Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Clinical Biomechanics 21 (2006) 33–40
CLINICAL BIOMECHANICS
www.elsevier.com/locate/clinbiomech

A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings

Kevin R. Ford [a,*], Gregory D. Myer [a], Rose L. Smith [b], Rebecca M. Vianello [b], Shelly L. Seiwert [b], Timothy E. Hewett [a,b,c]

[a] *Sports Medicine Biodynamics Center and Human Performance Laboratory, Cincinnati Children's Hospital Research Foundation, 3333 Burnet Avenue, MLC 10001, Cincinnati, OH 45229, USA*
[b] *College of Allied Health Sciences, Physical Therapy Department, University of Cincinnati, Cincinnati, OH 45221, USA*
[c] *College of Medicine, Departments of Pediatrics and Orthopaedic Surgery, University of Cincinnati, Cincinnati, OH 45221, USA*

Received 12 May 2005; accepted 10 August 2005

Abstract

Background. Despite recent evidence supporting the use of neuromuscular training to reduce anterior cruciate ligament injury risk, female athletes continue to show an increased anterior cruciate ligament injury rate in collegiate basketball and soccer when compared to males. The purpose of the current study was to identify gender and task differences in measures that may increase the risk of anterior cruciate ligament injury in female basketball and soccer athletes.

Methods. Eleven female and 11 male collegiate basketball and soccer athletes were height (female mean 176 (SD 8 cm), male mean 176 (SD 8 cm)) and weight (female mean 73 (SD 7 kg), male mean 74 (SD 6 kg)) matched. Three-dimensional motion analysis was used to calculate differences in total coronal plane angular joint excursion (maximum–minimum) between male and female athletes when performing a series of medially and laterally directed drop landings.

Findings. Female athletes demonstrated increased total coronal plane excursion for the hip, knee and ankle ($P < 0.05$) during the medial drop landing. During the lateral drop landing females displayed increased excursion at the hip and knee. When comparing tasks, the lateral drop landing resulted in greater coronal plane excursion at the hip ($P < 0.05$) while the knee showed no differences between movements. In contrast, females demonstrated increased ankle excursion during the medial drop task ($P < 0.05$).

Interpretation. Female athletes demonstrate increased lower extremity coronal plane excursion when performing single leg drop landing in both the medial and lateral direction when compared to height/weight matched male athletes. This increased coronal plane oscillation of lower extremity joints may be related to the increased risk of anterior cruciate ligament injury for female basketball and soccer athletes.

Keywords: Valgus knee; ACL injury; Gender differences; Neuromuscular; Biomechanics

1. Introduction

Females who participate in pivoting and jumping sports suffer anterior cruciate ligament (ACL) injuries at a 4- to 6-fold greater rate than males participating in the same landing and pivoting sports (Malone et al., 1993; Arendt and Dick, 1995). Specifically, collegiate basketball and soccer athletes over the past decade show consistent gender differences in non-contact ACL injuries (Agel et al., 2005). The combination of greater ACL injury risk and dramatically larger number of female sports participants over the last 30 years has

* Corresponding author.
E-mail address: kevin.ford@cchmc.org (K.R. Ford).

0268-0033/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2005.08.010

increased public awareness and led to both mechanistic and intervention-related investigations into the cause and prevention of the increased rate of ACL injuries in female basketball and soccer players (NCAA, 2002).

A recent prospective study identified several biomechanical risk factors that were predictive of ACL injuries in female athletes (Hewett et al., 2005). Hewett et al. found that coronal plane angles at the knee (initial contact and maximum) were greater during a landing task in athletes who subsequently sustained an ACL injury than those that did not (Hewett et al., 2005). In the same group of athletes, coronal hip measures at landing directly correlated to knee abduction measures used to predict future ACL injury risk (Hewett et al., 2005).

Examination of lower extremity coronal plane motion or the angular excursion of hip and knee abduction–adduction and ankle eversion–inversion motion in female athletes appears to be valuable for the identification of ACL injury risk in female athletes (Hewett et al., 2005; Ford et al., 2003, 2005; McLean et al., 2004a). Coronal plane excursion is operationally defined in this study as the angular displacement in the coronal plane of the lower extremity joints during landing. Coronal plane excursion is especially evident at the knee, which often can be visually identified as medial knee motion, although multiple joints and joint rotations may be involved (Myer et al., 2000, 2002, 2004; Olsen et al., 2004). Repeated performance of high risk maneuvers, with large coronal plane excursion, may increase the tendency for lower extremity valgus collapse and ACL rupture (Myer et al., 2005a; McLean et al., 2004a; Hewett et al., 2005; Olsen et al., 2004; Boden et al., 2000).

Previous studies that identified kinematic variables associated with coronal plane motion often only reported the extreme values (maximum, minimum) or values at a certain event (initial contact, maximum force etc.) during the observed maneuver. Several authors have reported the increased tendency of female athletes to demonstrate dynamic lower extremity valgus (hip adduction, knee abduction and ankle eversion) when performing athletic maneuvers (Malinzak et al., 2001; McLean et al., 2004b; Ford et al., 2003, 2005; Hewett et al., 2004). Hurd et al. reported that females demonstrated increased coronal plane knee excursion compared to males during normal and perturbed gait. Their calculation of excursion was from the point of perturbation to the absolute maximum during the stance phase of gait and did not represent the oscillation through abduction and adduction as during gait this typically would displace angularly in one direction. McLean et al. first described the visual representation of an oscillatory pattern in total knee adduction–abduction that occurred in females during more dynamic tasks (McLean et al., 2004b). This coronal plane oscillatory knee pattern was demonstrated in angle measures assessed during unanticipated cutting (Ford et al., 2005) and in moments during jump landings (Hewett et al., 2005). Thus this rapid lower extremity coronal plane excursion or oscillation may play a role in gender related mechanisms of ACL injuries in female athletes suffered during sports participation (Ford et al., 2005; Hewett et al., 2005; McLean et al., 2004b).

The injury mechanism most often related to ACL injuries involves single leg landings or quick changes of direction (Olsen et al., 2004; Boden et al., 2000; McNair et al., 1990). Non-contact ACL injuries account for up to four-fifths of ACL injuries (McNair et al., 1990; Boden et al., 2000; Griffin et al., 2000) A detailed video analysis of ACL injuries showed that 95% of the plant and cut injuries occurred while the athlete was moving in a lateral direction and attempting to change direction medially (Olsen et al., 2004). Olsen et al. reported that the other common ACL injury mechanism occurred during single leg landing, with all the injuries occurring on the same leg used to takeoff (Olsen et al., 2004). Although they do not report the direction of the landing (medially or laterally), their representative figure shows a medially directed landing during this injury mechanism. Hewett et al. demonstrated that measures of lower extremity coronal plane motion during landing were highly sensitive and specific to predicting ACL injury risk in female athletes (Hewett et al., 2005). Therefore, it appears salient for ACL mechanistic studies to investigate the potential gender and task related differences in measures related to ACL injury (Hewett et al., 2005; Olsen et al., 2004). Specifically, to investigate the effects of single leg deceleration tasks involving a medially or laterally directed motion of the body and to determine the effects gender has on lower extremity coronal plane motion related to increased ACL injury risk in females (Hewett et al., 2005; Olsen et al., 2004). Increased ability to detect high risk motions demonstrated by athletes during tasks related to the ACL injury mechanisms may identify individual athletes at increased risk of injury. Identification of high risk athletes may help target those in need of training to reduce their tendency toward these motions and reduce their risk of injury during sports competition (Hewett et al., 2005; Myer et al., 2005b).

The purposes of this study were to assess gender differences in coronal plane excursion between matched male and female athletes and to identify whether the direction of motion of the landing would influence the magnitude of measured coronal plane excursion. The first hypothesis was that female athletes would demonstrate increased hip, knee and ankle coronal plane excursion during both medial and lateral drop landings. The second hypothesis was that the lateral directed drop landing would increase the amount of lower extremity coronal plane excursion in both genders.

2. Methods

2.1. Subjects

Eleven females and 11 males collegiate athletes were height (female mean 176 (SD 8 cm), male mean 176 (SD 8 cm)) and weight (female mean 73 (SD 7 kg), male mean 74 (SD 6 kg)) matched (15 soccer, 7 basketball). All subjects read and signed the informed written consent, approved by the Institutional Review Board, prior to participation. After the informed consent was obtained, the dominant leg was determined for each subject by asking which leg they would use to kick a ball for distance (Ford et al., 2003).

2.2. Procedures

Each subject was instrumented with 37 retroreflective markers placed on the sacrum, left PSIS, sternum and bilaterally on the shoulder, elbow, wrist, ASIS, greater trochanter, mid thigh, medial and lateral knee, tibial tubercle, mid shank, distal shank, medial and lateral ankle, heel, dorsal surface of the midfoot, lateral foot (fifth metarsal) and toe (between second and third metatarsals) (Fig. 1). A static trial was first collected in which the subject was instructed to stand still and was aligned as closely with the laboratory coordinate system as possible. This measurement was used as each subject's neutral (zero) alignment; subsequent kinematic measures were in relation to this position. Each subject was shown the single leg landings and allowed to practice the movements prior to testing. The landings consisted of balancing on one leg on top of a 13.5 cm block positioned adjacent to an embedded force plate (AMTI, Watertown, MA, USA). They were then randomly instructed to drop off the block either medially or laterally and land on the same leg (Online Supplement File 1). Immediately after landing they had to balance on that leg for ≈2 s before placing their contralateral leg down. Three trials were collected on each leg for each direction (12 total trials). Before the data collection session, the motion analysis system was calibrated according to manufacturer recommendations.

2.3. Data analysis

An 8 camera, high-speed motion analysis system (Eagle, Motion Analysis Corp., Santa Rosa, CA, USA) with a force platform (AMTI) was used for data collection. Video and force data were time synchronized and collected at 240 Hz and 1200 Hz, respectively. The kinematic data were low-pass filtered with a cubic smoothing spline at a 15 Hz cut-off frequency (Woltring et al., 1985). A kinematic model was defined from a standing static trial using Mocap Solver (Motion Analysis Corp.) (McLean et al., 2003). The model consisted of nine skeletal segments including the pelvis and bilateral foot, talus, shank and thigh segments. The kinematic analysis

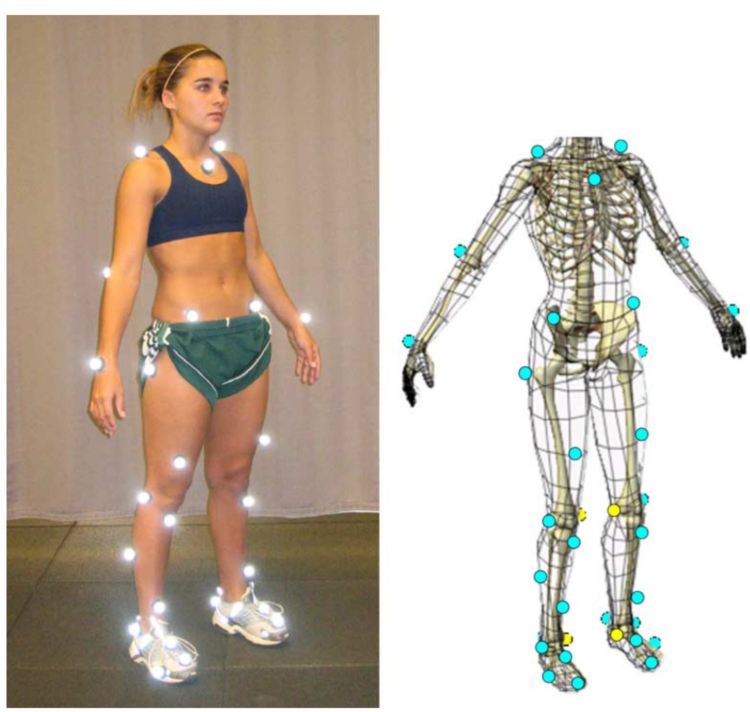

Fig. 1. Locations of the reflective markers during data collection. Medial knee and ankle markers (yellow) were removed after collection of the static trial. Sacrum, left PSIS, left mid tibia and right heel markers are not visible in this view. (For interpretation of colours in this figure legend the reader is referred to the web version of this article.)

used in this study incorporated the global least-squares optimization approach and has been previously detailed elsewhere (Lu and O'Connor, 1999). Coronal plane joint rotations at the hip, knee and ankle were calculated and expressed relative to a neutral position where all segment axes were aligned. By convention, hip and knee abduction–adduction (valgus–varus) angles were presented as negative numbers representing abduction while negative ankle eversion–inversion angles represent an everted position.

The vertical ground reaction force (VGRF) data were utilized to calculate initial contact (IC) with the ground immediately after the subject dropped from the box. IC was determined when VGRF first exceeded 10 N. Joint rotations at IC, as well as the maximum and minimum values between IC and 500 ms, were determined for each trial. Total joint excursion (maximum–minimum) was calculated for each joint rotation.

2.4. Statistical analyses

Statistical means and standard deviations for each variable were calculated for each subject. A three-way MANOVA was utilized to determine the effect of gender (male and female), landing task (medial and lateral) and side (dominant and non-dominant) on each dependent variable. No significant interactions or effects of side were found, therefore the dominant and non-dominant data were pooled and analyzed with a two-way MANOVA (gender × landing task). A Pearson correlation coefficient was calculated to determine the relationship between joint kinematic variables during each landing (all dependent variables). An alpha level of 0.05 was selected to identify statistical significance. Statistical analyses were conducted in SPSS (Version 12.0, Chicago, IL, USA).

3. Results

3.1. Comparison of height and weight matched males and females

A summary of lower extremity coronal plane kinematics is presented in Table 1. Ensemble averaged knee joint angles (abduction–adduction) during each landing are shown in Fig. 2. There was a significant multivariate difference between gender groups ($F_{9,12} = 4.1$, $P = 0.013$) and between the type of landing ($F_{9,12} = 51.3$, $P < 0.001$). Total coronal plane knee excursion was significantly larger in female athletes (medial mean 6.6 (SD 2.1°), lateral mean 6.1 (SD 1.8°)) compared to height and weight matched males (medial mean 5.1 (SD 1.2°), lateral mean 4.8 (SD 1.1°); gender main effect $F_{1,20} = 6.2$, $P = 0.02$, Fig. 3). A group main effect for gender was found for knee abduction angle at initial contact ($P < 0.001$). Females had greater knee abduction at initial contact compared

Table 1
Coronal plane hip, knee and ankle kinematics

	Lateral		Medial		Univariate statistical significance	
	Female	Male	Female	Male	Task	Gender
Hip abduction/adduction (°)						
Initial contact	−16.7 (5.4)	−15.2 (4.1)	−6.7 (6.2)	−6.7 (4.3)	$F_{1,20} = 167$, $P < 0.001$[a]	$F_{1,20} = 0.2$, $P = 0.7$
Maximum adduction (+)	1.9 (6.7)	−1.5 (4.0)	7.3 (6.2)	4.0 (3.7)	$F_{1,20} = 84.5$, $P < 0.001$[a]	$F_{1,20} = 3.7$, $P = 0.07$
Maximum abduction (−)	−17.0 (5.4)	−15.9 (4.0)	−7.6 (5.9)	−7.6 (4.2)	$F_{1,20} = 180$, $P < 0.001$[a]	$F_{1,20} = 0.1$, $P = 0.7$
Knee abduction/adduction (°)						
Initial contact	−2.4 (2.0)	1.7 (2.3)	−0.5 (2.2)	3.0 (2.8)	$F_{1,20} = 62.3, P < 0.001$[a]	$F_{1,20} = 20.0$, $P < 0.001$[b]
Maximum adduction (+)	1.1 (3.4)	5.0 (2.9)	2.4 (3.2)	5.6 (3.1)	$F_{1,20} = 11.1$, $P = 0.003$[a]	$F_{1,20} = 10.0$, $P = 0.005$[b]
Maximum abduction (−)	−4.9 (3.1)	0.1 (3.1)	−4.2 (3.9)	0.5 (3.9)	$F_{1,20} = 4.2$, $P = 0.054$	$F_{1,20} = 14.5$, $P < 0.001$[b]
Ankle eversion/inversion (°)						
Initial contact	−1.2 (3.6)	2.3 (3.0)	6.4 (2.9)	6.4 (4.2)	$F_{1,20} = 118$, $P < 0.001$[a]	$F_{1,20} = 3.0$, $P = 0.097$
Maximum inversion (+)	2.1 (4.2)	5.2 (3.3)	6.8 (3.0)	6.9 (3.6)	$F_{1,20} = 25.2$, $P < 0.001$[a]	$F_{1,20} = 2.2$, $P = 0.155$
Maximum eversion (−)	−15.0 (4.5)	−12.4 (3.1)	−19.2 (5.1)	−14.3 (3.7)	$F_{1,20} = 36.5$, $P < 0.001$[a]	$F_{1,20} = 8.3$, $P = 0.009$[b]

[a] Significant task main effect $P < 0.05$.
[b] Significant gender main effect $P < 0.05$.

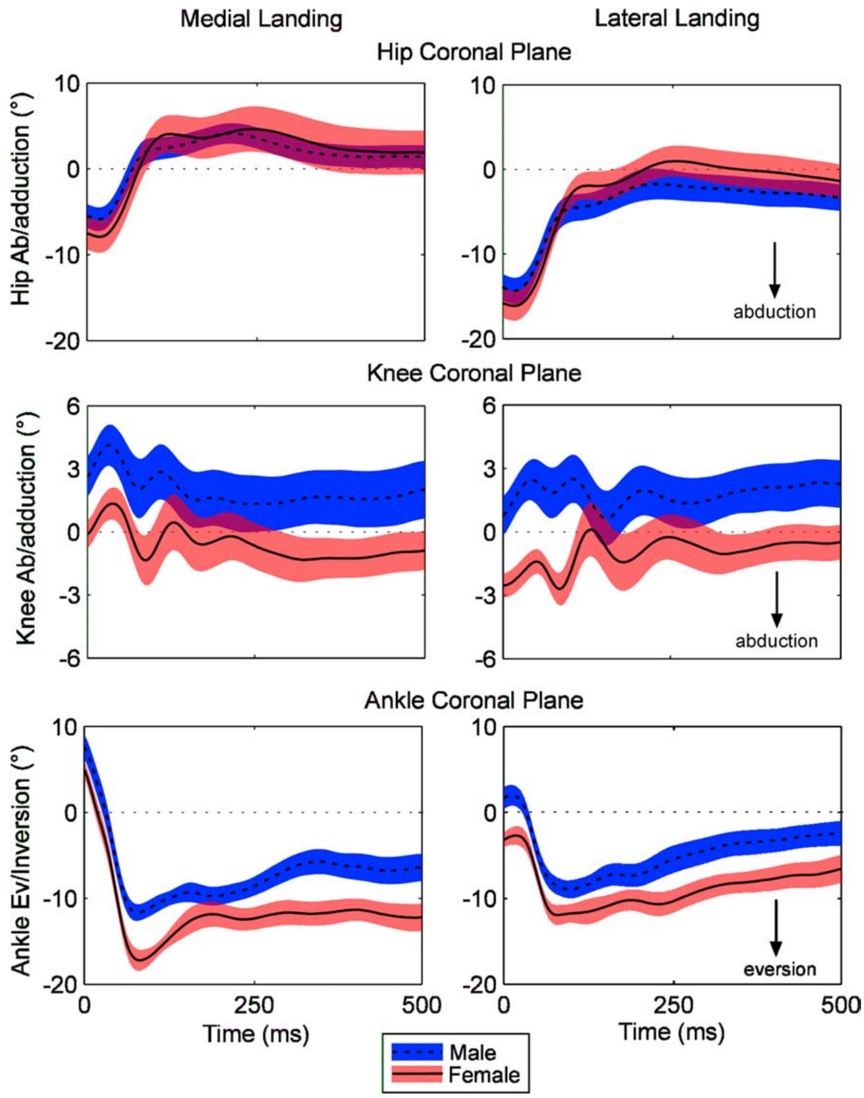

Fig. 2. Ensemble average of hip, knee and ankle coronal plane kinematics during medial and lateral landings in male and female athletes.

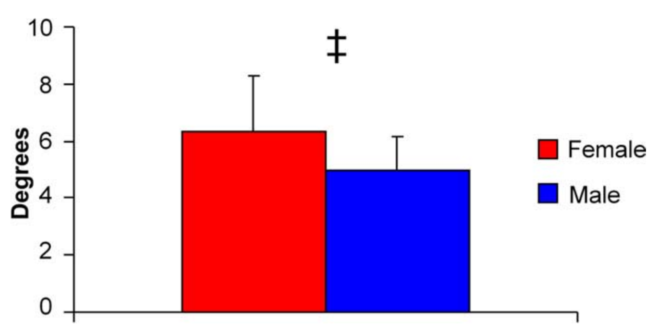

Fig. 3. Knee abduction–adduction excursion collapsed across landing conditions, ‡ Significant gender main effect $P < 0.05$.

to male athletes during both landings (Fig. 2). A main effect of gender was also found for maximum knee abduction angle ($P < 0.001$) and maximum knee adduction angle ($P = 0.005$) during the first 500 ms of each landing.

Fig. 2 displays male and female ensemble averaged hip abduction–adduction angles during medial and lateral landings. Female athletes demonstrated increased coronal plane hip excursion compared to males (female: medial mean 14.9 (SD 5.5°), lateral mean 18.9 (SD 5.4°); male: medial mean 11.5 (SD 2.2°), lateral mean 14.5 (SD 3.4°); gender main effect $F_{1,20} = 6.8$, $P = 0.017$, Fig. 4). There were, however, no gender differences for hip abduction at IC, maximum hip abduction or maximum hip adduction (Table 1). Female athletes showed significant correlations between coronal plane hip and knee initial contact angles during both types of landings (medial $r = -0.682$, $P = 0.021$; lateral $r = -0.749$, $P = 0.008$) while no similar correlations were found in males (medial $r = 0.023$, $P = 0.95$; lateral $r = -0.145$, $P = 0.7$).

Ankle eversion–inversion angles during landing are displayed in Fig. 2. A significant difference between male

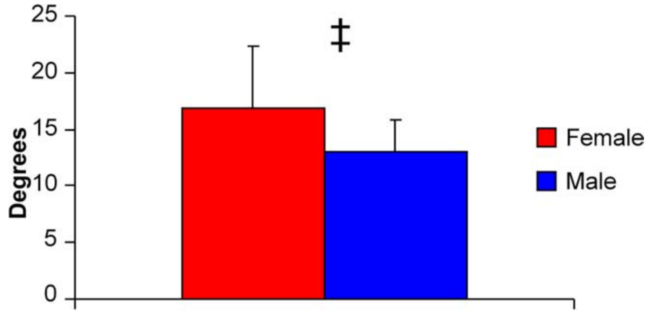

Fig. 4. Hip abduction–adduction excursion collapsed across landing conditions. ‡ Significant gender main effect $P < 0.05$.

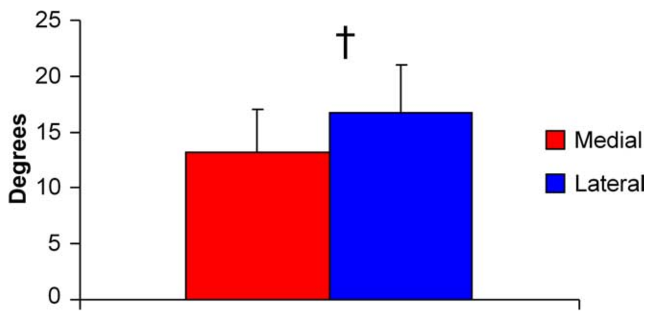

Fig. 5. Hip abduction–adduction excursion collapsed across male and females. † Significant task main effect $P < 0.05$.

and female athletes was found for maximum ankle eversion, with females going into greater eversion compared to males (Table 1). There was no gender difference in the total ankle eversion–inversion excursion (female: medial mean 26.0 (SD 3.7°), lateral mean 17.2 (SD 3.9°); male: medial mean 21.2 (SD 4.0°), lateral mean 17.5 (SD 4.4°); gender main effect $F_{1,20} = 2.6$, $P = 0.121$.

3.2. Comparison of medial versus lateral landing

The lateral landings had greater total hip abduction–adduction excursion (main effect landing, $F_{1,20} = 66.3$, $P < 0.001$; Fig. 5) while no differences were found in total knee abduction excursion (main effect landing, $F_{1,20} = 2.4$, $P = 0.14$). In contrast, the ankle eversion–inversion excursion were significantly larger during the medial landings (main effect landing, $F_{1,20} = 75.6$, $P < 0.001$). Female athletes showed significant correlations between medial and lateral landings in both knee ($r = 0.791$, $P = 0.004$) and hip ($r = 0.809$, $P = 0.003$) abduction–adduction excursion while no similar correlations were found in males (knee: $r = 0.284$, $P = 0.4$; hip: $r = -0.309$, $P = 0.4$).

4. Discussion

The purpose of this study was first, to determine if gender differences in lower extremity joint kinematics would be observed during medial and lateral landings and second, to elucidate which type of landing would result in greater total excursion. Female athletes had greater knee coronal plane excursion measures during landing from both the medial and lateral directions than height and weight matched males. Increased knee abduction angles were also found at initial contact and at the maximum knee abduction angle during landing in females. Gender differences in knee abduction angles have been reported during numerous sports maneuvers. For example, it has previously been observed that female athletes show increased knee abduction (valgus) angles during drop vertical jumps (Ford et al., 2003; Hewett et al., 2004), unanticipated cutting and the athletic ready position (Ford et al., 2005). McLean et al. found similar results during side step cutting in both recreational athletes (McLean et al., 1999) and in collegiate athletes (McLean et al., 2004b).

Females in the current study had greater levels of hip coronal plane excursion during both types of landing compared to males. We did not, however, find gender differences in other hip abduction measures. This is in contrast to gender differences in peak hip abduction previously observed during cutting maneuvers (McLean et al., 2004b). Correlations between hip and knee coronal plane kinematics were observed during athletic maneuvers in female athletes who subsequently ruptured their ACL (Hewett et al., 2005). Specifically, hip adduction moment and knee abduction moment, as well as knee abduction angle and peak vertical ground reaction force were significantly correlated with one another (Hewett et al., 2005). In the current study, female athletes demonstrated significant correlations between hip adduction and knee abduction angle at initial contact during both types of landings. Padua et al. reported that athletes with greater hip adduction and rotation and reduced gluteus medius strength exhibited greater knee abduction (valgus) angles (Padua et al., 2005). Therefore, hip abduction motion and strength appear to be important variables potentially related to increased ACL injury risk in females (Hewett et al., 2005; Padua et al., 2005).

During the medial landings, increased ankle eversion–inversion excursion was found as well as greater maximum eversion in females compared to males. Increased ankle eversion may be a potential factor related to the gender differences in ACL injury rates. Increased valgus stress on the knee and a preloading effect on the ACL may result from excessive eversion or pronation (Nyland et al., 1999; Loudon et al., 1996). This may be due in part to a coupling of foot eversion and internal tibial rotation and anterior tibial translation (Mundermann et al., 2003; Nyland et al., 1999; Bellchamber and van den Bogert, 2000). Loudon et al. reported significantly increased subtalar joint pronation in ACL injured patients compared to controls (Loudon et al., 1996). A potentially injurious valgus position prior to and during landing may be amplified when combined with ankle eversion and tibial rotation.

Identification of an oscillatory varus–valgus (adduction–abduction) pattern has been observed and reported in the literature during cutting maneuvers and landings (McLean et al., 2004b; Ford et al., 2005; Hewett et al., 2005). This rapid coronal plane knee motion (total excursion) may play an important role in mechanisms of an ACL injury, but had not previously been calculated and reported. Female hip, knee and ankle coronal plane excursion were significantly greater than males during medial landings and females demonstrated greater hip and knee excursion during the lateral landings. This tendency in female athletes to exhibit larger excursion in the coronal plane may be directly related to increased risk of ACL injury (McLean et al., 2004b; Ford et al., 2005; Hewett et al., 2005). Neuromuscular training that reduces ACL injury in female athletes, also reduces the maximum coronal plane moments at the knee (Hewett et al., 1996, 1999). While knee abduction measures can predict increased risk of ACL injury in female athletes, the results of the current study combined with previous training data indicate that total coronal knee excursion and moments may also be a critical measure related to the reduction risk of injury through neuromuscular training (Hewett et al., 1996, 1999, 2005). Use of coronal plane excursion may be a valuable tool to assess the effectiveness of training to reduce potential injury risk, and warrants future investigation. Recently, a two-dimensional method of identifying excessive valgus in individual athletes was presented (McLean et al., 2005). These techniques may be incorporated with coronal plane excursion measures and potentially used on a more wide-spread basis.

A secondary purpose of this study was to determine whether the medial landing or lateral landing would induce greater total excursion. We hypothesized that the medial landing would involve greater coronal plane excursion. This hypothesis was not supported at the knee as no differences between movements in abduction–adduction coronal excursion were found between these two types of single leg landings. Although hip and ankle excursion were different between the movements, the lateral landing had greater excursion at the hip while the medial landing had greater excursion at the ankle. Increased excursion at both the hip and ankle is likely to relate to the initial contact position of each joint that would result in possibly more total angular motion. Non-contact ACL injuries occur from both medially and laterally directed movements, but neither has been identified to result in more injuries (Olsen et al., 2004). Further investigations into the effects of these separate maneuvers should be pursued, but it appears that coronal plane excursion at the knee is similar between medial and lateral movements and is greater overall in female athletes than male athletes.

5. Conclusion

Female athletes demonstrate increased lower extremity coronal plane excursion when performing single leg drop landings from both the medial and lateral direction when compared to height and weight matched male athletes. This increased coronal plane oscillation of the lower extremity joints may be related to the increased risk of ACL injury in female basketball and soccer players. An enhanced ability to detect high risk motions demonstrated by athletes during tasks related to the ACL injury mechanisms may identify athletes at increased risk of injury. Identification of high risk athletes may help target those in need of training to reduce their tendency to employ these identified motions and reduce their risk of injury during competition (Hewett et al., 2005; Myer et al., 2005b). In addition, the results of this study suggest that measures of total excursion may be useful for the assessment of the effectiveness of neuromuscular training interventions to reduce kinematic risk factors for ACL injuries.

Acknowledgment

This work was supported by NIH Grant R101-ARO49735-01A1/AR/NIAMS. We would like to acknowledge Antonie J. van den Bogert, Ph.D. and Scott G. McLean Ph.D. for technical assistance and software development.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.clinbiomech.2005.08.010.

References

Agel, J., Arendt, E.A., Bershadsky, B., 2005. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. Am. J. Sports Med. 33, 524–530.

Arendt, E., Dick, R., 1995. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. Am. J. Sports Med. 23, 694–701.

Bellchamber, T.L., van den Bogert, A.J., 2000. Contributions of proximal and distal moments to axial tibial rotation during walking and running. J. Biomech. 33, 1397–1403.

Boden, B.P., Dean, G.S., Feagin, J.A., Garrett, W.E., 2000. Mechanisms of anterior cruciate ligament injury. Orthopaedics 23, 573–578.

Ford, K.R., Myer, G.D., Hewett, T.E., 2003. Valgus knee motion during landing in high school female and male basketball players. Med. Sci. Sports Exerc. 35, 1745–1750.

Ford, K.R., Myer, G.D., Toms, H.E., Hewett, T.E., 2005. Gender differences in the kinematics of unanticipated cutting in young athletes. Med. Sci. Sports Exerc. 37, 124–129.

Griffin, L.Y., Agel, J., Albohm, M.J., Arendt, E.A., Dick, R.W., Garrett, W.E., Garrick, J.G., Hewett, T.E., Huston, L., Ireland, M.L., Johnson, R.J., Kibler, W.B., Lephart, S., Lewis, J.L., Lindenfeld, T.N., Mandelbaum, B.R., Marchak, P., Teitz, C.C., Wojtys, E.M., 2000. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. J. Am. Acad. Orthop. Surg. 8, 141–150.

Hewett, T.E., Lindenfeld, T.N., Riccobene, J.V., Noyes, F.R., 1999. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am. J. Sports Med. 27, 699–706.

Hewett, T.E., Myer, G.D., Ford, K.R., 2004. Decrease in neuromuscular control about the knee with maturation in female athletes. J. Bone Joint Surg. Am. 86-A, 1601–1608.

Hewett, T.E., Myer, G.D., Ford, K.R., Heidt Jr., R.S., Colosimo, A.J., McLean, S.G., van den Bogert, A.J., Paterno, M.V., Succop, P., 2005. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes. Am. J. Sports Med. 33, 492–501.

Hewett, T.E., Stroupe, A.L., Nance, T.A., Noyes, F.R., 1996. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am. J. Sports Med. 24, 765–773.

Loudon, J.K., Jenkins, W., Loudon, K.L., 1996. The relationship between static posture and ACL injury in female athletes. J. Orthop. Sports Phys. Ther. 24, 91–97.

Lu, T.W., O'Connor, J.J., 1999. Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. J. Biomech. 32, 129–134.

Malinzak, R.A., Colby, S.M., Kirkendall, D.T., Yu, B., Garrett, W.E., 2001. A comparison of knee joint motion patterns between men and women in selected athletic tasks. Clin. Biomech. 16, 438–445.

Malone, T.R., Hardaker, W.T., Garrett, W.E., Feagin, J.A., Bassett, F.H., 1993. Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. J. Southern Orthop. Assoc. 2, 36–39.

McLean, S.G., Huang, X., Su, A., van den Bogert, A.J., 2004a. Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. Clin. Biomech. 19, 828–838.

McLean, S.G., Lipfert, S.W., van den Bogert, A.J., 2004b. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. Med. Sci. Sports Exerc. 36, 1008–1016.

McLean, S.G., Neal, R.J., Myers, P.T., Walters, M.R., 1999. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. Med. Sci. Sports Exerc. 31, 959–968.

McLean, S.G., Su, A., van den Bogert, A.J., 2003. Development and validation of a 3-D model to predict knee joint loading during dynamic movement. J. Biol. Chem. 125, 864–874.

McLean, S.G., Walker, K., Ford, K.R., Myer, G.D., Hewett, T.E., van den Bogert, A.J., 2005. Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. Br. J. Sports Med. 39, 355–362.

McNair, P.J., Marshall, R.N., Matheson, J.A., 1990. Important features associated with acute anterior cruciate ligament injury. N. Z. Med. J. 103, 537–539.

Mundermann, A., Nigg, B.M., Humble, R.N., Stefanyshyn, D.J., 2003. Foot orthotics affect lower extremity kinematics and kinetics during running. Clin. Biomech. 18, 254–262.

Myer, G.D., Ford, K.R., Hewett, T.E., 2002. A comparison of medial knee motion in basketball players when performing a basketball rebound. Med. Sci. Sports Exerc. 34, S5.

Myer, G.D., Ford, K.R., Hewett, T.E., 2004. Rationale and clinical techniques for anterior cruciate ligament injury prevention in female athletes. J. Athl. Train. 39, 352–364.

Myer, G.D., Ford, K.R., Hewett, T.E., 2005a. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. J. Electromyogr. Kinesiol. 15, 181–189.

Myer, G.D., Ford, K.R., Palumbo, J.P., Hewett, T.E., 2005b. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. J. Strength Cond. Res. 19, 51–60.

Myer, G.D., Hewett, T.E., Noyes, F.R., 2000. The use of video analysis to identify athletes with increased valgus knee excursion: effects of gender and training. Med. Sci. Sports Exerc. 32, S298.

NCAA, 2002. National Collegiate Athletic Association, Indianapolis.

Nyland, J., Caborn, D.N., Shapiro, R., Johnson, D.L., Fang, H., 1999. Hamstring extensibility and transverse plane knee control relationship in athletic women. Knee Surg. Sports Traumatol. Arthrosc. 7, 257–261.

Olsen, O.E., Myklebust, G., Engebretsen, L., Bahr, R., 2004. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am. J. Sports Med. 32, 1002–1012.

Padua, D.A., Marshall, S.W., Beutler, A.I., DeMaio, M., Boden, B.P., Yu, B., Garrett, W.E., 2005. Predictors of knee valgus angle during a jump-landing task. Med. Sci. Sports Exerc. 37, S398.

Woltring, H.J., Huiskes, R., de Lange, A., Veldpaus, F.E., 1985. Finite centroid and helical axis estimation from noisy landmark measurements in the study of human joint kinematics. J. Biomech. 18, 379–389.