate data. Finally, for the NIM, the jumping height \(H_{NIM}\) is calculated by the impulse–momentum relationship \((\frac{1}{2} \cdot m \cdot v_{takeoff}^2 = m \cdot g \cdot h)\). In this respect, the takeoff velocity \(v_{takeoff}\) is calculated by dividing the area \(A3\) (minus \(A4\)) of the force time curve by the body mass (see Figure 1). Subsequently, the desired jumping height \(H_{NIM}\) is equal to \(v_{takeoff}^2/(2 \cdot g)\).

A two-tailed Student’s \(t\) test for paired comparisons was used to test for differences between methods and between different time phases. The significance level was set at 5%.
Results

The results for all jumping height calculations are listed in Table 1. The largest values were found for $H_{FAM}$. It was interesting that these values were larger than those for the NIM ($p < .001$) and the FTM ($p < .001$), with $H_{FTM}$ being larger than real. In regard to the latter, consistently lower or equal (Subject 7) CG heights at the landing as compared to the takeoff were found (Table 2), and the difference was highly significant ($p < .01$). This is in agreement with the more flexed ankle joint ($p < .01$) and knee joint ($p < .001$) at landing that were present for all subjects. For the hip angle, all subjects except Subjects 4, 6, and 8 had smaller or equal values at landing as compared to the takeoff. The difference was not significant. Nevertheless, it was concluded that the CG position was lower at landing as compared to the takeoff and that the time from takeoff to peak was less than the time from peak to landing. By that argument, $H_{FTM}$ was calculated larger than real. In contrast, $H_{NIM}$ was found to be less than or equal to $H_{FTM}$ for all subjects (NS, $p = .076$) except for Subject 7. In this subject, it is interesting to find practically the same CG heights at takeoff and at landing, with ankle, knee, and hip joints being more flexed at landing.

Next to the jumping height estimates, values for the countermovement amplitude (CA) are listed in Table 1. Those measures were calculated using the FAM and the NIM. Values for $CA_{FAM}$ were consistently larger than those for $CA_{NIM}$ ($p < .001$). The largest amplitudes for the countermovement were close to 40 cm. The remaining two columns in Table 1 hold values for stretching time ($T_{Str}$) and stretching amplitude ($A_{Str}$), which were

Table 1  Characteristics of Countermovement Jumps ($N = 8$): Jump Heights (cm), Amplitude of Countermovement (cm), Stretching Time (ms), and Stretching Amplitude (cm)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Jump heights</th>
<th>Amplitude of countermovement</th>
<th>Stretching time and stretching amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H_{FAM}$</td>
<td>$H_{NIM}$</td>
<td>$H_{FTM}$</td>
</tr>
<tr>
<td>1</td>
<td>33.1</td>
<td>31.2</td>
<td>31.1</td>
</tr>
<tr>
<td>2</td>
<td>29.8</td>
<td>26.0</td>
<td>27.0</td>
</tr>
<tr>
<td>3</td>
<td>39.1</td>
<td>35.8</td>
<td>37.2</td>
</tr>
<tr>
<td>4</td>
<td>37.7</td>
<td>36.6</td>
<td>37.8</td>
</tr>
<tr>
<td>5</td>
<td>28.6</td>
<td>25.4</td>
<td>25.8</td>
</tr>
<tr>
<td>6</td>
<td>44.1</td>
<td>41.4</td>
<td>42.0</td>
</tr>
<tr>
<td>7</td>
<td>26.2</td>
<td>25.1</td>
<td>24.4</td>
</tr>
<tr>
<td>8</td>
<td>22.6</td>
<td>20.5</td>
<td>20.8</td>
</tr>
<tr>
<td>Mean</td>
<td>32.7</td>
<td>30.2</td>
<td>30.8</td>
</tr>
<tr>
<td>SD</td>
<td>±7.2</td>
<td>±7.2</td>
<td>±7.5</td>
</tr>
</tbody>
</table>

Note. Individual values and mean values ($±SD$) are given for jumping height evaluated by the film analysis method (FAM), the numerical integration method (NIM), and the flight time method (FTM). The amplitudes of the countermovement (CA) were evaluated by the FAM and the NIM. Individual values and means ($±SD$) for stretching time ($T_{Str}$) and stretching amplitude ($A_{Str}$) are listed in the last two columns. They were calculated by the NIM and refer to the extensor muscular system envisioned as one entity.
calculated by the NIM and refer to the extensor muscular system hypothetically envisioned as one entity. The stretching times varied between 100 and 167 ms, indicating a short and a long stretching phase. The largest stretching amplitude was 15.6 cm (8.9% of body length) for Subject 3. The shortest stretching amplitude was present in Subject 7 (7.4 cm or 4.5% of the body length).

Table 2  Characteristics of Countermovement Jumps (N = 8): CG Heigths (cm) and Ankle, Knee and Hip Angles (degrees)

<table>
<thead>
<tr>
<th>Subject</th>
<th>CG t</th>
<th>CG l</th>
<th>FA t</th>
<th>FA l</th>
<th>KA t</th>
<th>KA l</th>
<th>HA t</th>
<th>HA l</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>12.6</td>
<td>11.9</td>
<td>136</td>
<td>136</td>
<td>168</td>
<td>154</td>
<td>156</td>
<td>156</td>
</tr>
<tr>
<td>2</td>
<td>10.3</td>
<td>9.2</td>
<td>144</td>
<td>140</td>
<td>175</td>
<td>170</td>
<td>168</td>
<td>168</td>
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<td>3</td>
<td>11.6</td>
<td>8.7</td>
<td>139</td>
<td>118</td>
<td>169</td>
<td>164</td>
<td>173</td>
<td>154</td>
</tr>
<tr>
<td>4</td>
<td>14.9</td>
<td>9.3</td>
<td>131</td>
<td>123</td>
<td>170</td>
<td>160</td>
<td>169</td>
<td>170</td>
</tr>
<tr>
<td>5</td>
<td>12.6</td>
<td>10.4</td>
<td>134</td>
<td>130</td>
<td>177</td>
<td>154</td>
<td>176</td>
<td>156</td>
</tr>
<tr>
<td>6</td>
<td>12.3</td>
<td>9.0</td>
<td>134</td>
<td>123</td>
<td>173</td>
<td>156</td>
<td>157</td>
<td>183</td>
</tr>
<tr>
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<td>12.4</td>
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<td>159</td>
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<td>168</td>
</tr>
<tr>
<td>8</td>
<td>6.6</td>
<td>4.7</td>
<td>141</td>
<td>127</td>
<td>167</td>
<td>160</td>
<td>149</td>
<td>157</td>
</tr>
<tr>
<td>Mean</td>
<td>11.6</td>
<td>9.4</td>
<td>138</td>
<td>129</td>
<td>172</td>
<td>160</td>
<td>165</td>
<td>164</td>
</tr>
<tr>
<td>SD</td>
<td>±2.4</td>
<td>±2.4</td>
<td>±5</td>
<td>±8</td>
<td>±4</td>
<td>±5</td>
<td>±10</td>
<td>±10</td>
</tr>
</tbody>
</table>

Note. Individual values and mean values (±SD) are given for center of gravity (CG) heights as well as for ankle, knee, and hip angles at takeoff (t) and at landing (l). CG t and CG l are expressed relative to the CG height in upright standing.

Discussion

In elite sport, improvements in jumping performance of even a few centimeters are important. Therefore, coaches and scientists who are comparing training regimens have to make sure that their laboratory procedures do not involve errors that are larger than the differences they are supposed to measure. In this regard, the present paper outlines possibilities and limitations in a routine biomechanical analysis (without cine data) of countermovement jumps based on force plate data only. The results are intended to provide guidelines for researchers who are developing standard testing routines for athletic jumping performance.

Probably the most common measure of jumping performance is jump height. For standard testing routines, this parameter is usually calculated by the flight time method (FTM) or the numerical integration method (NIM). It has been customary to validate these methods with a film analysis incorporating a CG model. However, very few articles have outlined the problems involved in using a CG model for a complex body movement.

In the present study, the well-known Dempster model was used because of its frequent use in studies of jumping performance (Bobbert et al., 1986; Komi & Bosco, 1978; Lamb & Stothart, 1978; Luhtanen & Komi, 1978; Virmavirta et al., 1995). According to the present results, researchers should take care when comparing CG data based on the
Dempster model with measures originating from a force plate or from another data source. This can be readily demonstrated by the following example.

For the Dempster model, the CG of the trunk is assumed to be located on a straight line between the shoulder and the hip joint landmark. However, in CMJs most subjects bend their trunks when performing a countermovement. When the subject’s trunk is bent, the Dempster model assumes the CG to be too low. With a relative contribution of the trunk at 49% of body mass, this problem becomes particularly important. Accordingly, the amplitudes of the countermovement were clearly larger in all subjects for the FAM than for the NIM (Table 1). The mean difference was 2.3 ± 0.9 cm. Figure 2 shows the vertical CG coordinates in one subject for both evaluation methods (lower graph) and the segment length between the shoulder and the hip joint (upper graph). This segment length was 60.3 cm for standing upright and 53.3 cm for the inflection point of the countermovement. It is probably due to the flexibility of the S-shaped spine that this segment length is so variable and even increases toward the takeoff point beyond the segment length at the upright standing position. This clearly shows that the trunk should not be thought of as one rigid body, which was a prerequisite for the Dempster model.

For a simple error estimate at the inflection point of the countermovement, the trunk was assumed to consist of several rigid bodies instead of one, with their CGs equally distributed on the segment of a circle with the endpoints identical to the shoulder and hip joints. Based on that assumption, the difference was calculated between the vertical coor-

![Figure 2 — Center of gravity displacements from one subject beginning at upright stance during the countermovement and the propulsion (lower graph), and segment length between the shoulder joint and the hip joint (upper graph).](image)
ordinates of the respective net CG for the multisegment trunk and the original CG for the rigid trunk in the Dempster model. For this calculation, the length of the circle segment at the inflection point of the countermovement equal to the distance between the shoulder joint and the hip joint standing upright was used. The difference in vertical coordinates of the net CG for the multisegment trunk and the CG for the rigid trunk was approximately 3.98 cm if the number of segments was larger than 10. However, a five-segment trunk was sufficient to give a difference of 4.1 cm.

Further information on this issue was provided by Gubitz (1978). In that study, CG models with different body segment parameters were analyzed for different body postures executed on a CG scale. Subsequently, the respective CG coordinates were compared to the coordinates from the scale. The largest deviations were found for bent body postures. For the Dempster model, differences were found to be 5 cm in the CG coordinate in respect to longitudinal axis of the trunk. For an extended body posture, differences were smaller but still as large as 3 cm. According to Gubitz, deviations from the CG scale are present not only in the Dempster model but also in other models, by about the same amount (Braune & Fischer, 1889; Clauser, McConville, & Young, 1969). Subsequently, Gubitz introduced a new model with body segment parameters based on a statistical error reduction procedure.

I have not used this new model by Gubitz, or any other model, to identify the most appropriate body segment parameters, a strategy followed by Hinrichs (1987). Rather, I found the general assumption of a rigid trunk segment to be the crucial factor inherent in all Dempster-like models no matter what body segment parameters are used. In this regard, there are mathematical models of the human body that avoid the general assumption of a rigid trunk (e.g., deLeva, 1996; Hanavan, 1964; Hatze, 1980). However, to apply those models, additional assumptions have to be made to transform the cine data for the trunk (shoulder and hip landmarks) into parameter values for the corresponding anthropometric segments. In addition, these models involve preparatory anthropometric measurements that require at least 60 min to complete.

Although I have only looked at the countermovement amplitude so far, another line of evidence supports a reasonable skepticism toward the use of Dempster’s CG model when comparing kinematic with kinetic measures. The argument concerns the larger jumping heights calculated by the FAM as compared to the FTM. From the ankle angles and the knee angles, there is reason to assume the body posture to be more bent at landing as compared to takeoff. Therefore, \((\frac{1}{g} \cdot \text{flight time})\) is larger than the upward movement time during the airborne phase and \(H_{FAM}\) is larger than real. Since \(H_{FAM}\) was larger than \(H_{FTM}\), there is reason to question the validity of the CG calculations.

The exact cause for the overestimated \(H_{FAM}\) values is somewhat unclear. However, since \(H_{FAM}\) is the difference between CG height in the apex and at takeoff, one of those heights has to be more biased than the other. It appears from the ankle, knee, and hip angles that the body posture at takeoff is not yet completely extended. By same argument as for the countermovement amplitude, it is concluded that the CG heights at takeoff were estimated too low by the Dempster model. In contrast to this, the ankle, knee, and hip angles in the apex of the airborne phase (mean values: 151 ± 12°, 176 ± 5°, 173 ± 6°) were larger \((p < .05, p = .07, p < .05)\) than those at takeoff. This would explain the larger values for \(H_{FAM}\) as compared to \(H_{FTM}\) and \(H_{NIM}\). The difference between \(H_{FTM}\) and \(H_{NIM}\) did not reach the level of significance. However, the respective error probability (7.6%) was close to the 5% level for statistical significance. Moreover, \(H_{NIM}\) was found to be less than or equal to \(H_{FTM}\) for all subjects except for one. Although this difference was not statistically significant, it was of practical significance.
Further, I analyzed the same source of error by a parabola approximation (least squares) for the CG heights during the airborne phase. The ratio between the sum of squares and the degrees of freedom (SS/df) is the measure $s^2$ for the goodness of the fit, which was found to be less than 0.05 for all trials (mean value: $0.026 \pm 0.01$). The individual slopes for the parabola derivatives averaged $9.85 \pm 0.28 \text{ m/s}^2$, which is very close to the constant of gravity. The group difference (31.9 ± 6.8 cm) between the parabola value in the apex and at takeoff was less than $H_{\text{FAM}}$ for all subjects ($p < .01$) but still larger than $H_{\text{FTM}}$ and $H_{\text{NIM}}$. The differences between the parabola values and the original CG coordinates during the airborne phase were largest toward the endpoints (takeoff and landing) of the data array. The difference between the original CG coordinate from the FAM and the respective parabola value was $1.4 \pm 0.73 \text{ cm}$ at takeoff. This is in agreement with the above-mentioned problems of the Dempster model when the body posture is flexed as at takeoff rather than erect as in the apex.

A further problem regarding the limitations of the FAM concerns the precision by which CG coordinates can be determined for given points of time, such as takeoff, for example. With a resolution of 200 frames per second, there is a time difference of 5 ms from frame to frame. For the takeoff in CMJ, this resulted in a CG displacement between 1.1 and 1.6 cm from one frame (reference lamp on) to the next frame (reference lamp off) in our subjects. Differences for the ankle, knee, and hip angle were $4.38 \pm 2.2^\circ$, $3.88 \pm 0.83^\circ$, and $2.63 \pm 0.92^\circ$, respectively. Since the mean values were used for those measures between the last frame with reference lamp on and the next frame with reference lamp off, these absolute errors were reduced by 50%. In contrast, there was an error of less than 1 ms possibly originating from the threshold circuit. With a threshold of 5 N, as used in the experimental setup, and at rate of change in the force values of 10 to 15 N/ms at takeoff, this error can be considered insignificant.

From the above it can be concluded that researchers should take care when using Dempster-like CG models in film analysis as a reference for methods that estimate jumping height. The errors involved may be larger than the precision required to determine small improvements in the jumping performance. On the other hand, the numerical integration method (NIM) appears to be a reasonable alternative for calculating jumping height as well as net velocity and net displacement parameters. However, even for the NIM, incidental errors should not be completely ruled out. For example, in a standard testing routine it is unclear whether the vertical ground reaction force is exclusively efficient for the takeoff impulse in the vertical direction or if it produces an angular impulse along the horizontal axis of the body. Therefore, I suggest the combined use of the NIM and the FTM in a standard testing routine. Since both methods are usually available in a biomechanics laboratory, respective jumping heights from both methods should not differ by more than ±5% to reassure the experimenter of an acceptable jumping technique.

**Future Perspectives for Standard Testing Routines in Jumping**

The NIM provides important information on net velocity and net displacement curves. With those curves, detailed graphic illustrations about jumping performance are available to coaches and athletes. In fact, very little information can be found in the literature referring to any evaluation standard in the physiological testing of athletic jumping performance. Figures 3 and 4 show a displacement–velocity diagram and a velocity–force diagram for the same three jumpers. The shapes of the different curves reveal the characteristics of the individual performances. For example, Figure 3 shows that Jumpers 1 and 3 have almost identical curves except for the last phase of the push-off. However, briefly
Figure 3 — Displacement–velocity diagram for three different jumpers. The movement starts at the origin of the diagram. For an interindividual comparison, displacements of the CG are given as percentages of body length.

Figure 4 — Velocity–force diagram for three different jumpers. The movement starts at the origin of the diagram.
before the upright stance level, Jumper 1 shows additional gain in CG velocity possibly originating from more powerful dorsiflexion in the ankle joint. In contrast, Jumper 2 shows a much larger countermovement amplitude, which means that this jumper is taking advantage of the longer acceleration pathway. Figure 4 shows graphs of the three jumpers in a velocity–force diagram. It is interesting that all jumpers show major gains in CG velocity at forces between 750 and 900 N.

In addition to graphic illustrations, specific parameters should be provided in standard testing routines that go beyond the measurement of jumping height only. In this regard, it is still unclear what type of countermovement characteristic leads to the most powerful vertical jump. From Table 1 and Figure 3, for example, a long countermovement amplitude appears to be more beneficial for jumping height as compared to a short countermovement. However, results from the literature are inconclusive on this point. Collecting extensive data in standard testing routines from high-performance athletes as well as from recreational athletes and nonathletic subjects and analyzing these data statistically would help reveal the contribution of countermovement amplitude and velocity to a powerful push-off. Therefore, those measures should be included in the data output of standard testing routines.

References


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