Validity and Reliability of Methods for Testing Vertical Jumping Performance

Herbert Hatze

The validity and reliability of the jumping ergometer method for evaluating performance in two-legged vertical countermovement and serial rebound jumps were investigated. The internal segmental and nonvertical energy flow components for drop jumps were also studied. The exact dynamic equations governing the jumping motion in three dimensions were derived and used together with the approximate relations of the jumping ergometer method to evaluate a total of 72 vertical jumps of different types executed by 22 subjects (15 males, 7 females), average age 24.59 years. The force-plate method was selected as a reference procedure, to which the jumping ergometer results were related. For countermovement jumps, the relative error for jumping height was 3.55% (±2.92%), and for average power per kilogram body mass during the propulsion phase it was 23.79% (±4.85%). For serial rebound jumps, the respective errors were 7.40% (±4.58%) and 5.09% (±4.48%). Internal and nonvertical energy flow components amounted to about 3% of the total. It was concluded that, because of a number of invalid assumptions, unpredictable errors, and contradictory performance requirements, the validity and reliability of the jumping ergometer method for evaluating certain aspects of athletic performance are highly questionable.

Key Words: countermovement jumps, serial rebound jumps, energy flow components, jumping phase classification

Various methods are currently used to evaluate the myodynamic capability of the lower body musculature by means of two-legged vertical maximum effort jumps. Maximum effort is defined to mean either the attempt to obtain the individual maximum lifting height of the body center of mass (CM) by means of a single squat jump (from an initial squatting position), countermovement jump (from an initially erect standing position), or drop jump, or the attempt to achieve maximum heights in each of a series of vertical rebound jumps. While single jumps are purely anaerobic performances, continually executed maximum effort jumps may exhibit a substantial aerobic component depending, of course, on the duration of the series.

The parameters most commonly used (Bosco, Luhtanen, & Komi, 1983; Hamar & Tkac, 1990; Viitasalo, Österback, Alen, Rahkila, & Havas, 1987) to characterize the myodynamic jumping performance are the jumping height \( H \) (lifting height of the CM from the liftoff position to the vertex of the flight trajectory); the translational work done, \( w \), per kilogram body mass in accelerating the CM vertically during the (upward) propul-

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sion phase; the maximum (translational) power per kilogram body mass, $\bar{w}_{\text{max}}$, during that phase; and the corresponding average (translational) power, $\bar{w}$. An implicit assumption is, of course, that the motions involved in two-legged vertical jumps are simple enough that individual variations in the jumping technique are small and therefore do not significantly influence the results.

Fundamental to all the testing methods discussed here is the assumption that the vertical translational motion of the body CM represents the total body motion. This is not true in general because all body segments execute rotational and translational motions relative to the CM and, in addition, the CM itself executes nonvertical motions in the sagittal and lateral directions. This implies that an additional amount of skeletomechanical kinetic energy, the relative segmental kinetic or “internal” energy plus the nonvertical energy of the CM, is present in the system which is not accounted for by analyzing the vertical motion of the CM alone and may significantly influence the values of the energetic parameters.

The purposes of this study were (a) to investigate, for two-legged vertical jumps, the significance of the internal and nonvertical energy expended during the propulsion phase in relation to the total skeletomechanical energy of the system during that phase, and (b) to compare parameter values relating to the motion of the CM obtained using a force plate with the corresponding values determined by the jumping ergometer method (Bosco et al., 1983).

**Methods**

**Fundamental Relations and the Point Mass Body Model**

Any motion of the human body as a system of interconnected segments is governed by the mechanical laws determining the dynamics of multibody systems. For an appropriate model of the human skeletal system, the respective set of ordinary second-order differential equations describing the system dynamics can be derived and used to simulate motions for given initial conditions. This is the direct dynamics approach resulting in motion synthesis (Hatze, 1980a). Conversely, the differential equations of motion may be inverted, requiring as input the observed configurational coordinate histories, their first and second time derivatives, external forces, and other observable quantities. The output consists of nonobservables such as joint forces and torques, position and velocity of the body CM, translational and rotational energy, and power flow relations. This is the inverse dynamics approach representing biomechanical motion analysis (Hatze, 1980a, 1980b, 1984, 1986).

Both approaches are used to analyze vertical jumping performance. While the detailed biomechanical analysis of two-legged vertical jumps employing a segmented body model may serve as a reference method for determining all motion characteristics, synthesis of the motion of a point mass body model may provide some indirect insight into the muscular mechanisms producing that motion. The concept basic to the latter approach and hence to all the jumping evaluation methods to be discussed is that the internal muscle moments together with gravitational forces generate ground reaction forces either that can be measured directly (force plate method) or whose impulse can be inferred from other observables such as the flight time (jumping ergometer method).

Figure 1 displays the contour of a subject performing a two-legged vertical jump with his hands kept on his hips. The position vector $\mathbf{p} = (p_x, p_y, p_z)$ of the body center of mass, $G$, is taken relative to the spatial coordinate system OXYZ, with the X-axis pointing out of the plane. The external force vectors acting on the point mass model are the weight $-Mg\mathbf{k}$, with $\mathbf{k}$ denoting a unit vector in the Z-direction, and the ground reaction force
Figure 1 — Diagrammatic representation of the CM position vector $\mathbf{r}$ and the external force vectors acting on a subject performing a two-legged vertical jump. Details are in the text.

The vector $\mathbf{F}(t) = (F_x(t), F_y(t), F_z(t))$. Applying Newton’s second law in all three directions yields the three dynamic equations of motion for the center of mass $G$:

$$
\frac{d^2 \mathbf{r}_x}{dt^2} = \frac{F_x(t)}{M},
\frac{d^2 \mathbf{r}_y}{dt^2} = \frac{F_y(t)}{M},
\frac{d^2 \mathbf{r}_z}{dt^2} = \frac{F_z(t)}{M} - g,
$$

where $\frac{d^2 \mathbf{r}_{x,y,z}}{dt^2}$ are the accelerations in the three directions, $M$ is the mass of the subject, and $g = 9.81 \text{ m} \cdot \text{s}^{-2}$. In most cases, but not always, the jumps are executed fairly vertically so that the $X$- and $Y$-components of the ground reaction force may be negligible and only Equation 3 remains relevant. It may be instructive to show the graphs of typical functions as they appear on the right-hand sides of Equations 1–3. This is done in Figure 2 for a drop jump.

Integrating Equation 3 once yields the vertical velocity $\frac{d \mathbf{r}_z}{dt} = \dot{\mathbf{r}}_z$ of the CM as

$$
\dot{\mathbf{r}}_z(t) = \dot{\mathbf{r}}_{z_0} + \int_{t_0}^{t} [F_z(u)/M - g] \, du,
$$

with $\dot{\mathbf{r}}_{z_0}$ denoting the initial vertical velocity at $t = t_0$. A second integration gives the vertical position $\mathbf{r}_z(t)$ of the CM as

$$
\mathbf{r}_z(t) = \mathbf{r}_{z_0} + \int_{t_0}^{t} \dot{\mathbf{r}}_z(u) \, du,
$$

where $\mathbf{r}_{z_0}$ is the initial position at $t = t_0$.

If a force plate is used to record the reaction force components, then the integral in Equation 4 can be evaluated numerically. However, the initial vertical velocity $\dot{\mathbf{r}}_{z_0}$ and
position $\rho_{zo}$ are generally unknown, so that Equations 4 and 5 cannot be evaluated without additional information. This information can be obtained from a detailed biomechanical analysis of the jump, in which case all the required parameter values are available anyway without the need for further experiments. Or, the initial conditions of the vertical jump are such that the initial velocity either is zero (which is the case for countermovement and squat jumps starting from an initial resting position) or can be computed from information resulting from previous jumps. In the latter case, the liftoff velocity $\dot{\rho}_{zt}$ of the previous jump and the subsequent flight time $T_f$ are known, so that the initial velocity $\dot{\rho}_{zo}$ of the present jump can easily be found from

$$\dot{\rho}_{zo} = -\left(g T_f - \dot{\rho}_{zt}\right).$$  \hspace{1cm} (5a)

Thus, if $\dot{\rho}_{zo}$ is known, the vertical CM velocity can be found from Equation 4 and plotted in a graph. If, in addition, the initial vertical position $\rho_{zo}$ of the CM is also known, Equation 5 can also be solved and the vertical CM position may be plotted as a function of time. This has been done in Figure 3 for the drop jump whose characteristics were shown in Figure 2.

Phase Classification of the Jumping Motion

For the subsequent discussion, the following phase classification of the jumping motion is important. Only the dominant vertical motion will be considered. Referring to Figure 4, two major and four subphases can be identified:

1. Preparation Phase
   Characteristics: Downward motion of the CM ($\dot{\rho}_z < 0$).
   Duration: From $t = t_c = 0$ to $t = t_a$ (see Figure 4).
Figure 3 — Vertical CM velocity $\dot{r}_z(t)$ (thick line) and vertical CM position $r_z(t)$ (thin line) of the drop jump of Figure 2. The initial values are $\dot{r}_{z0} = -2.69 \text{ m} \cdot \text{s}^{-1}$ and $r_{z0} = 1.1107 \text{ m}$ and were obtained by a complete motion analysis of this drop jump.

Figure 4 — Phase classification of vertical jumping motions. Vertical acceleration (thick line) and velocity curve (thin line) relating to a drop jump. Detailed explanations are in the text.
Subphases:

a. Equalization Phase (present only in drop and serial rebound jumps)
Characteristics: Downward velocity is the same at beginning and end of phase.
\[ \dot{r}_z(t_{e}) = \dot{r}_z(t_{c}) = \dot{r}_z(t_0) \].
Duration: From \( t_{c} = 0 \) to \( t_{e} \).
Impulse: \( J_e(t_{e}, t_{c}) = 0 \).

b. Compression Phase
Characteristics: End of phase is determined by zero velocity, lowest point of CM has been reached (\( \dot{r}_z(t_a) = 0 \)).
Duration: From \( t_{c} \) to \( t_a \).
Impulse: \( J_c(t_{c}, t_a) = |\dot{r}_z(t_a)| \).

2. Propulsion Phase
Characteristics: Upward propulsion of the CM (\( \dot{r}_z > 0 \)).
Duration: From \( t_a \) to \( t_{l} \) (liftoff instant).
Subphases:

a. Acceleration Phase
Characteristics: Positive (upward) velocity and positive acceleration (\( \dot{r}_z > 0, \ddot{r}_z > 0 \)).
Maximum velocity is attained at the end of this phase.
Duration: From \( t_a \) to \( t_d \).
Impulse: \( J_a(t_a, t_d) > 0 \).

b. Deceleration Phase
Characteristics: Positive velocity but negative acceleration (\( \dot{r}_z > 0, \ddot{r}_z < 0 \)).
Duration: From \( t_d \) to \( t_{l} \).
Impulse: \( J_d(t_d, t_{l}) < 0 \).

Skeletomechanical Energy Flows

The total skeletomechanical energy content \( E \) of a segmented human body model equals the sum of the individual segmental energies \( E_i \). For a 17-segment model (Hatze, 1986), skeletomechanical energy content is given by

\[
E = \sum_{i=1}^{17} E_i = \sum_{i=1}^{17} (E_{i,\text{pot}} + E_{i,\text{tr}} + E_{i,\text{rot}}),
\]

(6)

where \( E_{i,\text{pot}}, E_{i,\text{tr}}, \) and \( E_{i,\text{rot}} \) denote respectively the potential, translational, and rotational energy of the \( i \)th segment. (More detailed expressions are given in the appendix.)

On the other hand, the total energy content \( E \) may also be expressed as the sum of the energy of the point mass \( M \) located at the CM and the sum of the “internal” energies \( E_{\text{int}} \) resulting from translational and rotational motions of the segments relative to the CM. Thus,

\[
E = Mg\dot{r}_z + \frac{1}{2} M(\dot{r}_z^2 + \dot{\dot{r}}_z^2) + \frac{1}{2} M\dot{\dot{r}}_z^2 + \sum_{i=1}^{17} E_{\text{int}},
\]

(7)

where the first, second, and third terms are the potential, nonvertical, and vertical kinetic energy of the CM, respectively, and the last term denotes the sums of the internal energies, an example of which is shown in Figure 5. Hence, if \( E \) can be computed from Equation 6, then the sum of the internal energies appearing in Equation 7 can easily be found by subtracting the CM energy contribution from \( E \).

Of special interest is, of course, the work done during the propulsion phase (see Figure 4). The total work \( W_{\text{tot}} \) done is given by the difference \( E(t_{l}) - E(t_a) \) between the
energy content of the system at liftoff time $t_l$ and that at time $t_a$ at the beginning of the propulsion phase. Equations 6 and 7 reveal (since $\dot{z}_a = 0$)

$$W = M g (\dot{z}_l - \dot{z}_a) + \frac{1}{2} M \ddot{z}_l^2 + \frac{1}{2} M (\dot{x}_l^2 + \dot{y}_l^2) + \sum_{i=1}^{17} \left[ E_{int}(t_i) - E_{int}(t_a) \right],$$

where the first two terms express the work $W_z$ done in the vertical direction only. The total skeletomechanical power $\dot{E}$ is obtained by simply differentiating Equations 6 and 7 with respect to time and substituting Equations 1–3:

$$\dot{E} = \sum_{i=1}^{17} \dot{E}_i = F_x \dot{x}_l + F_y \dot{y}_l + F_z \dot{z}_l + \sum_{i=1}^{17} \dot{E}_{int}.$$  

Again, if the total power $\dot{E}$ is known, the sum of the internal powers can be found from Equation 9, in which the first three terms on the right-hand side express the power of the CM. Using Equations 6, 7, and 8, the exact values of the internal segmental energies and the total work done can be computed and compared with the corresponding CM values.

**Performance Characteristic Parameters**

The following parameters relate to the point mass human body model moving vertically. The jumping height $H$ is easily found from the vertical liftoff velocity $\dot{z}(t_l)$ of the CM to be

$$H = \frac{\dot{z}_l^2(t_l)}{2g},$$

while the work done per kilogram body mass in accelerating the CM from its lowest to its liftoff position in the vertical direction over the propulsion distance $H_c$ is given by the sum of its potential and kinetic energy increments, that is, by

Figure 5 — History of the sum of all internal segmental energies present during the contact phase of a typical drop jump.
\begin{align*}
w &= g \int_{t_i}^{\hat{t}} \dot{\rho}_c(u) du + \frac{1}{2} \dot{\rho}_c(t_i) = gH_c + gH. \tag{11}
\end{align*}

The maximum vertical power per kilogram body mass during the propulsion phase is

\begin{align*}
\dot{w}_{\text{max}} &= \max \left[ F_z(t) \dot{\rho}_c(t)/M \right], \quad t \in [t_i, t_f], \tag{12}
\end{align*}

and the corresponding average power per kilogram body mass

\begin{align*}
\bar{w} &= w/(t_f - t_i). \tag{13}
\end{align*}

If a force plate recording $F_z(t)$ is used and the initial velocity $\dot{\rho}_{zo}$ is known, all of the above parameters can be computed with high precision.

The situation is, however, different for the jumping ergometer. With this device only contact and flight time in a series of repeated jumps can be recorded. From these two values, all of the above parameters, except $w_{\text{max}}$, can be computed, provided a number of assumptions hold true. As will be seen, these assumptions invalidate the jumping ergometer procedure. The relations corresponding to Equations 10, 11, and 13 for the jumping ergometer have been derived by Bosco et al. (1983) and are given by

\begin{align*}
H^* &= \frac{1}{2} g(T_c/2)^2, \tag{14}
\end{align*}

\begin{align*}
w^* &= gH^*_c + gH^*, \tag{15}
\end{align*}

\begin{align*}
\bar{w}^* &= w^*/(T_c/2), \tag{16}
\end{align*}

where $T_c$ and $T_f$ denote the contact and flight time, respectively, and the propulsion height $H^*_c$ (vertical distance of the CM from lowest to liftoff position) is computed from

\begin{align*}
H^*_c &= gT_cT_f/8. \tag{17}
\end{align*}

To distinguish the ergometer parameters from the force plate parameters, the former have been designated by an asterisk after the respective symbols.

**Error Analysis of the Force-Plate Method**

Since the force-plate method serves as a reference here, it is necessary to analyze the errors inherent in this technique. The accuracy in detecting the start of the motion is \pm 2 ms (four time steps of 0.5 ms each) and that of detecting the liftoff time is \pm 1 ms. The former error is of little consequence since the value of the integrand in Equation 4 is approximately equal to zero at $t = t_o$. Because the average contact time in serial rebound jumps is about 480 ms, the effective average time detection error is therefore 0.21%. The absolute error in the magnitude of the impulse is $\pm (-g \times 1 \text{ ms}) = \pm 0.00981 \text{ m} \cdot \text{s}^{-1}$ or 0.198% of the total impulse for an average jumping height of 0.313 m. Since the force plate was calibrated every time a trial was performed, the only significant error related to the magnitude of the force measurement was the nonlinearity, which is smaller than 0.05% for this type of force plate. Because of the extremely small intervals (0.5 ms) taken in evaluating the integral in Equation 4, the total error of the force-plate method amounts to maximally 0.41%. In view of the much larger discrepancies that occurred between force plate and
ergometer results (see Table 2 below), the choice of the force-plate method as a reference procedure appears to be well justified.

**Experimental Protocol**

Detailed biomechanical motion analysis was performed on six drop jumps, executed by 5 male subjects, to obtain information about possibly significant amounts of internal segmental energies and powers during vertical jumps. A series of countermovement and serial rebound jumps involving 17 subjects (10 males, 7 females) were used to compare the values of performance characteristic parameters obtained by the force-plate with those obtained by the jumping ergometer method. All subjects involved in this study gave informed consent. The subjects were students of physical education with an average age of 24.59 (±1.2) years, an average height of 179.2 (±8.7) cm for the males and 165.9 (±7.1) cm for the females, and an average body mass of 74.9 (±6.8) kg for the males and 57.9 (±8.3) kg for the females. Each countermovement jump was executed three times and the one with the highest performance was selected for analysis. Of the serial rebound jumps, the second one was analyzed.

The drop jumps started from a height of 38 cm. In all types of jumps performed, the subjects were instructed to keep their hands on their hips throughout the motion. All drop jumps were recorded with a Kodak-EM 1000 high-speed video system at a rate of 250 frames/s, while for all types of jumps the ground reaction forces were sampled by a Kistler force plate (type 9261A with amplifier type 9803) at a rate of 2,000/s. In addition, the contact and flight times of the jumps were also obtained from the force-plate records. Video and reaction force recordings were synchronized. An automatic marker image detection procedure was used to extract, from each recorded frame, the image coordinates of each of the eight landmarks attached to the subject’s body. The BIOMLIB® computer program MORECO performed the complete calibration and motion reconstruction procedure using for calibration the image coordinates of a calibration frame carrying 50 control markers with known spatial coordinates. The anthropometric-computational method of Hatze (1980b) together with the BIOMLIB® computer program ANSEPA was used to determine the segmental parameters of the subjects. With these and the time functions of the configurational coordinates and ground reaction forces as inputs, the BIOMLIB® program HOM2D2 computed all quantities required for a complete biomechanical motion analysis of the drop jumps. The values of the performance characteristic parameters 10–13 were computed by the BIOMLIB® program BIOSIG, using the ground reaction forces as inputs.

With $W_{\text{tot}}$ denoting the total work done during the propulsion phase and computed from Equation 8, and $W_z$, the work done in the vertical direction only, the relative error $\Delta_{wz}$ as a percentage can be calculated from

$$\Delta_{wz} = 100 \frac{|W_{\text{tot}} - W_z|}{W_{\text{tot}}}.$$  \hspace{1cm} (18)

**Results**

For six drop jumps, $W_{\text{tot}}$, $W_z$, and the relative error $\Delta_{wz}$ are presented in Table 1. Twenty-six countermovement and 40 serial rebound jumps performed by 17 subjects were analyzed with respect to performance characteristic parameters. For both the countermovement and serial rebound jumps, the respective means and standard deviations are listed in Table 2. All relative errors $\Delta_x$ were computed analogous to Equation 18 above.
Table 1  Work Done During Propulsion Phase

<table>
<thead>
<tr>
<th>Jump no.</th>
<th>$W_{tot}$ (J)</th>
<th>$W_z$ (J)</th>
<th>$\Delta_{wz}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3</td>
<td>571.5</td>
<td>565.2</td>
<td>1.09</td>
</tr>
<tr>
<td>B5</td>
<td>420.6</td>
<td>394.8</td>
<td>6.14</td>
</tr>
<tr>
<td>C3</td>
<td>401.8</td>
<td>387.2</td>
<td>3.63</td>
</tr>
<tr>
<td>C4</td>
<td>408.4</td>
<td>401.4</td>
<td>1.73</td>
</tr>
<tr>
<td>D5</td>
<td>570.2</td>
<td>552.4</td>
<td>3.12</td>
</tr>
<tr>
<td>E3</td>
<td>472.4</td>
<td>470.6</td>
<td>0.38</td>
</tr>
<tr>
<td>Mean</td>
<td>474.2</td>
<td>461.9</td>
<td>2.7</td>
</tr>
<tr>
<td>SD</td>
<td>78.9</td>
<td>80.8</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Note. $W_{tot}$ (J) = total work done; $W_z$ (J) = work done in vertical direction only; $\Delta_{wz}$ (%) = relative error.

Table 2  Performance Characteristic Parameter Values

<table>
<thead>
<tr>
<th>Type of motion</th>
<th>Countermovement jump $(n = 26)$</th>
<th>Serial rebound jump $(n = 40)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$</td>
<td>$SD$</td>
</tr>
<tr>
<td>$H$ (m)</td>
<td>0.313</td>
<td>0.057</td>
</tr>
<tr>
<td>$H*$</td>
<td>0.324</td>
<td>0.058</td>
</tr>
<tr>
<td>$\Delta_H$ (%)</td>
<td>3.55</td>
<td>2.92</td>
</tr>
<tr>
<td>$w$ (J/kg)</td>
<td>7.33</td>
<td>0.96</td>
</tr>
<tr>
<td>$w*$</td>
<td>8.48</td>
<td>1.17</td>
</tr>
<tr>
<td>$\Delta w$ (%)</td>
<td>15.81</td>
<td>8.52</td>
</tr>
<tr>
<td>$\bar{w}$ (W/kg)</td>
<td>26.04</td>
<td>3.96</td>
</tr>
<tr>
<td>$\bar{w}*$</td>
<td>19.79</td>
<td>2.73</td>
</tr>
<tr>
<td>$\bar{\Delta} w$ (%)</td>
<td>23.79</td>
<td>4.85</td>
</tr>
<tr>
<td>$\dot{w}_{max}$ (W/kg)</td>
<td>44.4</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Note. $H$ = jumping height; $w$ = work done per kilogram body mass during propulsion phase; $\bar{w}$ = average power per kg body mass during propulsion phase; $\Delta$ = respective relative error; $\dot{w}_{max}$ = max power per kg body mass during propulsion phase. Symbols designated by an asterisk relate to jumping ergometer parameters.
In Table 3 are the means and standard deviations of the propulsion height $H_c$ as computed from Equations 10 and 11, $H_c^*$ as calculated from Equation 14, the relative error $\Delta_{hc}$, and the propulsion to total contact time ratio $\tau/T_c$.

### Discussion and Conclusion

#### Efficiency of Vertical Propulsion

The first objective of this study was to investigate the relationship between the (useful) work done in the vertical direction during the propulsion phase of drop jumps and the total work performed during that phase. As can be seen from Table 1, the average relative difference is 2.7% with a maximum of 6.14%. This means that during drop (and serial rebound) jumps, a comparatively small average amount, about 3%, of the total muscular work done during propulsion is expended for internal and nonvertical propulsive efforts. The large standard deviation of 2.9% indicates the great variability of this energy component. A similar situation is likely to prevail in countermovement jumps.

Also of interest is the shape of the curve depicting the internal energy fluctuations as shown in Figure 5. As the subject lands on the force plate ($t = 0$), the internal energy of the system is small because there is little motion of the segments relative to the CM. This changes during the compression phase, where the internal energy content rises considerably and subsequently falls. At the end of the compression and beginning of the propulsion phase ($t \approx 0.105$ s), this content reaches a minimum again because the subjects are almost stationary at this point. Subsequently, the internal energy rises again because of vigorous propulsive movements and then declines rapidly toward the moment of liftoff. The internal skeletomechanical energies just discussed are not, or are only partly, related to the energy transfers taking place between the skeletal and the muscular system (stretch–shortening cycles) during the compression and propulsion phase.

#### Performance Characteristic Parameters

The second objective of the present investigation was to compare the performance characteristic parameter values of countermovement and serial rebound jumps obtained with the force-plate (reference) method with the corresponding values determined using the jump-

### Table 3  Propulsion Height and Time Ratio

<table>
<thead>
<tr>
<th>Type of motion</th>
<th>Countermovement jump ($n = 26$)</th>
<th>Serial rebound jump ($n = 40$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$</td>
<td>$SD$</td>
</tr>
<tr>
<td>$H_c$ (m)</td>
<td>0.434</td>
<td>0.058</td>
</tr>
<tr>
<td>$H_c^*$ (m)</td>
<td>0.541</td>
<td>0.080</td>
</tr>
<tr>
<td>$\Delta_{hc}$ (%)</td>
<td>24.99</td>
<td>14.63</td>
</tr>
<tr>
<td>$\tau/T_c$</td>
<td>0.332</td>
<td>0.037</td>
</tr>
</tbody>
</table>

*Note.* $H_c$ = propulsion height; $H_c^*$ = propulsion height as computed from Equation 17; $\Delta_{hc}$ = relative error; $\tau/T_c$ = ratio of propulsion to total contact time.
ing ergometer. In the Methods section it was shown that the errors associated with the
force-plate method are negligibly small so that use of this method as a reference pro-
dure is well justified. The results relating to both types of jumps are summarized in Tables
2 and 3. Parameters not designated by asterisks pertain to the force-plate (reference) method.

The relative average error \( \Delta_H \) for the jumping height \( H \) is 3.55% for countermove-
ment jumps and 7.40% for serial rebound jumps. The value found for countermovement
jumps compares well with the relative average error of 2.81% \((N = 18)\) obtained by Frick,
Schmidtbleicher, and Wörn (1991) in a similar investigation. However, the 18 jumps that
Frick et al. chose for analysis represent a biased sample selected by visual inspection of
the jumping motion from a sample of 91 jumps. The selection criterion was the similarity
between takeoff and landing configuration of the body. This explains the relatively small
error found by Frick et al., because the difference between the takeoff and landing con-
figuration is responsible for the discrepancy between \( H \) and \( H^* \). These authors did not
study serial rebound jumps.

The larger average error of 7.40% for serial rebound jumps can be explained by a
more unstable jumping motion resulting from the effort to maximize performance in re-
peted jumps. It was also observed that in all jumps executed (countermovement and
serial rebound), the value of \( H^* \) was always larger than that of \( H \), which agrees with the
findings of Frick et al. (1991) and is explained by the fact that the leg joints are more
flexed during landing than at takeoff, resulting in a longer flight time and larger \( H^* \). In
addition, the variation in the error is comparatively large, ranging from 0.38% to 11.36%
for countermovement jumps and from 0.0% to 19.12% for serial rebound jumps, making
it practically impossible to predict the size of the error.

The most important performance characteristic parameter is the average power per
kilogram body mass, \( \bar{w} \), exerted during the propulsion phase. The average error \( \Delta_w \) found
(see Table 2) is 23.79% \((\pm 4.85\%)\) for countermovement jumps and 5.09% for serial re-
bound jumps, albeit with a comparatively large standard deviation of 4.48%.

The origin of the errors observed can be traced back to the assumptions that Bosco
et al. (1983) made in deriving their Equations 4–10. These assumptions were that (a)
takeoff and landing body configurations are identical, (b) vertical CM velocity increases
linearly during the propulsion phase, and (c) the propulsion period is equal to half the total
contact time. In general, none of these assumptions holds true. The errors introduced by
the first assumption are most clearly visible in the discrepancy between \( H \) and \( H^* \) and have
already been discussed. The second assumption implies, by Equation 4, that the ground
reaction force remains constant during the propulsion phase. That this is certainly not the
case can be inferred from Figure 2. In addition, Figure 3 quite clearly demonstrates that
vertical velocity does not increase linearly during that phase but increases in a highly
nonlinear fashion and finally actually decreases just before takeoff. The third assumption,
that the ratio \( \tau/T c \) of propulsion to total contact time is always equal to 0.5, is also incorrect
as is evident from Table 3. Indeed, this ratio varies between 0.476 and 0.639 with a mean
value of 0.538 for the serial rebound jumps investigated, while for countermovement jumps,
the mean value is as low as 0.332. This low value of \( \tau/T c \) implies that the value of \( T/2 \) is
grossly overestimated, which, by Equation 17 and by including the effect of the velocity
linearity assumption, inflates the value of \( H^* \) (see Table 3). This, in turn, generates large
values of \( w^* \), as can be seen from Table 2. Dividing \( w^* \) by the incorrectly large value of \( T/2 \)
(see Equation 16) overcompensates the previous effects and gives an average power that
is too small (Table 2).

For serial rebound jumps, the situation is reversed: \( H^* \) is underestimated by 25%,
leading to reduced values of the normalized propulsion work \( w^* \). But, owing to overin-
flated values of $\tau/T_c$ (see Table 3), the values of $T_c/2$ used in Equation 16 become too small, which, purely by chance, results in realistic values of the normalized average power. The average error of 5.09% ($\pm 4.48\%$) would just be acceptable were it not for the randomness of the large variations, which range from 0.29% to as much as 14.58% and are due partly to intrasubject and partly to intersubject variability. In summary, the effects of all three invalid assumptions listed above combine to produce the erroneous results observed.

As regards the 29.7 W/kg found in the present investigation for average power in serial rebound jumps, its magnitude compares well with the values frequently reported in the literature for volleyball (26.7 W/kg) and basketball (24.7 W/kg) players executing serial rebound jumps over a 15 s period. The value obtained in the present study is somewhat higher because the second, maximally executed, serial jump was analyzed, while the values reported in the literature reflect an average performance over 15 s. Lower values (mean 20.1 W/kg) were reported by Viitasalo et al. (1987) for young athletes aged 9 to 17 years, while Kirkendall and Street (1986) found low values (average 20.37 W/kg) for professional athletes, at least partly because their tests lasted for long periods—60 s. The results reported by Hamar and Tkac (1990) for 73 young athletes cover a wide range (19–51 W/kg) but are difficult to interpret because they were computed using erroneous formulas (formulas 12, 14, 16, and 17 of Hamar & Tkac, 1990).

In discussing the normalized average power values obtained with the jumping ergometer method for serial rebound jumps, it must be pointed out that the conditions prescribed by Bosco et al. (1983, p. 274) for executing the jumps are, in fact, contradictory. The authors required that the jumps be performed “with maximal effort,” thereby imposing an optimality criterion and, at the same time, demanded that subjects “bend the knees to about 90 degrees” to “standardize the knee angular displacement during the contact phase.” The latter requirement imposes a motion constraint that directly contradicts the maximum-effort criterion. Either a motion is optimal in the above maximum-effort sense and therefore is free of standardization constraints, or its form is prescribed by normalization requirements and thus is restricted and no longer optimal. The simultaneous fulfillment of both conditions is not possible. This is a serious shortcoming of the jumping ergometer method.

In conclusion, about 97% of the total power (energy) exerted during vertical maximum-effort jumps is used for pure vertical propulsion. The rest is “lost” in the form of internal segmental energy flows and nonvertical power components. The above results demonstrate that the jumping ergometer method is not suitable for evaluating single countermovement jumps, a fact that cannot be held against the method, since it was not devised for this purpose. On the other hand, the combined and largely unpredictable effects of the invalid assumptions discussed above, together with an average error of about 5% associated with an excessively large standard deviation of 4.48%, seriously call into question the validity and reliability of the jumping ergometer method for evaluating serial rebound jumps also. A further argument in this direction is the inconsistency of the maximum-effort requirement and the imposed motion constraint, as has already been discussed. Because of this, the results obtained in a specific series of jumps will strongly depend on which of the two contradicting criteria dominates. Thus, the jumping ergometer method cannot be considered reliable for evaluating certain aspects of athletic performance.

References


**Appendix**

**Total Skeletomechanical Energy and Power of a Three-Dimensional Segmented Human Body Model**

The total energy is given by (Hatze, 1986)

\[
E = \sum_{i=1}^{17} m_i g r_i + \frac{1}{2} m_i (\ddot{r}_i^2 + \dot{r}_i \cdot \dot{r}_i + \dot{r}_i \cdot \dot{r}_i) + \frac{1}{2} \omega_i \cdot J_i \cdot \omega_i, \quad (A1)
\]

where \( m_i \), \( r_i \), \( \dot{r}_i \), \( \ddot{r}_i \), \( \omega_i \), and \( J_i \) denote, respectively, the mass, Z-component of the segmental CM position vector, X-, Y-, and Z-component of the segmental CM velocity vector, angular velocity vector, and inertia tensor of the \( i \)th segment. The constant \( g \) has a value of 9.81 m · s \(^{-2}\). The total power is

\[
E = \sum_{i=1}^{17} m_i g \dot{r}_i + m_i \ddot{r}_i \cdot \dot{r}_i + \omega_i \cdot J_i \cdot \omega_i, \quad (A2)
\]

where \( \dot{r}_i \) is the segmental CM velocity vector, \( \ddot{r}_i \) is the segmental CM acceleration vector, \( \omega_i \) is the angular acceleration vector, and the remaining symbols have the meanings defined previously.

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