Lower extremity kinematic asymmetry in male and female athletes performing jump-landing tasks

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Abstract

Objectives: Higher side-to-side asymmetry among female athletes compared to their male counterparts during bilateral athletic tasks such as landing from a jump has been proposed as a potential source of non contact knee injuries. However, the kinematic symmetry and potential sex differences during the initial (and most dangerous) phase of bilateral landings have not been examined. The objective of this project is to evaluate lower extremity kinematic asymmetry among recreational athletes during forward jump landing and drop landing tasks.

Design: Repeated measures laboratory experiment.

Methods: Thirteen male and 15 female athletes performed landing tasks on a force plate while kinematic data were collected. Kinematic asymmetry between legs was calculated for the initial phase of landing for lower extremity kinematics. ANOVA tests and effect size calculations were used to measure the effect of sex, landing task and their interaction on kinematic asymmetry.

Results: Athletes exhibited higher asymmetry for knee valgus ($d=0.5$, $p=0.006$) and hip adduction ($d=0.5$, $p=0.057$) when performing forward compared to drop landings. Females landed with greater knee valgus asymmetry than males during forward landings ($d=0.7$, $p=0.078$) and with greater ankle abduction asymmetry during drop landings ($d=0.5$, 0.091). Conclusions: Female athletes exhibited greater frontal plane knee and ankle kinematic asymmetry than males during forward landings which may be related to the higher rate of ACL injury. Forward landings elicited greater hip adduction and knee valgus asymmetries than drop landings and, therefore it may be more appropriate for field testing when screening for asymmetries.

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1. Introduction

Female athletes are substantially more susceptible than male athletes in suffering acute non-contact injury of the anterior cruciate ligament (ACL).\textsuperscript{1} The theories that have been proposed to explain this phenomenon include the ligament dominance, quadriceps dominance, trunk dominance, and leg dominance theories.\textsuperscript{2} These theories suggest that athletes predisposed to ACL tear rely more on their ligaments by landing with excessive knee valgus (ligament dominance), recruit the quadriceps more than the hamstrings (quadriceps dominance), present with trunk control deficits (trunk dominance), and exhibit kinetic and kinematic leg asymmetries during bilateral tasks (leg dominance). Previous studies have provided support for the ligament dominance theory by demonstrating that females exhibit greater knee valgus than males\textsuperscript{3,4} and that within females greater knee valgus angle and moment during landing predicts ACL injury.\textsuperscript{5} Support for the quadriceps dominance theory has been provided by studies that found that females preferentially activate the quadriceps more than males.\textsuperscript{5,7} Other studies found that trunk control deficits predict knee injury in female athletes\textsuperscript{8} and that females exhibit less activation of the abdominal internal obliques than males during landing,\textsuperscript{5} therefore supporting the trunk dominance theory.

However, very limited research exists on the leg dominance theory. It has been demonstrated that side-to-side
knee valgus moment asymmetry predicts future ACL injury in female athletes. Additionally, it has been shown that knee flexion moment asymmetry predicts re-injury in athletes who had an ACL reconstruction. One way to test the leg dominance theory is to compare leg asymmetries between male and female athletes performing challenging task such as landing from a jump. Two-thirds of ACL injuries occur via a non-contact mechanism, and the majority of these injuries occur at landing from a jump. As females are at much higher risk of suffering ACL injury than males they could present with greater kinematic asymmetries than males during landing tasks. To our knowledge, only one study directly addressed asymmetry during landing between males and females but the measurement was limited to peak knee valgus angle during one task (bilateral drop jumps). Peak knee valgus angles occur toward the end of the landing cycle when risk of ACL injury is decreased and at different time points in the two legs. Therefore, measuring asymmetry by comparing angles that occurred at different times at the right and left legs may not be representative of the time-synchronized asymmetry during landing tasks. Additionally, investigating asymmetries across all lower extremity joints instead of focusing on one motion has the potential to provide a more comprehensive assessment of faulty motion patterns that may be related to injury. Finally, investigating asymmetries across more than one athletic tasks has the potential to identify the most appropriate task for screening purposes as there is strong evidence that sex differences are task dependent. In this project we chose two distinctly different landing tasks: a highly controlled task (drop landing) that consists of only the eccentric phase of the jump-landing cycle and a more functional task (forward landing) that consists of both a concentric (take-off) and an eccentric (landing) phase.

A study that investigates asymmetry of lower extremity angles at the initial (and most dangerous for the ACL) phase of landing tasks by directly comparing time-synchronized angles between legs can provide valuable information on the validity of the leg dominance theory as a potential explanation of sex disparity for ACL injuries. There were three objectives to this study: (a) to evaluate sex differences for hip, knee and ankle kinematic asymmetries during landing tasks, (b) to compare asymmetries between two commonly used types of landing, and (c) to report normative values for kinematic asymmetry among healthy male and female athletes.

2. Methods

Thirteen male [age: 26(2) years, height: 182(7) cm, weight: 84(11) kg] and 15 female [age: 25(3) years, height: 167(6) cm, weight: 59(7) kg] recreational athletes without history of lower extremity injury completed the protocol at the Harkness Dance Center Motion Analysis Laboratory, NYU – Hospital for Joint Diseases. The inclusion criteria included participation in recreational sports that involved jump-landing activities at least twice per week for a minimum of 45 min per practice session. Participants were excluded if they had received specialized training in jumping and landing techniques such as through participation in injury prevention programs, gymnastics or dance. All participants were right-leg dominant as determined by the answer the question about what is their preferred leg to kick a ball.

The force plate was an OR6-5 AMTI biomechanical platform (AMTI, Watertown, MA). Kinematic data were collected with the use of eight Eagle cameras (Motion Analysis Corp. Santa Rosa, CA). The force platform was time synchronized to motion analysis system. The software for data collection was the EvaRT 4.0 (Motion Analysis Corp. Santa Rosa, CA). The kinetic data were sampled at 1200 Hz and the kinematic data were sampled at 240 Hz as appropriate for fast athletic maneuvers. Before each data collection session the system was calibrated to the manufacturer’s recommendations. Reflective markers were placed on the sacrum and the left posterior superior iliac spine (offset) and bilaterally on the second metatarsal, calcaneus, lateral malleolus, fibula, lateral femoral epicondyle, thigh, anterior superior iliac spine, acromion, lateral humeral epicondyle, and distal radioulnar joint as per the “Helen Hayes” system. The analysis of the data was performed with the Orthotrak 5.0 (Motion Analysis Corp. Santa Rosa, CA). Kinematic data were smoothed using a Butterworth fourth order low pass filter with a cut-off frequency of 6 Hz.

Participants were informed of the study protocol and all risks and possible harms as described in the consent form. Ethics approval was obtained from the NYU School of Medicine IRB. Participants were measured for height, weight, knee width, foot width, and foot length. They performed three maximum bilateral forward jump-landings (FL) from 20 cm away from the force plate and three bilateral drop landings (DL) from a 40 cm box with both legs on the force plate in a randomized order. The athletes performed two practice jumps before each task to familiarize themselves with the FL and DL. For the FL, they were instructed to start with the front of both shoes aligned with a mark on the ground that was placed 20 cm from the force plate, jump as high as they can and land with both legs on the force plate. For the DL, they were instructed to drop directly down off the box and land with both legs on the force plate. Participants did not receive any instructions on the landing technique to avoid a coaching effect and they were instructed to keep their gaze forward for all trials. The effect of the arms was minimized by asking the participants to keep their arms crossed against their chest. Trials were repeated when they were judged as non-acceptable (such as when participants lost their balance). The landing cycle was defined as the time between initial contact and peak knee flexion.

An initial “neutral” standing position of each athlete was used to account for skeletal alignment differences as in similar studies. With this technique, zero degree angles were defined as the angles between adjacent segments during the neutral standing trial. The reliability of lower extremity angles during landing using a similar protocol and identical data collection
system to the one used for the present study was high (ICC range = 0.93–0.99) while the typical errors ranged from 0.9° for knee valgus to 3.2° for knee flexion (Table 1). Additionally, as the same researcher placed the markers on all subjects we eliminated the greatest contributor to kinematic error. Kinematic symmetry during both bilateral tasks was measured as the absolute difference between the right and left leg for each data frame and it was averaged across the first 40 ms after landing for hip adduction, hip flexion, knee valgus, knee flexion, ankle abduction (frontal plane motion only) and ankle flexion. The combination of this methodology with the bilateral nature of the tasks allows for the assessment of symmetry by comparing simultaneously occurring angles of the left and right leg. The first 40 ms after landing were chosen as it has been demonstrated that this is the phase of landing when ACL injuries occur. The values were averaged for the three trials. We chose to measure asymmetry as the absolute difference between the two legs as opposed to subtracting the non-dominant leg angle from the dominant leg angle because of evidence showing that there is no ACL injury risk difference between the two legs.

Six separate ANOVAs were performed to statistically evaluate the effect of task (FL vs. DL), sex (male vs. female) and their interaction on each one of the kinematic variables. The α level was set a priori at 0.05 while values ≤ 0.10 and >0.05 were considered statistical trends. Cohen’s d statistic of effect size was calculated in order to provide a more complete picture of the effect of the independent variables on the dependent variables. The effect size was defined as trivial if it was <0.2, small 0.2–0.5, medium 0.5–0.8, and large >0.8. A power calculation demonstrated that we needed a minimum of 9 athletes per group to detect a 20% difference in mean values between males and females.

3. Results

Task had a significant effect on knee valgus with athletes exhibiting more asymmetry in FL compared to DL (p = 0.006). Additionally, a trend was found for higher hip adduction asymmetry during FL than DL (p = 0.057). Trends were also observed for the interaction of task and sex on knee valgus with females exhibiting higher asymmetry than males during FL but not during DL (p = 0.078) and on ankle abduction with females exhibiting higher asymmetry than males during DL but not during FL (p = 0.091). Overall, there was more asymmetry between the two legs for hip and knee frontal plane than for sagittal plane variables (Table 1). All effect sizes for the comparisons that were either significant or had a statistical trend were medium while all effects sizes for the comparisons that had p values higher than 0.10 were trivial or small.

4. Discussion

It has been long theorized that among the reasons predisposing females to ACL injuries more than males is their performance of landing tasks with asymmetry for a variety of jump characteristics. The current study investigated sex differences in kinematic asymmetry during two types of landing. The findings provide indirect support to the leg dominance theory. Females exhibited greater asymmetry than males in knee valgus and ankle abduction during FL; both of them frontal plane kinematic variables. Increased knee valgus has been directly linked to the ACL mechanism of injury. In this case, asymmetric kinematics would suggest higher demands and load for a given limb. Asymmetry has been investigated by previous studies that found that female athletes have higher side-to-side asymmetry for hamstrings isokinetic torque and hamstrings-to-quadriceps ratio. During running, asymmetries in frontal plane kinematics may contribute to increased risk of overuse injury. However, to the best of our knowledge, this is the first study to demonstrate that asymmetries in lower extremity kinematics during jump-landing tasks may exist and differ between male and female athletes during the initial phase of landing. A previous study also found similar sex effect but during a DL task. The present study found that females exhibit more asymmetrical valgus kinematics than males during FL but not during DL. We also found that the absolute differences in the present study were in the magnitude of 4–6° and, therefore quite lower than the 15° that

Table 1
Leg asymmetries for kinematic variables. Data are presented as the average side-to-side difference for each task.

<table>
<thead>
<tr>
<th>Side-to-side difference [° (SD)]</th>
<th>Typical errors17</th>
<th>Forward jump-landings</th>
<th>Drop landings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
<td>Effect size for sex</td>
</tr>
<tr>
<td>Hip adduction</td>
<td>1.6</td>
<td>7.1 (4.0)</td>
<td>7.6 (5.0)</td>
</tr>
<tr>
<td>Hip flexion</td>
<td>2.9</td>
<td>1.8 (1.2)</td>
<td>1.9 (0.8)</td>
</tr>
<tr>
<td>Knee valgus</td>
<td>0.9</td>
<td>4.0 (3.2)</td>
<td>6.2 (3.3)</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>3.2</td>
<td>3.9 (2.6)</td>
<td>4.6 (3.8)</td>
</tr>
<tr>
<td>Ankle abduction</td>
<td>1.9</td>
<td>3.4 (4.0)</td>
<td>2.9 (2.6)</td>
</tr>
<tr>
<td>Ankle flexion</td>
<td>1.6</td>
<td>3.5 (1.9)</td>
<td>3.7 (2.5)</td>
</tr>
</tbody>
</table>

aTrend for higher asymmetry in forward jump-landings compared to drop landings (p = 0.006).
bHigher asymmetry in forward jump-landings compared to drop landings (p = 0.057).
cTrend for higher asymmetry in females compared to males (p ≤ 0.091).
was reported for females in the previous study. The difference in the findings of the two studies may be explained by the different methodology, particularly in respect to the different phases of the landing cycle that they evaluated. We focused on the initial phase where knee valgus angles tend to be lower while the previous study compared peak knee valgus angles that occur toward the end of the landing cycle.

The importance of frontal plane knee kinematic variables during landing from a jump for potentially explaining the sex disparity on ACL injuries has been previously demonstrated by studies that found females landing from a jump with higher knee valgus angles than males and that high knee valgus angles during DL are predictors of ACL injury among females. The higher asymmetry in knee valgus kinematics in the present study may potentially explain the higher risk for ACL injury in female athletes by leading to greater load on ligaments. It adds to a list of biomechanical variables that have been found to be different between males and females. The kinematic asymmetries can influence those muscle–skeletal relations such as force–length relationship, alter the distribution of forces between the two legs, place the inert structures of one knee under greater load, and put disproportionate demands on the musculature of one lower extremity. An alternative or parallel explanation may be that asymmetries during bilateral tasks are surrogates of motor coordination and, therefore less coordinated athletes (who also exhibit greater asymmetries) are at a higher risk of ACL injury. Analysis of ACL injuries captured on camera showed that when a female athlete tears her ACL there are large asymmetries in weight distribution between the two legs. Asymmetries in bilateral tasks may mean that excessive load is placed on one leg while the other leg is protected (and possibly de-trained) from successfully decelerating the body during landing. This may lead to increased risk of injury for both legs.

Although most of the literature on biomechanics related to ACL injury has focused on the knee and the joints proximal to it the importance of ankle biomechanics has been demonstrated by a recent study of ACL injuries captured on video where athletes who tore their ACL landed with lower ankle plantarflexion than controls. The present study found differences in frontal plane ankle kinematic asymmetry between males and females during DL. Frontal plane ankle motion is an important component of the shock absorption mechanism as it allows the transformation of the foot from a rigid lever to a pliable segment that is capable of effective shock absorption. Asymmetries in ankle joint kinematics are transferred to the proximal joints and can place them in a vulnerable position. Excessive frontal plane ankle motion has been linked to preloading of the ACL as there is a direct connection with internal rotation of the tibia. Additionally, static measures associated with ankle abduction (navicular drop and subtalar pronation) are higher in athletes who suffered ACL tear compared to uninjured athletes. Previous investigators have demonstrated that female athletes exhibit greater subtalar joint motion during athletic tasks than males, however, this is the first study to show that females also demonstrate greater asymmetries.

A comparison between the two tasks revealed that FL elicited greater asymmetry for hip adduction and knee valgus compared to the DL task. The two tasks are inherently different with FL having both a concentric and eccentric phase while DL has only an eccentric phase. Athletes are more familiar with the FL task that is commonly practiced during sports and may, therefore be more generalizable to the field while DL is easier to standardize in the laboratory setting. Athletes commonly have a preferred jumping leg which during bilateral forward jumps may create asymmetry that is not corrected during the airborne phase causing the athletes to land with greater asymmetries compared to DL. The FL task appears to be more appropriate for testing for asymmetries than the DL task. A recent research retreat on ACL injuries concluded that biomechanical differences between males and females may be task dependent and that “care should be taken not to overgeneralize results from one specific task to other tasks”. The findings of the present study provide further support to this notion as we found that sex differences in kinematic asymmetry vary between FL and DL and that frontal plane knee and hip asymmetries are more prominent during one type of landing task but not in the other. Athletes with obvious asymmetries should be identified early and referred to qualified personnel for specialized training programs that gradually correct these deficits.

It may be advisable for injury prevention programs to emphasize symmetry during functional tasks and for pre-season screening to include assessment of obvious asymmetries during landing tasks, particularly for females athletes who appear to be more susceptible to asymmetries during landing. The findings of the present study suggest that FL tasks may be more sensitive in eliciting asymmetry deficits than DL tasks and, therefore, should be an integral part of landing technique assessment. Visual feedback techniques such as performing jump landing tasks in front of a mirror may be used to restore symmetry in addition to traditional plyometric, stretching and strengthening interventions. There is evidence suggesting that performing unilateral tasks on each leg may assist in decreasing side-to-side asymmetries by using neuromuscular feedback loops and bilateral neurological systems to improve symmetry. However, the benefit and feasibility of restoring leg-to-leg symmetry in athletes needs to be evaluated by prospective studies that identify athlete with high asymmetries and enroll them into injury prevention programs. Until these studies become available, the level of evidence for recommending asymmetry correction in athletes is rather low.
differences found in the present study fall within the typical error and need to be interpreted with caution. Although every effort was made to use methodology that minimizes error, kinematic measurements of functional tasks have well-described limitations. For example, the 0.5° difference between the two tasks in knee valgus within males is almost half of the typical error (0.9°) and may be the result of system error instead of genuine differences between tasks. In terms of the minimum angles that produce increased ACL forces, it has been demonstrated that significant increases in ACL strain occur when a valgus moment that causes a 2.5° increase in knee valgus angle is applied on the loaded lower extremity. The musculature that crosses the knee joint is designed to effectively absorb forces in the sagittal plane where most of its range of motion occurs, but not in the frontal plane where most of the stability is provided by the inert structures. Therefore, even small kinematic deviations in the frontal plane may cause excessive forces within knee ligaments that cannot be easily ameliorated by the musculature. We found knee valgus leg-to-leg differences of 3.5–6.2° which are higher than the angle required to increase ACL strain. However, differences for the effect of sex were closer to this threshold (2.2°) while differences for the effect of task were close the threshold for females but not for males (2.1° and 0.5°, respectively).

Additional limitations of this study include low sample size and subsequent low statistical power. Kinetic variables could not be calculated as athletes landed with both legs on the force plate. We found in our pilot work that some athletes naturally land with their feet close together which would preclude landing on two force plates while maintaining their natural landing style due to the necessary distance that has to be maintained between force plates in the biomechanics lab to insure valid measurements. Each one of the landing tasks has advantages and disadvantages. The DL is standardized for height but it is not commonly practiced in most sports. The FL – on the other hand – is commonly observed in the athletic field but the landing height is not the same for all athletes as it depends on the athletic ability of each athlete.

Future studies should use larger sample sizes, additional tasks such as stop-jump landings and prospectively evaluate asymmetry in kinematic and kinetic variables as predictors of future injury. The optimal age to introduce injury prevention programs for maximizing their effectiveness in decreasing asymmetries needs to be investigated. The persistence of leg asymmetries after injury and optimal rehabilitation protocols to minimize them are also among further topics for investigation.

5. Conclusions

This study demonstrated that female recreational athletes exhibited greater side-to-side asymmetry than male athletes for knee valgus and ankle abduction kinematics during the initial phase of landing from a forward jump. The findings may provide insight into the biomechanical factors responsible for the higher rate of knee injuries among females and may guide the development and improvement of injury prevention programs. Differences in the asymmetry elicited by each task were observed; forward landing produced more prominent lower extremity kinematic asymmetry than drop landing highlighting the importance of using multiple landing tasks in biomechanical studies and not generalizing findings from one task to other tasks.

Practical implications

- Female athletes exhibit higher side-to-side asymmetries when landing for a jump.
- Forward landing may be a better screening tool for asymmetries than drop landing.
- Injury prevention programs should incorporate asymmetry reduction training particularly for female athletes.

Acknowledgement

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References