Intersession Reliability of Kinematic and Kinetic Variables During Vertical Jumps in Men and Women

Gavin L. Moir, Alberto Garcia, and Gregory B. Dwyer

Purpose: To investigate the intersession reliability of selected kinematic and kinetic variables during countermovement vertical jumps (CMJs). Methods: Thirty-five men and 35 women performed CMJs on a force platform during four testing sessions each separated by 1 wk. Kinematic variables included time in the air (TIA), take-off velocity (TOV), total vertical displacement of the center of mass (TJH), and countermovement depth, whereas kinetic variables included positive impulse, negative impulse, vertical stiffness, and rates of force development. Systematic bias was assessed by calculating the 90% confidence interval of the change in the mean between consecutive testing sessions and between the first and final testing session for each variable. Coefficients of variation (CV) and intraclass correlation coefficients (ICC) were also calculated. Results: Systematic bias was observed only for peak rate of force development during the concentric phase of the movement. For TIA, TOV, and TJH, CV values ranged from 1.7% to 6.6%, with ICC values ranging from 0.82 to 0.97. The other variables showed greater variation (CV range: 1.7% to 39.9%; ICC range: 0.04 to 0.99). Only slight gender differences were found in the reliability statistics, and the reliability of most of the variables was diminished as the time between the testing sessions was increased. Conclusion: Even though practitioners can expect good reliability for jump height measured from a force platform in men and women, other kinematic and kinetic variables often assessed during vertical jumps may not be reliable.

Keywords: countermovement vertical jump, force platform, reliability

Vertical jumps are commonly used to assess the explosive strength of the leg musculature of athletes.1,2 Although one of the most common variables calculated is jump height, through the use of a force platform, variables such as impulse, vertical stiffness, and rate of force development can provide practitioners and researchers with further information about athletic ability.3–8 Despite the appeal of using a force platform to measure vertical jump performance, practitioners and researchers must consider the reliability of the variables obtained. The reliability of a measure is concerned with the reproducibility across multiple trials, with a
reliable measure characterized by small within-subject variation and a high test–retest correlation. Recently, there has been a call for researchers to investigate the sources of variation associated with various biomechanical measurements because the quantification of the sources of variation can allow researchers to employ methods of minimizing errors.

A number of researchers have noted that low variation in the outcome measures associated with movement tasks can be achieved despite considerable variation in the execution of the movements themselves. It also appears that the outcome variables in biomechanical analyses may demonstrate high levels of reliability, whereas variables that characterize the execution of the movement may not. For example, in an analysis of the reliability of kinematic and kinetic variables associated with sprint running, Hunter, Marshall, and McNair found that the horizontal velocity of the center of mass demonstrated very good reliability, whereas the reliability of variables such as the relative height of the center of mass at takeoff and relative vertical ground reaction impulse was poor. In vertical jumps, jump height can be considered as the outcome of the movement, while variables such as rate of force development contribute to the performance but can be regarded as variables that characterize the execution of the movement. During a series of squat jumps, Moir et al reported that takeoff velocity, from which jump height can be calculated, showed greater reliability than peak rate of force development measured on a force platform in men. Moreover, Aragón-Vargas and Gross showed that even the best male jumpers demonstrated large variation in certain mechanical variables, such as time differences between joint torques and joint reversals during countermovement vertical jumps (CMJ) despite low variation in the outcome of the movement (jump height). These findings have implications for the reliability of mechanical variables associated with vertical jumps performed on a force platform, particularly those performance variables that characterize the execution of the movement, such as negative and positive impulse, vertical stiffness, and rate of force development.

The magnitude of a change in a given variable required for a real effect to have occurred can be calculated using reliability statistics, whereas sample sizes required for future research studies can also be computed. Therefore, reliability statistics are important for both practitioners and researchers. However, much of the previous research investigating the reliability of biomechanical measures associated with vertical jumps has used small sample sizes, which have been shown to result in unacceptably large confidence limits associated with the reliability statistics. Similarly, male subjects are the main focus of previous studies investigating the reliability of force variables recorded from force platforms, with no data available on women—an important omission given that previous investigators have identified gender as a source of between-subject error in biomechanical measures. Therefore, the purpose of the current study was to calculate the intersession reliability of kinematic and kinetic measures associated with CMJs performed by men and women.

**Methods**

**Subjects**

Thirty-five physically active men (mean age = 21.5 ± 2.3 y; mean height = 1.78 ± 0.08 m; mean body mass = 83.1 ± 14.5 kg) and 35 physically active women (mean
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age = 21.0 ± 2.1 y; mean height = 1.64 ± 0.06 m; mean body mass = 63.1 ± 8.0 kg) volunteered to participate in this study, which was approved by the Institutional Review Board for the Protection of Human Subjects of East Stroudsburg University. Of the men, 45% were engaged in organized sport at the time of the study and had been competing in that sport for 8.6 ± 3.2 y. Fifty percent of these subjects were currently competing at the university level (football, soccer, track and field). The men reported working out 4.7 ± 1.1 times per week, with 90% reporting that they were currently engaged in resistance training, 55% reporting engaging in endurance training, and 30% reporting engaging in speed training. Fifty-two percent of the women reported being involved in organized sport at the time of the study, with 43% of these competing at the university level (soccer, softball, track and field, volleyball). They reported competing in their sport for 9.6 ± 4.9 y at the time of the study. The women reported working out 4.7 ± 1.2 times per week, with 76% reporting that they were currently engaged in some form of resistance training, 71% engaging in endurance training, and 19% engaging in speed training workouts.

Design

This study used a single-group, repeated-measures design. The subjects performed four testing sessions across a 4-wk period, with each session separated by 1 wk. The subjects reported to the laboratory at the same time of day each week and were advised to avoid strenuous physical activity 48 h before the tests and maintain their normal diet and physical activities throughout. Within each session, subjects completed three CMJs for maximum height and the mean kinematic and kinetic variables were calculated. Systematic bias was assessed by investigating the changes in the means between consecutive testing sessions and between the first and fourth sessions. Sessions were removed from the subsequent analysis if necessary. Within-subject variation and retest correlations were then calculated. Within-subject variation should be calculated across a brief period in which the changes in the mean are not likely to be considerable. Therefore, the reliability between consecutive testing sessions was included in the present investigation. However, when using retest correlations to estimate sample size for a longitudinal study, it is important that the reliability study reflect the length of the proposed longitudinal study, unless one assumes that the variation will not change substantially. For this reason, the reliability statistics were also calculated using the data from the first and fourth testing sessions.

Methodology

During each testing session, subjects completed a standardized warm-up consisting of dynamic exercises and then performed three CMJs for maximal height on a force platform (Kistler, type 9286AA, Winterthur, Switzerland). The analog signal was sampled by a 16-bit A/D board (DAS16/16, Measurement Computing, MA) at 1,202 Hz, as a frequency of this magnitude has been shown to reduce the error associated with vertical jump height calculated from a force platform. Neither the analog nor digital signals were filtered. Before each testing session, the reading from the force platform was verified using loads of known weight. The natural frequency (159.3 Hz), linearity error (3.90% [0.17% full scale output]), and maxi-
mum hysteresis (1.10% [0.05% full scale output]) associated with the vertical forces were calculated following the procedures of Psycharakis and Miller.\textsuperscript{22}

The subjects placed their hands around their neck during each jump to remove the influence of the arms, and 4 min of rest was provided between jumps. The rest interval was slightly greater than used in previous reliability studies because of the number of subjects involved, but the subjects were free to walk around the laboratory during this time. Five seconds of force data were collected during each jump, and the subject’s body weight was calculated by averaging the vertical force over the first 1 s of data collection, when the subject was stationary on the platform. The start of the movement was identified by calculating the peak residual from the vertical force trace during the 1 s of quiet stance (greatest difference between the vertical force trace and the subject’s body weight). Specifically, the start of the movement was identified as the first time instant when the vertical force trace was greater (less) than the addition (subtraction) of the peak residual during quiet stance and the subject’s body weight, depending upon whether the initial movement by the subject caused an increase or decrease of vertical force. From the start of the movement, the vertical force trace was then taken back until a value within 1 N of the subject’s body weight was identified, and this was used as the start of the jump. Takeoff was identified by calculating the peak residual across a 0.3-s period during the flight phase of the jump with the force platform unloaded (greatest difference between the vertical force trace and 0 N). This period was chosen because all subjects were able to produce a flight phase greater than 0.3 s. The peak residual during flight was used to identify both takeoff (when the vertical force trace < peak residual during flight) and contact after flight (when the vertical force trace > peak residual during flight). These methods of identifying the start of the movement and takeoff are similar to those previously used by Street et al.\textsuperscript{21}

The following kinematic variables were calculated from the vertical force trace:

- **Time in the air (TIA)** — the period between takeoff and contact after flight was used as the time in the air during the flight phase of the jump.
- **Vertical velocity at takeoff (TOV)** — the net vertical force trace was integrated using the trapezoid rule once the trace had been normalized to body mass to calculate the vertical velocity of the center of mass (COM) at takeoff. Integration began at the start of the jump and ended at takeoff.
- **Total vertical displacement of the center of mass (TJH)** — the total vertical displacement of the COM from the starting stance to the highest displacement achieved during flight was calculated by double integration of the net vertical force trace once the trace had been normalized to body mass. The positive vertical displacement of the COM before takeoff (the difference between vertical position of COM during stance and that at takeoff; Figure 1) was then added to the jump height calculated from the following equation of uniform acceleration:

\[
\text{Jump height} = \frac{\text{TOV}^2}{2g}
\]

(1)

where TOV = vertical velocity of the COM at takeoff and \(g = 9.81 \text{ m/s}^{-2}\). This allowed the calculation of total positive vertical displacement of the COM from the subject’s starting position to the maximum vertical projection during flight.

- **Countermovement depth (NDis)** — the negative displacement of the COM when the subject was in contact with the force platform was calculated through
Figure 1 — A representative graph of the vertical force trace and vertical displacement of the center of mass during contact of CMJ. The eccentric and concentric phases of the movement are highlighted, as are the regions on the force trace where the rate of force development calculations were made. Note. The vertical displacement of the center of mass rises above that during quiet stance before takeoff.
the double-integration of the net vertical force trace once the trace had been normalized to body mass. The greatest negative value was used for NDis (Figure 1).

The following kinetic variables were also calculated from the vertical force trace:

**Positive vertical impulse (PImp)**—the integration of the vertical force trace above body weight provided the positive vertical impulse during propulsion. Integration (trapezoid rule) began at the start of the jump and ended at takeoff.

**Negative vertical impulse (NImp)**—the integration of the vertical force trace below body weight provided the negative vertical impulse during propulsion. Integration (trapezoid rule) began at the start of the jump and ended at takeoff.

**Vertical stiffness (VStiff)**—the vertical stiffness during the contact phase of the jump was calculated as the ratio of the vertical force to NDis.

**Peak rate of force development during the concentric phase (CaRFD)**—the greatest value of the first derivative of vertical force with respect to time (calculated using the first central difference method) that occurred during the concentric phase of the movement provided the peak rate of force development during the concentric phase (Figure 1). The concentric phase of the movement was identified from the displacement of the COM when the subject was in contact with the force platform.

**Peak rate of force development during the eccentric phase (EaRFD)**—the greatest value of the first derivative of vertical force with respect to time (calculated using the first central difference method) that occurred during the eccentric phase of the movement provided the peak rate of force development during the eccentric phase (Figure 1). The eccentric phase of the movement was identified from the displacement of the COM when the subject was in contact with the force platform.

**Average rate of force development during the concentric phase (CaRFD)**—the difference between the maximum and minimum vertical force during the concentric phase of the movement was divided by the time between these two events to provide the average rate of force development during the concentric phase (Figure 1). The concentric phase of the movement was identified from the displacement of the COM when the subject was in contact with the force platform.

**Average rate of force development during the eccentric phase (EaRFD)**—the difference between the maximum and minimum vertical force during the eccentric phase of the movement was divided by the time between these two events to provide the average rate of force development during the eccentric phase (Figure 1). The eccentric phase of the movement was identified from the displacement of the COM when the subject was in contact with the force platform.

For the current study, TIA, TOV, and TJH were considered as outcome variables because jump height can be calculated from each of these variables. The other variables were considered to contribute to the outcome of the movement (jump height), but were regarded as those variables that characterize the execution of the movement, and so are referred to as *performance variables*.

**Statistical Analysis**

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows, version 15.0, SPSS Inc., Chicago, IL). Measures of
central tendency and spread of the data were represented as means and standard deviations (SD). Reliability was calculated as systematic bias, random error, and test–retest correlation. Systematic bias in the data were assessed by investigating the change in the mean between testing sessions through constructing the 90% confidence limits (90% CL) of the difference from a repeated-measures ANOVA. The data from sessions were removed if there were substantial differences between them. The heteroscedasticity of the data was assessed by plotting the standard deviation of the trials against the mean of the trials for each subject, and the data were log-transformed if necessary. Random error was calculated as the typical error derived from the subject error term of a two-way mixed-method consistency model. The typical error was expressed as a coefficient of variation (CV) for each variable. Test–retest correlations were calculated for each variable as intraclass correlation coefficients (ICC) derived from a two-way mixed-method consistency model. These statistics were calculated between consecutive testing sessions and also between the first and final testing sessions.

Results

Table 1 shows the mean (±SD) for the kinematic and kinetic variables calculated across the four testing sessions for both the men and women.

Systematic Bias

There were substantial changes in the mean for CpRFD between sessions 1 and 2 in women (mean difference: −1621 N∙s⁻¹; 90% CL: −2717 to −524 N∙s⁻¹) and between sessions 1 and 4 in men (mean difference: −1333 N∙s⁻¹; 90% CL: −2440 to −226 N∙s⁻¹). Therefore, CV and ICC statistics were not calculated across these sessions for CpRFD.

Coefficient of Variation and Intraclass Correlation Coefficients

Owing to the presence of heteroscedasticity, the data were log-transformed. Tables 2 and 3 show the CV and ICC values for each of the kinematic and kinetic variables.

Discussion

The purpose of the current study was to investigate the intersession reliability of selected kinematic and kinetic variables during CMJs in men and women. With the exception of CpRFD, there was no evidence of systematic bias for any of the variables recorded in the current study. Although previous researchers have reported a lack of systematic bias in kinematic and kinetic variables associated with squat jumps in physically active men, this is the first study to report such a finding in physically active women. It would appear that familiarization trials are not required when recording most kinematic and kinetic variables during CMJs when dealing with physically active subjects. This finding is probably caused by
the fact that the subjects used in the current study performed many jump-related movements in their reported physical activities.

From the results of previous research, it was proposed that those variables from which jump height could be calculated (outcome variables) would display less variation than the variables that characterize the execution of the movement (performance variables), such as countermovement depth, positive and negative impulse, vertical stiffness, and rates of force development. The results of the current study tend to confirm this proposition. For example, TIA, TOV, and TJH all demonstrated the lowest CV and some of the highest ICC values in both men and women (see Tables 2 and 3). In comparison, the largest variation was reported for NDis, NImp, VStiff, and rates of force development—all variables that, although contributing to the outcome of the jump, may be more related to the execution of the movement.

The results of the current study demonstrated that the reliability of the kinematic and kinetic variables between consecutive sessions tended to improve as more sessions were performed. However, when intersession statistics were calculated over a larger interval (Session 1 to Session 4), all variables tended to become less reliable (see Tables 2 and 3), confirming the findings of previous studies. Despite this, there was little difference between the reliability statistics for men and women, and so, unlike other movements, there does not appear to be any gender differences in the variation associated with kinematic and kinetic variables during CMJs.

Table 1  Values for the kinematic and kinetic variables calculated during countermovement vertical jumps in men and women averaged across the four testing sessions*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Men</th>
<th>Women</th>
</tr>
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<tbody>
<tr>
<td>TIA (s)</td>
<td>0.54 ± 0.05</td>
<td>0.41 ± 0.05</td>
</tr>
<tr>
<td>TOV (m s(^{-1}))</td>
<td>2.60 ± 0.21</td>
<td>1.97 ± 0.23</td>
</tr>
<tr>
<td>TJH (m)</td>
<td>0.45 ± 0.06</td>
<td>0.29 ± 0.05</td>
</tr>
<tr>
<td>NDis (m)</td>
<td>0.40 ± 0.06</td>
<td>0.33 ± 0.06</td>
</tr>
<tr>
<td>PImp (N s(^{-1}))</td>
<td>329 ± 59</td>
<td>208 ± 32</td>
</tr>
<tr>
<td>NImp (N s(^{-1}))</td>
<td>113 ± 23</td>
<td>80 ± 15</td>
</tr>
<tr>
<td>VStiff (kN s(^{-1}))</td>
<td>4.68 ± 0.95</td>
<td>3.91 ± 1.00</td>
</tr>
<tr>
<td>CpRFD (N s(^{-1}))</td>
<td>7,570 ± 1,437</td>
<td>7,165 ± 2,067</td>
</tr>
<tr>
<td>EpRFD (N s(^{-1}))</td>
<td>13,444 ± 3,132</td>
<td>11,585 ± 6,185</td>
</tr>
<tr>
<td>CaRFD (N s(^{-1}))</td>
<td>1,932 ± 569</td>
<td>1,405 ± 819</td>
</tr>
<tr>
<td>EaRFD (N s(^{-1}))</td>
<td>3,960 ± 1,347</td>
<td>2,674 ± 796</td>
</tr>
</tbody>
</table>

*Values are means ± standard deviations. TIA = time in air; TOV = take-off velocity; TJH = total jump height; NDis = negative displacement of the center of mass; PImp = positive impulse; NImp = negative impulse; VStiff = vertical stiffness; CpRFD = peak rate of force development during the concentric phase; EpRFD = peak rate of force development during the eccentric phase; CaRFD = average rate of force development during the concentric phase; EaRFD = average rate of force development during the eccentric phase.
<table>
<thead>
<tr>
<th></th>
<th>Session 1–Session 2</th>
<th>Session 2–Session 3</th>
<th>Session 3–Session 4</th>
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</tr>
</thead>
<tbody>
<tr>
<td>CV 90% CL ICC 90% CL</td>
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</tr>
<tr>
<td>TIA</td>
<td>2.3 1.9–2.9 0.92 0.86–0.95</td>
<td>1.7 1.4–2.1 0.97 0.95–0.98</td>
<td>1.9 1.6–2.4 0.95 0.91–0.97</td>
<td>2.9 2.4–3.6 0.87 0.78–0.93</td>
</tr>
<tr>
<td>TOV</td>
<td>2.1 1.8–2.6 0.93 0.88–0.96</td>
<td>1.9 1.6–2.4 0.95 0.91–0.97</td>
<td>1.7 1.4–2.1 0.96 0.93–0.98</td>
<td>2.8 2.3–3.5 0.88 0.80–0.93</td>
</tr>
<tr>
<td>TJH</td>
<td>3.3 2.8–4.1 0.93 0.88–0.96</td>
<td>3.4 2.8–4.3 0.94 0.90–0.97</td>
<td>3.3 2.8–4.1 0.94 0.90–0.97</td>
<td>5.6 4.7–7.0 0.82 0.70–0.90</td>
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<tr>
<td>NDis</td>
<td>6.7 5.6–8.4 0.86 0.76–0.92</td>
<td>5.9 4.9–7.4 0.90 0.83–0.94</td>
<td>4.6 3.9–5.8 0.92 0.86–0.95</td>
<td>10.0 8.4–12.5 0.63 0.42–0.77</td>
</tr>
<tr>
<td>PImp</td>
<td>2.7 2.3–3.4 0.98 0.96–0.99</td>
<td>1.7 1.4–2.1 0.99 0.98–0.99</td>
<td>2.6 2.2–3.3 0.98 0.96–0.99</td>
<td>3.6 3.0–4.5 0.96 0.93–0.98</td>
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<tr>
<td>NiImp</td>
<td>5.9 4.9–7.4 0.91 0.84–0.95</td>
<td>4.6 3.9–5.8 0.95 0.91–0.97</td>
<td>5.6 4.7–7.0 0.94 0.90–0.97</td>
<td>8.8 7.4–11.0 0.82 0.70–0.90</td>
</tr>
<tr>
<td>VStiff</td>
<td>7.1 5.9–8.9 0.89 0.81–0.94</td>
<td>5.1 4.3–6.4 0.95 0.91–0.97</td>
<td>5.2 4.4–6.5 0.93 0.88–0.96</td>
<td>9.3 7.8–11.7 0.78 0.64–0.87</td>
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<tr>
<td>CpRFD</td>
<td>27.8 23.3–34.8 0.48 0.24–0.67</td>
<td>33.2 27.8–41.6 0.15 –0.13–0.41</td>
<td>29.4 24.6–36.8 0.04 –0.25–0.31</td>
<td>N/A</td>
</tr>
<tr>
<td>EpRFD</td>
<td>20.5 17.2–25.7 0.61 0.40–0.76</td>
<td>21.8 18.2–27.3 0.58 0.36–0.74</td>
<td>19.1 16.0–23.9 0.58 0.35–0.74</td>
<td>18.5 15.5–23.2 0.58 0.36–0.74</td>
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<tr>
<td>CaRFD</td>
<td>30.0 25.1–37.6 0.64 0.45–0.78</td>
<td>33.4 27.9–41.8 0.48 0.23–0.67</td>
<td>26.3 22.0–33.0 0.53 0.29–0.70</td>
<td>35.6 29.8–44.6 0.37 0.11–0.59</td>
</tr>
<tr>
<td>EaRFD</td>
<td>17.3 14.5–21.7 0.80 0.67–0.88</td>
<td>13.2 11.0–16.5 0.90 0.83–0.94</td>
<td>15.6 13.1–19.5 0.85 0.75–0.91</td>
<td>20.6 17.2–25.8 0.69 0.51–0.81</td>
</tr>
</tbody>
</table>

CV = coefficient of variation (%); ICC = intraclass correlation coefficient; 90% CL = 90% confidence limits; TIA = time in air; TOV = take-off velocity; TJH = total jump height; NDis = negative displacement of the center of mass; PImp = positive impulse; NiImp = negative impulse = VStiff = vertical stiffness; CpRFD = peak rate of force development during the concentric phase; EpRFD = peak rate of force development during the eccentric phase; CaRFD = average rate of force development during the concentric phase; EaRFD = average rate of force development during the eccentric phase.
Table 3  Intersession reliability statistics for the kinematic and kinetic variables calculated during countermovement vertical jumps in women

<table>
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<tr>
<th></th>
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<td>2.6 2.2–3.3 0.95 0.91–0.97</td>
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</tr>
<tr>
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<td>2.2 1.8–2.8 0.97 0.95–0.98</td>
<td>2.4 2.0–3.0 0.96 0.93–0.98</td>
<td>2.2 1.8–2.8 0.97 0.95–0.98</td>
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</tr>
<tr>
<td>NDis</td>
<td>9.2 7.7–11.5 0.81 0.68–0.89</td>
<td>8.8 7.4–11.0 0.82 0.70–0.90</td>
<td>6.7 5.6–8.4 0.89 0.81–0.94</td>
<td>8.9 7.4–11.2 0.82 0.70–0.90</td>
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<td>Plmp</td>
<td>5.3 4.4–6.6 0.91 0.84–0.95</td>
<td>2.3 1.9–2.9 0.98 0.96–0.99</td>
<td>2.2 1.8–2.8 0.98 0.96–0.99</td>
<td>5.5 4.6–6.9 0.89 0.81–0.94</td>
</tr>
<tr>
<td>NImp</td>
<td>7.2 6.0–9.0 0.88 0.80–0.93</td>
<td>4.4 3.7–5.5 0.96 0.93–0.98</td>
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<td>CpRFD</td>
<td>N/A</td>
<td>31.1 26.0–39.0 0.51 0.26–0.69</td>
<td>39.9 33.3–50.0 0.23 −0.05–0.48</td>
<td>N/A</td>
</tr>
<tr>
<td>EpRFD</td>
<td>18.5 15.5–23.2 0.82 0.69–0.89</td>
<td>19.3 16.1–24.2 0.75 0.59–0.85</td>
<td>27.8 23.3–34.8 0.36 0.09–0.58</td>
<td>35.5 29.7–44.5 0.27 −0.05–0.51</td>
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<tr>
<td>CaRFD</td>
<td>31.5 26.4–39.5 0.70 0.52–0.82</td>
<td>31.3 26.2–39.2 0.71 0.54–0.83</td>
<td>28.2 23.6–35.3 0.71 0.53–0.82</td>
<td>28.4 23.8–35.6 0.69 0.51–0.81</td>
</tr>
<tr>
<td>EaRFD</td>
<td>17.2 14.4–21.6 0.80 0.66–0.88</td>
<td>19.9 16.6–24.9 0.72 0.55–0.83</td>
<td>14.3 12.0–17.9 0.82 0.71–0.90</td>
<td>18.4 15.4–23.1 0.74 0.57–0.84</td>
</tr>
</tbody>
</table>

CV = coefficient of variation; ICC = intraclass correlation coefficient; 90% CL = 90% confidence limits; TIA = time in air; TOV = take-off velocity; TJH = total jump height; NDis = negative displacement of the center of mass; Plmp = positive impulse; NImp = negative impulse = VStiff = vertical stiffness; CpRFD = peak rate of force development during the concentric phase; EpRFD = peak rate of force development during the eccentric phase; CaRFD = average rate of force development during the concentric phase; EaRFD = average rate of force development during the eccentric phase.
Previous investigators have recommended using TOV to calculate jump height from a force platform, as opposed to the TIA and TJH methods. From the impulse–momentum relationship, the magnitude of TOV is dependent upon the net vertical impulse (Plmp minus Nlmp) and the mass of the subject. For both men and women, TOV was very reliable, whereas Plmp and Nlmp demonstrated greater variation, with the variation in Nlmp being particularly large. The greater variation in Plmp and Nlmp compared with TOV may reflect compensatory strategies within the motor system whereby reciprocal alterations are produced in Plmp and Nlmp so that the outcome of the movement (jump height) is preserved between trials. Compensatory strategies have been identified in a number of throwing tasks in which the release parameters remain consistent despite relatively large variations in joint motions. For explosive movements, such as the vertical jump, the ability to produce low variation in the outcome of the movement may be related to the dynamics of the muscular system. For example, the stabilizing effects of intrinsic muscle properties have been implicated in preserving the consistency of the outcome in vertical jumps in the face of perturbations imposed on the motor system. It may be that practitioners and researchers should only expect intersession consistency in the outcome variables associated with a given movement. Such a suggestion has significant implications for the use of those variables that characterize the execution of the countermovement vertical jump, such as NDIs, Nlmp, VStiff and rates of force development, which may be used to gain further information about athletic ability.

Previous authors have predicted that the collection of further trials can improve the reliability of kinematic and kinetic variables in certain movements. However, when investigating the effect of trial number on joint kinetics during CMJ, Rodano and Squadrone reported that there were an optimal number of trials required to achieve an appropriate level of reliability. Beyond this number, no further improvements in reliability were noted. Therefore, the collection of more trials may aid the practitioner in improving the reliability of those unreliable measures only up to a point (it is also important to avoid fatigue during testing sessions as this introduces systematic bias into the measure). However, because of the way the motor system is theorized to function, perhaps one should not expect certain kinematic and kinetic variables to demonstrate acceptable reliability despite the collection of further trials.

It is not apparent from the present data what effect training status has on the reliability of the mechanical measures. Previous investigators have noted that those subjects who are more experienced with a given movement tend to display less variation in the outcome variables and the variables that characterize the execution of the movement. If this is the case with the mechanical variables calculated in the current study, then practitioners assessing well-trained athletes may need to reassess the associated variation in the measures. Recently, Cormack et al reported a CV of 3.3% for TIA recorded during CMJ performed by professional Australian Rules Football players in sessions separated by 1 wk, a within-subject variation comparable to that reported in the current study between sessions 1 and 2. When investigating the variability in the outcome of jumping and throwing events performed by elite athletes, Woo and Zatsiorsky reported that trial-to-trial variability in the elite athletes was similar to the values presented in published data collected during laboratory tests of maximal force, speed, and
power production. Typically, these laboratory tests are performed on subelite athletes and therefore one may conclude that the magnitude of variation in the outcome variables associated with strength and power tests are relatively consistent across a range of athletic abilities. Clearly, future studies are required to address the influence of training status on the variation associated with specific mechanical variables assessed during biomechanical analyses.

**Practical Applications**

Practitioners and researchers can use the present data in a number of ways. For example, the magnitude of a change in a variable required for a real effect to have occurred can be calculated using the typical error (TE) values (ratio typical errors can be calculated from the CV values in Tables 2 and 3 in the following manner: $\text{TE} = \frac{(\text{CV}/100)}{+ 1}$). Hopkins\(^9\) suggested that 1.5 to 2.0 times the typical error represents a suitable change in a value to identify a real change as a result of an intervention. As such, a real change may be considered to have taken place if a male athlete’s TOV increased from $2.60 \text{ m·s}^{-1}$ to $2.72 \text{ m·s}^{-1}$ between testing sessions separated by 1 wk in the absence of familiarization sessions ($2.60 \text{ m·s}^{-1} \times \text{TE}^2 = 2.71 \text{ m·s}^{-1}$), whereas a change in EpRFD from $13,444 \text{ N·s}^{-1}$ to $19,522 \text{ N·s}^{-1}$ for the same athlete could also be considered meaningful in these terms. It becomes apparent from this formula that a practitioner is better able to determine real changes in the jump height achieved during CMJ (calculated from TIA or TOV) than variables such as VStiff or any of the rate of force development measures. The practitioner should also be aware that the ability to track real changes in the kinematic and kinetic variables associated with CMJ performance tends to diminish as the time between consecutive testing sessions is increased.

The test–retest correlation values can be used to calculate the appropriate sample sizes for future studies using CMJs performed on a force platform:\(^9\)

$$\text{Estimated sample size} = 200 \times (1 - \text{ICC})$$

(2)

From Equation 2, 14 male subjects would be required in a study where TOV is the dependent variable assessed across a 1-wk period when no familiarization sessions are provided, whereas 78 male subjects would be required if EpRFD was the dependent variable. Again, these sample size would be predicted to increase if the dependent variables were assessed in a study across a 4-wk period.

**Conclusions**

The outcome variables associated with countermovement vertical jumps performed on a force platform (those variables from which jump height can be determined) demonstrate small within-subject variation and high test–retest correlation coefficients for both men and women between consecutive testing sessions. For most variables, reliability was improved as more sessions were performed, but diminished as the time between consecutive testing sessions was increased. The larger variation associated with the variables that characterize the execution of the movement (eg, countermovement depth, negative impulse, vertical stiffness, rates of force development) is in line with recent research investigating the control processes of human movements. Because of the way the motor system is theo-
rized to function, perhaps one should not expect certain kinematic and kinetic variables to demonstrate acceptable reliability. Practitioners and researchers can use the present data to estimate the magnitude of a change in the kinematic and kinetic variables associated with CMJ performance required for a real effect to have occurred or to calculate the appropriate sample sizes to be used in future studies. However, the reliability values presented here may not apply to samples of elite athletes.

References