A Mechanics Comparison Between Landing From a Countermovement Jump and Landing From Stepping Off a Box

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It is common practice to study jump landing mechanics by having subjects step off a box set at a certain height instead of landing from a jump. This practice assumes that the landing mechanics are similar between stepping off a box and a countermovement jump as long as the heights can be matched. The mechanics of the two methods had never been compared when landing from identical heights. Thus, the purpose of this study was to compare the mechanics of landing from a countermovement jump to landing from a step-off. Participants performed three maximal countermovement jumps. The mechanics of one countermovement jump was compared with a center of mass fall height matched step-off landing. The step-off landing showed a more rapid time to peak ground reaction force (GRF) in both genders and greater GRF peak and loading rate in males only. No difference was observed between joint angles at initial contact; however, the countermovement jump showed significantly greater joint flexion angles at peak GRF for both genders. EMG showed greater muscle activity during the countermovement jump condition in all subjects. It was concluded that countermovement jump landings are different from step-off landings; thus, results from analyses involving step-off landings should be taken with caution if the aim is to relate them to landing from a jump.

Keywords: biomechanics of landing, biomechanics research methods, landing kinematics, landing kinetics

The interest in the biomechanics of landing has increased as more and more injuries occur during landing. This is especially the case in the area of anterior cruciate ligament (ACL) injuries, as approximately 100,000 injuries occur annually in the United States alone (Hoxie et al., 2008). The medical cost for managing these cases is about $17,000 to $25,000 per injury (Hewett et al., 2006). Thus, the annual cost is approximately $1.7–2.5 billion. This is a huge concern, especially among female athletes who are 4–6 times more likely to injure their ACL than males (Myer et al., 2004). Understanding the biomechanics of landing would help in the development of injury prevention methods thus decreasing the number of injuries per year. However, very few have studied landings from a countermovement jump from the ground. Instead, the common practice is to study landing mechanics by having study participants step off or hop off a box onto the ground below (Edwards et al., 2010).

To our knowledge this common practice started in the early 1980s when Mizrahi and Susak (1982) analyzed impact forces with the ground. At the time, it was referred to as landing from a “free fall” and included participants hanging from a bar and then letting go. Later on, the method progressed to stepping off platforms of different heights (McNitt-Gray, 1991). However, with time it has been become so commonly used that rarely do researchers mention the reason for its use. Researchers continue to use stepping off to gain information about jump landings (Salci et al., 2004; Bisseling et al., 2007; Pollard et al., 2010; Ortiz et al., 2010; Yeow et al., 2010). It seems logical to have study participants perform countermovement jumps because in real athletic activities players perform jumps and do not step off a box on to the ground. The purpose of stepping off or hopping off a box is to make sure participants are landing from the same height (Swartz et al., 2005) or to isolate landing phase from the rest of the jump (Edwards et al., 2010). An assumption made that stepping off a box to the ground is similar to landing from a jump may be based on another assumption that touchdown velocity of the center of mass (CM) from stepping off a box of a certain height is always the same. Equal touchdown velocities can be achieved only if the fall height of the center of mass is identical for all participants. We have found that participants tend to lower their centers of mass differing amounts before becoming airborne, thus producing different fall heights from the same box height. Thus touchdown velocities are not the same even though the box height is the same.

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which is limited by the inability to say the two types of landings were conducted from identical heights.

Thus, the first purpose of this study was to determine if the mechanics of landing are similar between the countermovement jump and step-off. If the two landings are not similar, it would put into question using step-off to study jump landing. The second purpose was to determine if the mechanics of landing from countermovement jump and step-off are different in one or both genders. If countermovement jump and step-off landings are similar in one or both genders, then step-off can be an effective method for studying jump landings.

Methods

Eighteen healthy college students (9 males, 9 females) volunteered to participate in the study. All participants read and signed an informed consent as approved by Institutional Review Board at Arizona State University. All participants were given a questionnaire about their activity level and previous injuries before data collection. Participants were excluded from the study if they did not participate in any sport or exercise that involves jumping and landing for at least 2–3 times a week or if they had any orthopedic condition that would prevent them from jumping.

Participants were asked to wear shorts. Reflective markers were placed on the skin over the shoulder, greater trochanter, lateral femoral condyle, lateral malleolus, and fifth metatarsal head before data collection. All trials were video recorded from a sagittal view using a JVC GR-DVL-9500 digital video camera to allow a 2-D kinematic analysis of joint movements.

Ground reaction force (GRF) data were collected using a force platform (AMTI, model OR6–5-1, Watertown, MA). Data were collected at 1200 Hz for 4 s. The GRF data were acquired using custom software (LabView, National Instruments, Austin, TX).

Surface EMG was used to investigate muscle activity in the vastus lateralis, vastus medialis, medial hamstring, lateral hamstring, and lateral head of the gastrocnemius. These muscles were chosen because the hamstring muscles are thought to protect the ACL, the vastus lateralis and medialis work as antagonist to the hamstring, and the gastrocnemius also assists in knee flexion (Fagenbaum & Darling, 2003). Similar muscles were also used in the only study similar to ours (Edwards et al., 2010). Differential surface electrodes (Ag–AgCl; Therapeutics Unlimited Inc., Iowa City, IA; preamplification gain = 35; interelectrode distance = 22 mm; electrode diameter = 8 mm) were used. The electrodes were placed on the muscle belly parallel to the direction of the muscle fibers as described by Perotto (2005). Skin preparation of the electrode placement site included shaving, abrading, and rubbing with alcohol. A single reference electrode was placed on the participant’s right ulnar styloid process. Electrodes were placed on the participants’ skin and were not moved for the entire data collection period.

The EMG data were conditioned with an EMG-544 amplifier/processor module (Therapeutics Unlimited Inc., Iowa City, IA). Amplification gains ranged from 1,000–10,000 with a bandwidth ranging from 20 to 4,000 Hz adjusted to each subject. Input impedance was greater than 15 MΩ at 100 Hz with typical input bias current on the order of 3 μA DC. Common mode rejection ratio was 87 dB at 60 Hz. Data were collected at 1,200 Hz for 4 s from an MIO-16x16-bit A/D board (National Instruments, Austin, TX) interfaced to a desktop computer using custom LabView software.

After preparation, all participants were asked to undergo three maximum countermovement jumps (i.e., jump as high as they can) with hands on waist (to eliminate the effect of arm motion) and land with both feet on the force platform. Landing force was integrated using Simpson’s rule to calculate landing impulse, which was then used to compute landing velocity using the impulse-momentum relationship. Finally, CM fall height was calculated using projectile motion equations. Note that CM fall height is the equivalent fall height of the CM needed to achieve a given velocity at impact with the ground. It should not be confused with box height, which is the height of the box used during step-off landings. All calculations were made using custom software (LabView, National Instruments, Austin, TX). Participants were then asked to step off a box with their right foot and land with two feet onto the force platform while keeping hands on waist. Box heights were adjusted to try to match CM fall height from any of the three maximal countermovement jumps. After landing, step-off CM fall height was calculated. If CM fall height matched that of any of the countermovement jump landings then testing ended. If not, the height of the box was adjusted (increased or decreased depending on the need) until a match was found. The step-off and countermovement jump landings of matching height were then compared.

Factors analyzed from ground reaction force data were the time to peak GRF, peak GRF, and maximum loading rate (maximal slope in GRF curve between contact and peak force; Bus, 2003).

Peak Motus motion measurement system (Peak Performance, Englewood, CO) was used to digitize points at the shoulder, greater trochanter, lateral femoral condyle, lateral malleolus, and fifth metatarsal bone. Raw digitized coordinates were filtered at 12 Hz using a low-pass zero-lag Butterworth filter. Custom software (LabView, National Instruments, Austin, TX) was used to calculate the hip/trunk, knee, and ankle 2-D joint angles as described by Winter (2005). The hip angle was defined as the angle between the trunk and thigh. Knee and angle angles are shown in Figure 1 (Winter, 2005). Joint angles at initial ground contact and at peak GRF were analyzed (Bus, 2003). Subjective visual examination was used to identify general patterns of the change of joint angles with time for each condition.

Custom LabView software was used to remove bias voltage, full wave rectify, and filter raw EMG data.
Data were filtered using a Butterworth digital filter at 10 Hz creating a linear envelope, which is within the recommended range. Variables analyzed were the time to muscle activation defined as an increase of activation by 3 standard deviations from baseline. Norman, Nelson, and Cavanagh (1978) recommended a minimum of sampling time 75–80 ms intervals for EMG analysis, therefore, average integrated EMG during an interval 100 ms before peak GRF and average integrated EMG after impact for 100 ms for both conditions were measured and compared. The average integrated EMG was normalized to maximal integrated activation during the takeoff phase of the countermovement jump measured at 100 ms intervals.

A series of mixed design two-way ANOVAs with repeated measures (landing type × gender) with gender as the between-subjects factor were used to analyze if a difference exists between the ground reaction force, kinematic, and EMG variables in both step-off and countermovement jump landings. The alpha level was of .05 was used.

**Results**

We were successful in matching one maximal countermovement jump landing to one step-off landing for all participants. The number of step-off trials needed to produce a matching landing ranged from 3 to 11 trials.

A significant main effect for condition was seen for time to peak GRF, \( F(1,16) = 6.7, p < .05 \), with no significant condition × gender interaction, \( F(1,16) = .10, p > .05 \). The step-off landings produced significantly shorter times to peak GRF than did the countermovement jump landings (see Figure 2 and Table 1). Both peak GRF and maximal initial loading rate showed a significant jump type × gender interaction. A test of simple effects showed the step-off landing produced larger GRF and loading rates than did the countermovement jump for males only, \( F(1,16) = 17.65, p < .01 \) and \( F(1,16) = 12.95, p < .01 \), respectively.

No significant differences in hip, knee, and ankle joint angles were observed between landing types at initial contact (Table 2) with \( F(1,16) = 0.36, p > .05 \), \( F(1,16) = 0.55, p > .05 \), and \( F(1,16) = 0.10, p > .05 \), respectively. However, there were significantly greater hip flexion, knee flexion, and ankle dorsiflexion angles at peak ground reaction force during the countermovement jump condition (Table 3) with \( F(1,16) = 8.52, p < .05 \),

### Table 1  Mean ± SD for time to maximum GRF, maximum GRF, maximum loading rate for both countermovement jump and step-off landings for both genders

<table>
<thead>
<tr>
<th></th>
<th>Males</th>
<th>Females</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Countermovement</td>
<td>Step-off</td>
</tr>
<tr>
<td>Time to max (ms)</td>
<td>83.0 ± 14</td>
<td>63.8 ± 6*</td>
</tr>
<tr>
<td>Max GRF (BW)</td>
<td>4.8 ± 0.8</td>
<td>5.5 ± 0.9***</td>
</tr>
<tr>
<td>Max loading rate (N/s)</td>
<td>185.9 ± 97</td>
<td>303.7 ± 167**</td>
</tr>
</tbody>
</table>

*Significant difference between countermovement jump and step-off, \( p < .05 \).

**Significant difference between countermovement jump and step-off, \( p < .01 \).
Figure 2 — GRF in BW for both countermovement jump and step-off landings for a typical male participant.

Table 2  Mean joint angles for each condition in degrees at initial contact

<table>
<thead>
<tr>
<th></th>
<th>Countermovement jump</th>
<th>Step-off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip</td>
<td>16.6 ± 8.7</td>
<td>18.0 ± 7.5</td>
</tr>
<tr>
<td>Knee</td>
<td>22.7 ± 7.7</td>
<td>21.1 ± 5.2</td>
</tr>
<tr>
<td>Ankle</td>
<td>22.3 ± 10.4</td>
<td>23.2 ± 9.2</td>
</tr>
</tbody>
</table>

Table 3  Mean joint angles for each condition in degrees at maximum GRF

<table>
<thead>
<tr>
<th></th>
<th>Countermovement jump</th>
<th>Step-off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip</td>
<td>30.4 ± 9.1*</td>
<td>24.4 ± 8.6</td>
</tr>
<tr>
<td>Knee</td>
<td>50.4 ± 9.3**</td>
<td>42.6 ± 6.2</td>
</tr>
<tr>
<td>Ankle</td>
<td>−18.7 ± 7.1**</td>
<td>−10.5 ± 5.3</td>
</tr>
</tbody>
</table>

*Significant difference between countermovement jump and step-off, \( p < .05 \).

**Significant difference between countermovement jump and step-off, \( p < .01 \).”}

No statistical comparisons were made between the start of muscle activity for both conditions, as muscles in the countermovement jump condition were active throughout the trial (Figure 5) while muscles in the step-off condition generally started from no activation (Figure 6). Statistical tests revealed that in both males and females the calf muscle activity was significantly higher in the countermovement jump condition than the step-off condition during the 100 ms interval before the peak GRF, \( F(1,16) = 6.69, p < .05 \) (Table 4). No gender \( \times \) type interaction was seen for any of these comparisons.

Significantly more vastus lateralis, vastus medialis, and medial hamstring activity in the countermovement jump condition for the first 100 ms after impact for both genders with \( F(1,16) = 12.26, p < .01, F(1,16) = 6.00, p < .05 \) and \( F(1,16) = 5.37, p < .05 \), respectively (Table 4).

The difference in calf EMG activity between countermovement jump and step-off approached significance with \( F(1,16) = 3.29, p = .09 \). No gender \( \times \) type interaction was seen for any of these three comparisons.

Discussion

The purpose of this study was to compare the mechanics of landing from a countermovement jump to landing from stepping off a box to see if it is appropriate to use the data from stepping off a box when studying the mechanics of landing from a countermovement jump. Ground reaction force, 2-D kinematics, and EMG data from the two landings were compared.

Results showed a shorter time to peak GRF in the step-off condition for both males and females indicating that participants were less prepared for impact in the step-off condition as they had a significantly decreased hip flexion, knee flexion, and ankle dorsiflexion at peak GRF seen in the step-off compared with the countermovement jump condition. This decreased preparation may be explained by the need for the muscles to start activation during the fall in the step-off case whereas the
Figure 3 — Joint angles and GRF for the countermovement jump condition from the instant of touchdown.
Figure 4 — Joint angles and GRF for the step-off condition from the instant of touchdown.
Table 4  The average muscle activity for the 100 ms intervals before peak GRF and after initial contact for the countermovement jump and step-off conditions as a percentage of maximal activity

<table>
<thead>
<tr>
<th></th>
<th>Average muscle activity (%) before peak GRF</th>
<th>Average muscle activity (%) after initial contact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Countermovement jump</td>
<td>Countermovement Step-off</td>
</tr>
<tr>
<td>Males</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vastus lateralis</td>
<td>27.9 ± 23</td>
<td>31.0 ± 18</td>
</tr>
<tr>
<td>Vastus medialis</td>
<td>46.3 ± 25</td>
<td>62.2 ± 55</td>
</tr>
<tr>
<td>Lateral hamstring</td>
<td>34.6 ± 23</td>
<td>44.8 ± 47</td>
</tr>
<tr>
<td>Medial hamstring</td>
<td>90.9 ± 118</td>
<td>64.0 ± 56</td>
</tr>
<tr>
<td>Calf</td>
<td>58.7 ± 26*</td>
<td>47.8 ± 33</td>
</tr>
<tr>
<td>Females</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vastus lateralis</td>
<td>60.0 ± 45</td>
<td>48.0 ± 29</td>
</tr>
<tr>
<td>Vastus medialis</td>
<td>56.2 ± 16</td>
<td>51.0 ± 11</td>
</tr>
<tr>
<td>Lateral hamstring</td>
<td>49.4 ± 35</td>
<td>36.0 ± 24</td>
</tr>
<tr>
<td>Medial hamstring</td>
<td>57.8 ± 38</td>
<td>40.7 ± 21</td>
</tr>
<tr>
<td>Calf</td>
<td>123.9 ± 166*</td>
<td>63.2 ± 93</td>
</tr>
</tbody>
</table>

*Significant difference between countermovement jump and step-off, $p < .05$.

**Significant difference between countermovement jump and step-off, $p < .01$.

Figure 5 — Calf muscle EMG activity for a typical male participant for the countermovement jump condition.
muscles were already active from the jumping phase in the countermovement jump condition (Besier et al., 2003; Cowling & Steele, 2001). Although joint angles were not greater throughout landing for all participants (Figures 3 and 4), there were greater hip flexion, knee flexion, and ankle dorsiflexion at peak GRF in the countermovement jump condition for most participants as determined by the ANOVA. The few participants that had lesser joint flexion angles at peak GRF in the countermovement jump condition had greater peak GRF for the countermovement jump condition as determined by our visual examination suggesting that a greater flexion angle at peak GRF is a key to lowering GRF (Salci et al. 2004).

Peak GRF as well as maximum loading rate were significantly higher in the step-off condition for males only as revealed by the ANOVA. Although this may be an indication of a gender difference, it was most likely caused by the difference in CM fall height as males clearly jumped higher (means of 0.31 m and 0.22 m for males and females, respectively), \(F(1, 16) = 19.02, p < .001\). However, determining the exact reason would be difficult as in this study all participants performed maximal countermovement jumps. It would not be appropriate to have the female participants step off from higher heights as it would be more than what they would perform in a real life situation. Having the male participants step off from a lower height would lead us to compare a submaximal CM fall height (of the males) to a maximal CM fall height (of the females) which would still not be appropriate. Nevertheless these results indicate that step-off landing of approximately 0.22 m CM fall height may be used to simulate peak GRF and maximum loading rate of a countermovement jump for females. Our results are in agreement with Edwards et al. (2010) who found a significant difference in time to peak GRF, peak GRF, and maximum loading rate between countermovement jump landings and step-off landings. However, their CM fall height was set to 0.33 m which is similar to the CM fall height for males in our study (0.31 m average) thus we are not able to compare their results to the results of our female participants.

In addition to the continuous activation of all muscles in the countermovement jump landing condition there was a difference in the magnitude of activation. Both genders also demonstrated increased vastus lateralis, vastus medialis, and lateral hamstring activity in the first 100 ms after initial contact in the countermovement jump condition. This greater muscle activity was most likely a result of the continued activity observed during the countermovement jump condition. The decreased activity early in the step-off landing suggests that most of the impact shock absorption is conducted by the passive structures, thus increasing the potential of injury (Wojtys et al., 2003). Both genders demonstrated greater calf muscle activity in the countermovement jump condition in the first 100 ms after initial contact and the last 100 ms before peak GRF, which may emphasize the important role of the gastrocnemius in increasing knee flexion and providing greater plantar flexor torque to control the dorsiflexion after impact resulting in the difference in joint angles seen in both conditions.

Although not a focus of the study, it was noticed that measured CM fall height was on average 0.10 m lower
than actual box height. Thus, box heights needed to be about 0.10 m higher to achieve the target CM fall height. This by itself is worth noting considering the main reason for using stepping off is to control CM fall height.

This study clearly shows that step-off landing mechanics are different from countermovement jump landing mechanics. Thus, we would recommend the use of actual jumps as not only do they simulate what happens in real life but they carry a less chance of injury as study participants will have their muscles working to allow greater joint flexion reducing the GRF. It may not be obvious that knee extensors assist in controlling knee flexion, however, the greater force produced by the eccentric action of the quadriceps is an efficient way of dissipating the high loads experienced during landing (Palmieri-Smith et al., 2007). Step-off landings, however, may still be used in other types of studies such as those related to fall mechanics. However, it would be recommended that landing impulse be used to calculate the actual CM fall height since it appears that most people “cheat” and lower their centers of mass before they become airborne and fall less of a height before impact than the measured height of the box.

In this study only one countermovement jump trial was compared with one step-off trial. We recognize that multiple trials would be ideal for more reliable results. Participants did perform multiple trials. However, getting two trials of matching CM fall height was a daunting task and took extensive time to achieve. Getting multiple trials of matching CM fall height may not have been practical. Edwards et al. (2010) obtained five trials for each condition. However, the limitation of their study was obtaining accurately matched CM fall heights as subjects had a 0.08 m difference in CM displacement between the two conditions. Nevertheless, the results of our study are in agreement with Edwards et al. and taken together these two studies indicate that the stepping off a box onto the ground may not be the best way to study landings if the purpose is to generalize to real-world landings from a jump.

References


