Characteristics of Lower Extremity Work during the Impact Phase of Jumping and Weightlifting

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Running Title: Work during Impact in Jumping and Weightlifting

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1 ABSTRACT

2 Jumping and weightlifting tasks involve impact phases, where work is performed by the lower extremity to absorb energies present at contact. This study compared the lower extremity kinematic and kinetic strategies to absorb energy during the impact phase of jumping and weightlifting activities.

3 Ten women experienced in jumping and weightlifting performed four tasks (landing from a jump, drop landing, clean and power clean) in a motion analysis laboratory. Work performed at the hip, knee and ankle were calculated during the landing and receiving phases of jumping and weightlifting tasks, respectively. Additionally, segment and joint kinematics and net joint moments were determined. The most lower extremity work was performed in the clean and drop landing, followed by landing from a jump and the least work was performed in the power clean (p<0.05). For all tasks, work performed by the knee extensors was the greatest contributor to lower extremity work. Knee extensor net joint moment was greater in the power clean than jump and drop landings, and greater in the clean than all other tasks (p<0.05). Knee flexion angle was not different between the power clean and jump landing (p>0.05), but greater in the drop landing and clean (p<0.05). A common characteristic of the impact phase of jumping and weightlifting tasks is a large contribution of knee extensor work. Further, the correspondence in kinematics between impact phases of jumping and weightlifting tasks suggests similar muscular strategies are used to perform both types of activities. Weightlifting tasks, particularly the clean, may be important exercises to develop the muscular strength required for impact actions, due to their large knee extensor net joint moments.

21 Keywords: vertical jump; muscle strength; quadriceps; knee
INTRODUCTION

Many sports, such as basketball and volleyball, include jumping activities. Jumping involves three general phases: 1) propulsion, 2) flight and 3) landing. The landing phase is also described as the impact phase, as it involves a collision between the falling body and the ground. At impact, the body possesses kinetic energy as a result of the conservation of energy from the initial drop height potential energy. Following impact, work is performed using eccentric muscle loading to absorb this kinetic energy (12, 23). The work performed by the ankle plantar flexors, knee extensors and hip extensors during landing can be estimated using biomechanical techniques. Bobbert et al. (3, 4) suggested work is performed when landing from a jump in a distal to proximal manner, emphasizing the ankle plantar-flexors followed by the knee extensors.

Previous research found the technique used to land from a jump influences the work performed at the hip, knee and ankle. Bobbert et al. (3) compared the impact phase of bounce and countermovement drop jumps, where bounce drop jumps had less ankle dorsiflexion and knee flexion than countermovement drop jumps. In bounce drop jumps, more work was performed at the ankle whereas in countermovement drop jumps, work performed at the knee was greater. Similarly, DeVita et al. (12) compared landings with greater and less than 90 degrees of knee flexion. Landings with greater knee flexion required more work to be performed at the knee.

Impact is not unique to landing from a jump. Movements in the sport of weightlifting also involve propulsion, flight and impact phases. In weightlifting, impact is a result of 1) the feet returning to the ground after a momentary separation and 2) receiving the barbell on the shoulders (i.e. clean) or overhead (i.e. snatch) which occurs when the feet contact the ground (8). Similar to landing from a jump, eccentric muscle loading is required to perform work and absorb energy present at impact during weightlifting. Only one previous investigation has compared the mechanics of the impact phase of jumping versus weightlifting. Burkhardt et al. (7) reported lower ground reaction forces during a power
clean versus drop jump and jump landing tasks, however, did not investigate other biomechanical characteristics that may be important to compare weightlifting and landing tasks.

Further comparison is warranted to examine kinematic, kinetic and energetic correspondences between landing and weightlifting tasks. A comparison of work performed by the lower extremity during landing and weightlifting tasks has both theoretical and practical rationales. Theoretically, if these tasks have kinematic and kinetic similarities, the general mechanical characteristics of impact activities can be identified. Practically, weightlifting exercises are employed in strength training programs and similarity between weightlifting and landing may provide insight into training to improve landing performance. For example, comparing the muscular demands and strategies used to perform weightlifting and landing tasks could identify the exercises best suited for strengthening muscles used in landing activities. The purpose of this research was to examine the work performed by the lower extremity during impact activities including jump landing and weightlifting. Further, the joint and segment kinematics and kinetics to perform these tasks were examined.

METHODS

Experimental Approach

This study utilized a cross-sectional design to compare the biomechanics of two landing and two weightlifting tasks. The landing tasks studied were the landing phase of the countermovement jump and drop landings. The weightlifting tasks performed were the clean and power clean. Participants were athletes who used the clean and power clean in training under the supervision of a certified weightlifting coach. Participants performed two sessions, approximately one week apart. In the first session, maximum countermovement jump height was determined. This jump height was used as the height of the box for drop landings. Participants self-reported their one repetition maximum clean. In the second session, participants performed landings and weightlifting tasks while recorded using motion
analysis techniques. The order of tasks performed was jump landings, drop landings and weightlifting exercises. Because multiple sets of cleans and power cleans were performed, sets of these exercises were alternated. The same barbell load (80% one repetition maximum clean) was used for both the clean and power clean. Primary variables were the work performed by the lower extremity. Secondary variables were lower extremity joint and segment kinematics and kinetics.

Participants

Ten women athletes (volleyball and weightlifting) were recruited to participate in this investigation. Participants represented a sample of convenience and were athletes involved in: 1) sports with jumping activities and 2) strength and conditioning training involving weightlifting exercises. All participants had been taught to perform the clean and power clean by a certified weightlifting coach. Further, they had a minimum of 6 months experience performing these exercises under the supervision of the coach. A sample size of 10 participants allows detection of within-subject effect size differences of 0.2 standard deviations while minimizing type I error to 5% and type II error to 20% (power = 80%).

Study procedures were explained and participants provided written informed consent as approved by a Research Ethics Board at the author’s institution (Study ID: Pro00024475). Participant characteristics are presented in Table 1.

<INSERT FIGURE 1 ABOUT HERE>

Procedures

Participants completed two sessions, spaced approximately one week apart (Figure 1). During the first session, maximal countermovement jump height was determined. Countermovement jump height was determined using a two hand reach and a Vertec (Sports Imports, Inc., Columbus, OH).

Participants were allowed to perform maximum effort jumps until no greater jump height was achieved. Jump height was used to determine the height of the drop landing (provided in Table 1). Drop landings
were performed by standing on a box adjusted to the maximum jump height, stepping off the box and landing on two feet. Our pilot research indicates instruction and familiarization are required to achieve stable kinematics during landing tasks. Participants watched an instructional video, followed by performing five jump and five drop landing trials. The video instructed participants to:

- Land with feet symmetrical
- Land with knees and ankles bent
- Land with feet flat
- Land with the body upright; avoid leaning forward
- Absorb the landing using muscle tension

Practice for the clean and power clean were not required as these exercises were performed regularly in training.

In the second session, participants performed jump and drop landings, power cleans and cleans while data were collected using 3D motion capture techniques. Participants completed a brief warm-up consisting of two sets of five unloaded squats. After the warm-up, participants performed four repetitions of maximal-effort block jumps with landings, followed by four repetitions of drop landings from a height equal to their previously determined maximum vertical jump height. Pilot research indicates repeatable results within session when four repetitions are performed. Following jump and drop landing trials, the power clean and clean exercises were performed with a barbell load of 80% of the participant’s one repetition maximum clean. Participants’ self-reported one repetition maximum (Table 1) was the heaviest clean they had successfully completed in the past three months from their training journal, which was verified by their weightlifting coach. Three sets of two repetitions were performed for each of the power clean and clean. Sets of power cleans and cleans were alternated to prevent an ordering effect. Rest was provided *ad libitum* between repetitions and sets.

<INSERT TABLE 1 ABOUT HERE>
Motion Analysis

Retro-reflective markers were placed on participants’ lower extremities. All markers were placed by the same investigator. The marker set consisted of calibration and tracking markers (see Chiu & Salem (9) for details). Calibration markers were used during static trials to define the proximal and distal ends of segments. Clusters of markers fixed on a rigid plastic plate were used for tracking the thigh, leg and foot during dynamic trials. Calibration markers were removed for dynamic trials except for pelvic markers, which also served as tracking markers. Marker trajectories were captured at 120Hz using nine optoelectronic cameras (ProReflex MCU240; Qualisys, Gothenburg, Sweden). Additionally, ground reaction forces were sampled at 1,200Hz using two AMTI force platforms (OR6-6; AMTI, Watertown, MA). All data were collected using Qualisys Track Manager software (version 2.3.510).

Data were analyzed using Visual 3D software (version 4.82; C-Motion, Germantown, MD) where marker data were modelled as seven rigid segments (pelvis, left and right thighs, left and right legs, and left and right feet). Marker and force platform data were digitally filtered using a low-pass fourth order recursive Butterworth with a 10Hz cut-off frequency. Segment kinematics were determined as rotation of the segment relative to the laboratory using a ZYX Cardan sequence. The ankle, knee and hip joints were defined as motion of the proximal segment relative to the distal segment using an XYZ Cardan sequence. Cardan sequences were selected to allow segment and joint rotations to be interpreted consistent with anatomically defined rotations (11). Inverse dynamics procedures were used to calculate net joint moment (NJM) at the ankle, knee and hip with moments expressed in the coordinate system of the distal segment. Segments were modelled as conical frusta to determine the segment’s moment of inertia and center of mass location, and segment mass was determined as a percentage of total body mass using Dempster’s data (22).

Joint power was calculated as the dot product of NJM and joint angular velocity. Work was determined as the integral (or area under the curve) of joint power with respect to time from initial
contact to peak knee flexion. Initial contact was determined as one frame prior to contact with the force platform and peak knee flexion was the frame where knee flexion angle was largest. These points were chosen to represent the start and end of the landing phase. The work performed at the ankle, knee and hip were determined, as well as total work which was the sum of work at these joints and percentage of total work performed at each joint. All data were visually verified to determine similarity between left and right limbs. Kinematic data were averaged and kinetic data were summed between left and right limbs. Kinetic data were also normalized to body mass. Data were averaged across all trials performed for the same task.

Statistical Analysis

To examine if differences existed between tasks for the total work performed, a one-way analysis of variance (ANOVA) with repeated measures was used. To examine if there were differences for percentage work performed at the ankle, knee and hip, across tasks, a two-way (joint x task) repeated measures ANOVA was used. Repeated measures multivariate ANOVA was used to examine differences for secondary variables: 1) joint and segment angles at initial contact, 2) joint and segment angles at peak knee flexion, 3) joint excursion from initial contact to peak knee flexion and 4) NJM at peak knee flexion. Tukey’s Honestly Significant Difference test was used for post hoc comparisons. For all statistical tests, alpha was set a priori (α = 0.05) and data presented are mean ± standard deviation.

Statistical tests were performed in SPSS (version 11.0; SPSS Inc., Chicago, IL).

RESULTS

<INSERT FIGURE 2 ABOUT HERE>

A significant main effect was found for total work performed by the lower extremity in the four tasks (p < 0.001; Figure 2). The work performed in the clean (p = 0.001) and drop landing (p = 0.02) were
greater than in the jump landing, but not different from each other (p = 0.10). Work performed in the power clean was significantly less than the clean (p < 0.001), drop landing (p < 0.001) and jump landing (p < 0.001).

A significant interaction was found for the percentage contribution to total work performed by the hip, knee and ankle across tasks (p < 0.001; Figure 3). Percentage of total work performed at the ankle was greater for the jump than the clean (p < 0.001) and power clean (p = 0.006). Percentage ankle work was greater in the drop landing than the clean (p = 0.001) but not the power clean (p = 0.35).

Percentage of total work performed at the knee was greater for the clean (p = 0.001), power clean (p = 0.005) and drop landing (p = 0.02) than for the jump landing. The percentage of total work performed at the knee was greater than at the ankle in the jump landing (p < 0.001), drop landing (p < 0.001), clean (p < 0.001) and power clean (p < 0.001). The percentage of total work performed at the knee was greater than at the hip in the jump landing (p < 0.001), drop landing (p < 0.001), clean (p < 0.001) and power clean (p < 0.001). The percentage of total work performed at the hip was greater than at the ankle in the clean (p < 0.001) and power clean (p = 0.02), but not the jump (p = 0.98) and drop (p = 0.99) landings.

<INSERT FIGURE 3 ABOUT HERE>

<INSERT FIGURE 4 ABOUT HERE>

Significant multivariate effects were found for segment angles at initial contact (p < 0.001) and at peak knee flexion (p < 0.001). Univariate ANOVA found significant main effects for the foot (p < 0.001), leg (p < 0.001) and thigh (p < 0.001) at initial contact, and the thigh (p < 0.001) and pelvis (p < 0.001) at peak knee flexion (Figure 4). Significant multivariate effects were found for joint angles at initial contact (p < 0.001) and peak knee flexion (p < 0.001). Univariate ANOVA found significant main effects for the ankle (p < 0.001), knee (p < 0.001) and hip (p < 0.001) at initial contact, and the ankle (p < 0.001), knee (p < 0.001) and hip (p < 0.001) at peak knee flexion (Figure 5). Significant multivariate
effects were observed for joint excursions between initial contact \((p < 0.001)\) and peak knee flexion \((p < 0.001; \text{Table 2})\). Significant multivariate effects were also found for net joint moments at peak knee flexion \((p < 0.001; \text{Table 3})\).

<INSERT FIGURE 5 ABOUT HERE>

<INSERT TABLE 2 ABOUT HERE>

<INSERT TABLE 3 ABOUT HERE>

DISCUSSION

Work performed in jump landing and receiving the barbell in weightlifting, and the kinematic and kinetic strategies for performing these tasks, were examined. Work performed by the lower extremity was greatest in the drop landing and clean. Slightly less work was performed in landing from a jump and substantially less work was performed in the power clean. Despite the differences in total lower extremity work performed, the primary contributor in all tasks was work performed by the knee extensors. In the jump and drop landings, approximately one quarter of the work was performed by the ankle plantar-flexors, however, these muscles contributed less to the power clean and clean. The percentage contribution of the hip extensors to total lower body work performed was consistent across all four tasks. As work is performed by applying moments of force to control segment rotations, the kinematic and kinetic strategies used to perform work provides insight into general and task-specific characteristics of impact activities.

The large contribution of work performed by the knee extensors highlights the importance of these muscles in performing landing or impact type activities. All tasks required the leg to rotate forward at least 40 degrees at peak knee flexion, and increasing leg forward rotation increases knee extensor NJM during squat activities \((11, 13)\). Further, the leg and thigh segments rotated through large arcs, resulting in large knee joint angular excursions, particularly for the jump and drop landings, and the
clean. The combination of large knee extensor NJM and large knee joint angular excursions explains the large contribution of work at the knee to total lower extremity work performed. Contribution of knee extensor work was greatest in the clean, which also had the highest knee extensor NJM and knee joint angular excursion.

Work performed by the ankle plantar-flexors was higher in the jump and drop landings than the weightlifting tasks. The angles of the foot and leg segments at initial contact were also different for jump and drop landings versus weightlifting. In the jump and drop landings, the foot was more plantar-flexed while the leg was rotated forward less at initial contact compared to the clean and power clean. However, the foot and leg segment angles were not different at peak knee flexion, thus, the amount of foot dorsiflexion and leg forward rotation from initial contact to peak knee flexion was greater in the jump and drop landings. This corresponds with the larger proportion of work performed at the ankle in these tasks.

Our data suggest that work performed by the ankle plantar-flexors and knee extensors are not mutually exclusive, as has been suggested in previous research (12, 16, 23). That is, increasing ankle work does not have to be accompanied by decreased knee work or vice versa. Rather, work performed at the ankle and knee each fulfill independent functions during impact activities. Ankle plantar-flexor work eccentrically controls foot dorsiflexion and leg forward rotation when the leg is vertically aligned at initial contact. The relation between foot plantar-flexion and ankle plantar-flexor work is supported by Kovacs et al. (15) who found no ankle plantar-flexor work was performed when landing with the foot dorsiflexed. Knee extensor work eccentrically controls additional leg forward rotation and thigh posterior rotation, the latter serving to lower the body into a squat. Thus, muscular control of foot, leg and thigh rotations appear to be general characteristics of impact tasks and the work performed at the ankle and knee is dependent on the amount each of these segments rotates.
It is important to identify the general characteristics of impact or landing activities, as the optimal mechanics of landing have not been determined. A limitation of studying the landing versus propulsion phase of vertical jumping is that a well-defined objective of landing does not exist. The objective of propulsion in vertical jumping is simply to elevate the body’s center of mass. While many movement strategies are possible, only one strategy is optimal, which can be ascertained by determining which strategy results in maximum center of mass elevation (20). In the landing phase, the objective can be defined as absorbing energy present at contact, however, many strategies can be used to absorb energy (17, 18). For example, it has been suggested rotating the torso forward at initial contact, which increases hip extensor involvement, is a superior strategy compared to landing with an upright torso (2). However, whether forward torso rotation represents the optimal strategy is debateable.

Absorbing energy is also required in the receiving phase of the clean and power clean, but these tasks have a constraint not found in landing from a jump. In the clean and power clean, the torso must remain upright to prevent the barbell from falling off the shoulders. This constraint limits the strategies possible — specifically, rotating the torso forward at contact cannot occur. The similar energetics and kinematics at peak knee flexion observed in the jump landing and receiving the barbell in the clean and power clean suggests a knee extensor strategy with an upright torso may be optimal for landing tasks.

To utilize the knee extensor strategy with an upright torso, strong knee extensors are required. The present research also provides insight into how knee extensor strength may be developed for landing performance. Knee extensor NJM was higher in the power clean and clean than either jump or drop landings. Muscular strength training requires large forces to be applied to muscles and knee extensor NJM is an indicator of the minimum loading on the quadriceps muscles (6). As knee extensor loading was greater in the power clean and clean, this suggests these exercises may be used for strengthening the muscles required for landing from a jump. Ankle plantar-flexor NJM was also greater
in the power clean and clean than jump and drop landings, which may provide a strengthening stimulus for the ankle plantar-flexor muscles. In comparing between the weightlifting tasks, the clean appears to have the greatest potential for strengthening the lower extremity musculature as both knee and hip extensor NJM were greater. These findings parallel previous research from our group which reported knee and hip extensor loading increased with greater depth in back squat exercise (6). Further, Hartmann et al. (14) examined training using partial and full squat exercise, finding that partial squat exercise was not effective for strengthening the knee extensors. Collectively, these studies suggest squat exercise requiring more than 105 to 119 degrees of knee flexion is required to strengthen the knee extensors (6).

In summary, the energetics of the impact phase of jumping and weightlifting tasks were studied. The primary contributor to work performed in these tasks was the knee extensors. Work performed by the ankle plantar-flexors was greater in jump and drop landing than weightlifting tasks, due to the posture of the foot and leg segments at initial contact. The contribution of the knee and ankle to lower extremity work varied according to the magnitudes of thigh, leg and foot rotation, whereas contribution of hip work was similar across all tasks. Regardless of the task, the greatest contribution to lower extremity work was from the knee extensors, highlighting the importance of these muscles for performing landings. In combination with our previous research on squat exercise (6), the present study suggests weightlifting tasks, particularly the clean may be an effective exercise for training knee extensor strength.

**PRACTICAL APPLICATIONS**

Sports and activities involving jumping tasks invariably require individuals to land. Landing has been implicated in various injuries such as anterior cruciate ligament tears, patellar tendinopathy and patellofemoral pain (1, 5, 21). To absorb the kinetic energy present at contact, work must be
performed, ideally by muscles. If muscles are not able to perform work, energy may be absorbed by connective tissue, including ligaments and bones which may result in injury (19). To absorb energy in landing activities, strength of the knee extensors is critical. Weightlifting tasks share similar biomechanics to landing from a jump but require greater knee extensor effort. Thus, the power clean and clean may be used to develop knee extensor strength appropriate for landing from a jump. In particular, the clean requires greater knee extensor loading than the power clean, which is a similar comparison to the knee extensor loading in full versus partial squat exercise (6). Weightlifting exercises such as the snatch, clean and variations of these lifts are commonly used in strength training programs, however, there is an emphasis on the propulsion or pulling phase (10). The present research finds there are benefits to receiving the barbell in weightlifting exercises, especially in the deep squat position.

Strength and conditioning professionals should be aware of the benefits of weightlifting exercises such as the clean and snatch performed through a full range of motion. Athletes in sports involving impact activities, such as jumping and landing, should incorporate the clean exercise to develop the strength and flexibility required to absorb energies during impact.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Michael Kennedy who provided some equipment used in this investigation and Dr. Pierre Baudin who provided insight in analysis and interpretation of data.
REFERENCES


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Table 2. Joint excursions between initial contact and peak knee flexion. Positive values indicate ankle plantar-flexion, knee flexion and hip extension. Superscript abbreviations indicate significant greater excursion (p<0.05) than indicated tasks (\textsuperscript{pc} – Power Clean; \textsuperscript{cl} – Clean).

Table 3. Net joint moment at peak knee flexion. Positive values indicate internal ankle dorsiflexor, knee extensor and hip flexor net joint moment. Superscript abbreviations indicate significant greater net joint moment (p<0.05) than indicated tasks (\textsuperscript{h} – Jump Landing; \textsuperscript{dl} – Drop Landing; \textsuperscript{pc} – Power Clean).

LIST OF FIGURES

Figure 1. Timeline for research study.

Figure 2. Total work and work performed at lower extremity joints during impact activities. Superscript abbreviations indicate total work performed is significantly greater (p<0.05) than indicated tasks.

Figure 3. Percentage contribution of ankle, knee and hip to total lower extremity work during impact activities. Superscript abbreviations indicate percentage work at joint is significantly greater (p<0.05) than indicated tasks.

Figure 4. Segment angles during impact activities at initial contact and peak knee flexion. Superscript abbreviations indicate segment angle is significantly greater (p<0.05) than indicated tasks.

Figure 5. Joint angles during impact activities at initial contact and peak knee flexion. Superscript abbreviations indicate joint angle is significantly greater (p<0.05) than indicated tasks.
**Table 1.** Descriptive characteristics of participants (n=10).

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>1.79 ± 0.07</td>
<td>1.67 – 1.93</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>71.0 ± 8.9</td>
<td>59.7 – 91.4</td>
</tr>
<tr>
<td>Vertical jump height (m)</td>
<td>0.46 ± 0.04</td>
<td>0.41 – 0.53</td>
</tr>
<tr>
<td>Clean – One repetition maximum (kg)</td>
<td>60.3 ± 6.1</td>
<td>50.0 – 70.0</td>
</tr>
<tr>
<td>Clean – One repetition maximum : Body mass</td>
<td>0.86 ± 0.12</td>
<td>0.66 – 1.07</td>
</tr>
</tbody>
</table>
Table 2. Joint excursions between initial contact and peak knee flexion. Positive values indicate ankle plantar-flexion, knee flexion and hip extension. Superscript abbreviations indicate significant greater excursion (p<0.05) than indicated tasks (PC = Power Clean; CL = Clean).

<table>
<thead>
<tr>
<th></th>
<th>Jump</th>
<th>Drop Landing</th>
<th>Power Clean</th>
<th>Clean</th>
</tr>
</thead>
</table>
| Ankle | -60 ± 13
  | CL            | -54 ± 7       | -27 ± 10      | -29 ± 13      |
| Knee  | 78 ± 12
  | PC            | 86 ± 12       | 41 ± 18       | 86 ± 17
  | Hip   | -62 ± 11
  | PC            | -62 ± 11      | -34 ± 19      | -66 ± 16
  |
**Table 3.** Net joint moment at peak knee flexion. Positive values indicate internal ankle dorsiflexor, knee extensor and hip flexor net joint moment. Superscript abbreviations indicate significant greater net joint moment (p<0.05) than indicated tasks (\(^J\) – Jump Landing; \(^DL\) – Drop Landing; \(^PC\) – Power Clean).

<table>
<thead>
<tr>
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<th>Jump</th>
<th>Drop Landing</th>
<th>Power Clean</th>
<th>Clean</th>
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<tr>
<td>Ankle (N·m·kg(^{-1}))</td>
<td>-1.5 ± 0.4</td>
<td>-1.4 ± 0.4</td>
<td>-1.9 ± 0.4(^J,DL)</td>
<td>-2.0 ± 0.4(^J,DL)</td>
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<tr>
<td>Knee (N·m·kg(^{-1}))</td>
<td>2.9 ± 0.8</td>
<td>2.9 ± 1.0</td>
<td>3.7 ± 0.7(^J,DL)</td>
<td>4.5 ± 1.3(^J,DL,PC)</td>
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<tr>
<td>Hip (N·m·kg(^{-1}))</td>
<td>-2.5 ± 0.5</td>
<td>-2.1 ± 0.6</td>
<td>-2.3 ± 0.7</td>
<td>-3.6 ± 0.5(^J,DL,PC)</td>
</tr>
</tbody>
</table>
Session 1
1. Maximum Vertical Jump Testing
2. Drop Landing Practice

~1 week

Session 2: Motion Analysis
1. Jump Landings
2. Drop Landings
3. Power Clean/Clean (3 sets of each performed in alternating order)
Figure 4
Click here to download high resolution image

Initial Contact

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<tr>
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Drop Landing

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<td>-3 ± 10°</td>
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<td>48 ± 8°</td>
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<tr>
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<td>-41 ± 4°</td>
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Power Clean

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<td>-10 ± 6°</td>
<td>0 ± 6°</td>
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<td>Foot&lt;sub&gt;PC&lt;/sub&gt;</td>
<td>-6 ± 5°</td>
<td>-41 ± 4°</td>
<td>-41 ± 4°</td>
<td>-41 ± 4°</td>
</tr>
</tbody>
</table>

Clean

<table>
<thead>
<tr>
<th></th>
<th>Pelvis</th>
<th>Pelvis</th>
<th>Pelvis</th>
<th>Pelvis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-10 ± 6°</td>
<td>0 ± 6°</td>
<td>88 ± 8°</td>
<td>88 ± 8°</td>
</tr>
<tr>
<td>Thigh</td>
<td>-15 ± 6°</td>
<td>48 ± 8°</td>
<td>48 ± 8°</td>
<td>48 ± 8°</td>
</tr>
<tr>
<td>Leg</td>
<td>-40 ± 5°</td>
<td>-43 ± 7°</td>
<td>-43 ± 6°</td>
<td>-43 ± 6°</td>
</tr>
<tr>
<td>Foot&lt;sub&gt;PC&lt;/sub&gt;</td>
<td>-6 ± 5°</td>
<td>-41 ± 4°</td>
<td>-41 ± 4°</td>
<td>-41 ± 4°</td>
</tr>
</tbody>
</table>

Peak Knee Flexion

<table>
<thead>
<tr>
<th></th>
<th>Pelvis&lt;sub&gt;CL&lt;/sub&gt;</th>
<th>Pelvis&lt;sub&gt;PC,CL&lt;/sub&gt;</th>
<th>Pelvis&lt;sub&gt;DL,PC,CL&lt;/sub&gt;</th>
<th>Pelvis&lt;sub&gt;ICL&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-22 ± 6°</td>
<td>-22 ± 6°</td>
<td>-22 ± 6°</td>
<td>-22 ± 6°</td>
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<tr>
<td>Thigh</td>
<td>54 ± 13°</td>
<td>-15 ± 6°</td>
<td>68 ± 11°</td>
<td>48 ± 8°</td>
</tr>
<tr>
<td>Leg</td>
<td>-3 ± 1°</td>
<td>-40 ± 5°</td>
<td>-43 ± 7°</td>
<td>-3 ± 2°</td>
</tr>
<tr>
<td>Foot&lt;sub&gt;PC,CL&lt;/sub&gt;</td>
<td>-3 ± 1°</td>
<td>-40 ± 5°</td>
<td>-43 ± 7°</td>
<td>-43 ± 6°</td>
</tr>
<tr>
<td>Jump Landing</td>
<td>Drop Landing</td>
<td>Power Clean</td>
<td>Clean</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5

Initial Contact

<table>
<thead>
<tr>
<th></th>
<th>Jump Landing</th>
<th>Drop Landing</th>
<th>Power Clean</th>
<th>Clean</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hip</strong></td>
<td>Hip $-15 \pm 10^\circ$</td>
<td>Hip $-22 \pm 11^\circ$</td>
<td>Hip $-23 \pm 20^\circ$</td>
<td>Hip $-23 \pm 21^\circ$</td>
</tr>
<tr>
<td><strong>Knee</strong></td>
<td>Knee $17 \pm 7^\circ$</td>
<td>Knee $26 \pm 11^\circ$</td>
<td>Knee $48 \pm 18^\circ$</td>
<td>Knee $46 \pm 20^\circ$</td>
</tr>
<tr>
<td><strong>Ankle</strong></td>
<td>Ankle $25 \pm 12^\circ$</td>
<td>Ankle $20 \pm 10^\circ$</td>
<td>Ankle $-8 \pm 13^\circ$</td>
<td>Ankle $-8 \pm 15^\circ$</td>
</tr>
</tbody>
</table>

Peak Knee Flexion

<table>
<thead>
<tr>
<th></th>
<th>Jump Landing</th>
<th>Drop Landing</th>
<th>Power Clean</th>
<th>Clean</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hip</strong></td>
<td>Hip $-77 \pm 16^\circ$</td>
<td>Hip $-84 \pm 9^\circ$</td>
<td>Hip $-57 \pm 12^\circ$</td>
<td>Hip $-88 \pm 9^\circ$</td>
</tr>
<tr>
<td><strong>Knee</strong></td>
<td>Knee $95 \pm 14^\circ$</td>
<td>Knee $112 \pm 14^\circ$</td>
<td>Knee $90 \pm 10^\circ$</td>
<td>Knee $131 \pm 8^\circ$</td>
</tr>
<tr>
<td><strong>Ankle</strong></td>
<td>Ankle $-35 \pm 6^\circ$</td>
<td>Ankle $-35 \pm 7^\circ$</td>
<td>Ankle $-35 \pm 6^\circ$</td>
<td>Ankle $-38 \pm 7^\circ$</td>
</tr>
</tbody>
</table>