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Gender differences in lower extremity kinematics, kinetics and energy absorption during landing

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Abstract

Objective. To determine whether gender differences exist in lower extremity joint motions and energy absorption landing strategies between age and skill matched recreational athletes.

Design. Mixed factor, repeated measures design.

Background. Compared to males, females execute high demand activities in a more erect posture potentially predisposing the anterior cruciate ligament to greater loads and injury. The preferred energy absorption strategy may provide insight for this performance difference.

Methods. Inverse dynamic solutions estimated lower extremity joint kinematics, kinetics and energetic profiles for twelve males and nine females performing a 60 cm drop landing.

Results. Females demonstrated a more erect landing posture and utilized greater hip and ankle joint range of motions and maximum joint angular velocities compared to males. Females also exhibited greater energy absorption and peak powers from the knee extensors and ankle plantar-flexors compared to the males. Examinations of the energy absorption contributions revealed that the knee was the primary shock absorber for both genders, whereas the ankle plantar-flexors muscles was the second largest contributor to energy absorption for the females and the hip extensors muscles for the males.

Conclusions. Females may choose to land in a more erect posture to maximize the energy absorption from the joints most proximal to ground contact.

Relevance

Females may be at a greater risk to anterior cruciate ligament injury during landing due to their energy absorption strategy.

Keywords: ACL; Knee; Injury; Gender; Kinetics; Biomechanics

1. Introduction

Numerous studies have found females to possess a higher rate of non-contact anterior cruciate ligament (ACL) injury compared to males during athletic competition (Arendt and Dick, 1995; Ferretti et al., 1992). An emerging theory for this gender disparity proposes that females perform high demand athletic maneuvers differently than males and in a manner that predisposes them to higher knee joint stress (Colby et al., 2000; Cowling and Steele, 2001; Huston et al., 2001; Kirkendall and Garrett, 2000; Wojtys et al., 2002). Kirkendall and Garrett (2000) reported ACL injuries occurring in basketball and soccer were most often (64 of 72 injuries, 88%) non-contact in nature and a result of a deceleration type of movement (landing from a jump was reported in 30 of the 72 injuries, 41%). Similarly, others have reported that landing from a jump is one of the primary non-contact mechanisms for ACL injury in female basketball and volleyball players (Ferretti et al., 1992; Kirkendall and Garrett, 2000; Gerberich et al., 1987; Gray et al., 1985; Noyes et al., 1983). In light of these observations, controlled laboratory experiments have investigated the performance of females during

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cutting and landing tasks (Colby et al., 2000; Cowling and Steele, 2001; Huston et al., 2001; Malinzak et al., 2001; McLean et al., 1999). Consensus of these reports indicate that the female knee is in a more extended position at ground contact, and thus predispose the ACL to greater loads; and that the neuromuscular function, particularly of the hamstring musculature, is inadequate in females compared to males (Colby et al., 2000; Rozzi et al., 1999).

Although it is generally accepted that external and internal forces can be mediated by manipulating the lower extremity joint kinematics during landing, no consensus has been reached regarding gender differences in the primary energy absorption strategy. However, the alteration of joint positions and angular velocities at ground contact and throughout the landing motion can influence the magnitudes and temporal relationships of the peak joint moment and power profiles and thus, mediate stresses placed on internal knee structures (Zhang et al., 2000). Landing performance differences between male and female athletes, therefore, require investigations beyond the kinematic level of analysis to understand the underlying neuromuscular performance criteria by which genders select an energy absorption strategy during landing.

Currently, few studies have included both genders during landing (Huston et al., 2001; McNitt-Gray et al., 1994), and none have investigated gender differences during landing at the level of kinetic and energetic detail. Gender differences in the muscular landing strategy may explain the disparity in ACL injury rates if one gender's landing strategy requires a geometry that is more likely to result in ACL injury. The purpose of this study was to determine whether gender differences exist in the kinematic (hip, knee and ankle joint angles and joint angular velocities), kinetic (hip, knee and ankle joint moments) and energetic (hip, knee and ankle joint powers and work) profiles during landing from a drop-jump.

2. Methods

Twelve male (age, 28.3 (SD, 3.9 years); height, 1.8 (SD, 0.06 m); mass, 81.8 (SD, 9.1 kg)) and 9 female (age, 26.4 (SD, 4.5 years); height, 1.7 (SD, 0.06 m); mass, 60.1 (SD, 5.6 kg)) recreational athletes participated in this study. All athletes were currently involved in competitive intramural court sports consisting of volleyball and basketball, sponsored by the local public recreation district. Each subject had participated in these sports at least three times per week and had been active in the sport in a competitive capacity for at least five years prior. All subjects reported no history of orthopaedic injury to the lower extremity joints.

Upon signing the written informed consent that was approved by local ethics committee for human subject participation in medical research, the participants were fitted for a standardized court shoe and asked to warm-up on a treadmill for 5 min. After the subjects practiced the landing task and felt comfortable with the performance requirements, eight vertical drop-landings were collected. In a pilot study, 5–7 practice trials followed by the 8 trials during data collection were determined to sufficiently capture the true landing performance without fatigue or systematic performance variability. The landing task consisted of stepping off a 60 cm box onto a landing platform. The subjects were instructed to fold their arms across their chest and step off the box, without jumping up, or stepping down and to land as naturally as possible with both feet on the landing platform. One foot landed upon a force plate (Bertec, Corp., Columbus, Ohio, USA), and the other landed next to the force plate on the landing platform.

The force plate sampled the ground reaction forces at 1200 Hz. A positive vertical ground reaction force (GRF) indicates a force acting upward on the body, while a positive horizontal GRF represents a force acting to accelerate the body forward. The point of application of the GRFs on the body was calculated as the center of pressure (Winter, 1990).

Three-dimensional (3D) coordinates of a 13 marker set that defined a four-segment rigid link model of the lower limb were captured (120 Hz) with a five camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA, USA) (Kadaba et al., 1989; Kadaba et al., 1990). Based on a frequency content analysis of the digitized coordinate data, marker trajectories were filtered at 10 Hz using a fourth order Butterworth filter (Bobbert et al., 1987). Joint angular position and velocities were calculated from the filtered 3D marker coordinate data. By convention and as measured in the sagittal plane, zero degrees at the hip, knee and ankle corresponds to an erect, standing posture with the trunk, thigh and lower leg in a straight line and the foot segment at a right angle to the leg.

Internal joint moment values for each joint were calculated by combining the kinematic and force plate data with anthropometric data in an inverse dynamics solution. By convention, hip and knee extensor and ankle plantar-flexor moments were assigned to be positive. Hip, knee and ankle muscle powers were calculated as the product of the instantaneous joint moment and joint angular velocity data sets of each trial. Mechanical joint work is defined as the amount of muscular power conducted over a time period. Thus, the muscle power curves were mathematically integrated to calculate negative and positive joint work values for the impact phase defined as the first 100 ms after initial ground contact (Schot et al., 1994). Positive and negative work values indicate energy production and absorption through concentric and eccentric muscular contractions, respectively (Winter, 1990). All joint torque parameters were scaled to percent body weight and height (%BW * ht) and all joint power parameters were scaled to %BW * ht/s to reduce within and between group anthropometric differences and to aid in detecting significant differences between groups by reducing within subject and intersubject performance variability (Pierrynowski and Galea, 2001). The data were interpolated to 100 points during the impact phase for graphical purposes only.

A 2×3 (group × joint) mixed factor ANOVA was computed from the 8 trial means for contact position, range of motion (RoM) and peak joint angular velocity for the landing phase delineated from initial ground contact to maximum knee flexion. In addition, the maximum extensor joint moments, minimum joint powers and negative joint work occurring during the impact phase were chosen for analysis. Two distinct peaks were analyzed from the knee extensor moment and negative knee power curves (Zhang et al., 2000; McNitt-Gray, 1993), and one peak from each of the hip and ankle extensor moment and negative power curves (Zhang et al., 2000; McNitt-Gray, 1993). Tukey post hoc analyses were used to determine specific differences when appropriate (alpha = 0.05). An un-paired t-test was used to contrast between group landing phase times and the magnitude, time and loading rates of the peak, vertical ground reaction forces (VGRF).

3. Results

Landing style and kinematics. All subjects performed forefoot rear-foot landings and group mean landing phase times were not different between groups (male group, 0.191 (SD, 0.046 s); female group, 0.209 (SD, 0.034 s); $P > 0.05$). In addition, both groups demonstrated similar maximum knee flexion angles (males, −93.0 (SD, 10.8°); females −98.4 (SD, 10.6°)) ($P > 0.05$). Group means and standard deviations for the impact phase kinematics are located in Table 1 and graphically presented in Fig. 1. The female group demonstrated greater knee extension and ankle plantar-flexion angles at initial ground contact compared to the male group (both $P < 0.05$). Although the female group used greater knee and ankle ROM compared to the male group ($P < 0.05$), all lower extremity joints of the female group revealed greater peak angular velocities ($P < 0.05$).

Ground reaction forces. Group means and standard deviations for the VGRF parameters are located in Table 2 and graphically represented in Fig. 2. No differences ($P > 0.05$) were found between groups for any of the VGRF variables selected for analysis.

Kinetics. Group means and standard deviations for the impact phase kinetics are located in Table 3 and graphically presented in Fig. 3. Within group comparisons revealed the peak hip extensor moment was significantly larger than the peak ankle plantar-flexor moment for the female group (all $P < 0.05$). However, the peak hip extensor moment was greater than both peak knee extensor and the peak ankle plantar-flexor moments for the male group (all $P < 0.05$). No peak moment differences were found between groups at each joint (all $P > 0.05$). However, there were significant differences between genders regarding the temporal occurrence of peak knee extensor moment ($P = 0.004$). For females, the time to the peak knee extensor moment occurred 0.063 (SD, 0.023) seconds after ground contact which corresponded in time with the F2 peak of the VGRF. Conversely, the peak knee extensor moment for the males occurred 0.038 (SD, 0.013) seconds after ground contact which corresponded in time with the F1 peak of the VGRF.

Table 1
Means (SD) of kinematic variables during the landing phase

	Males	Females
Contact position (deg)		
Hip	−30.8	−24.0
	(7.8)	(10.6)
Knee	−30.0	−22.8*
	(7.7)	(8.0)
Ankle	−11.3	−21.3*
	(5.1)	(9.6)
Range of motion (deg)		
Hip	50.4	57.9
	(13.0)	(13.8)
Knee	63.4	75.8*
	(9.3)	(9.1)
Ankle	41.6	58.0*
	(6.9)	(7.9)
Peak angular velocity (deg/s)		
Hip	−443.6	−579.4*
	(75.1)	(78.2)
Knee	−601.7	−725.8*
	(51.9)	(103.3)
Ankle	−573.0	−1044.1*
	(154.3)	(230.6)

*$P < 0.05$; deg = degrees; deg/s = degrees per second.

Energetics. Group means and standard deviations for peak joint powers and relative joint contributions to energy absorption are located in Table 3 and graphically represented in Fig. 4. Within group comparisons revealed the peak, negative hip power was larger than the peak, negative ankle and knee powers for the male group (all $P < 0.05$). The female group, however, demonstrated no statistical differences between the peak negative powers of the lower extremity (all $P > 0.05$). Compared to the female group, the male group exhibited smaller values for the second peak, negative knee power and peak, negative ankle power (both $P < 0.05$).

Within group comparisons of negative joint work for the female group demonstrated greater energy absorption from the knee and ankle compared to the hip ($P < 0.05$); whereas the male group demonstrated

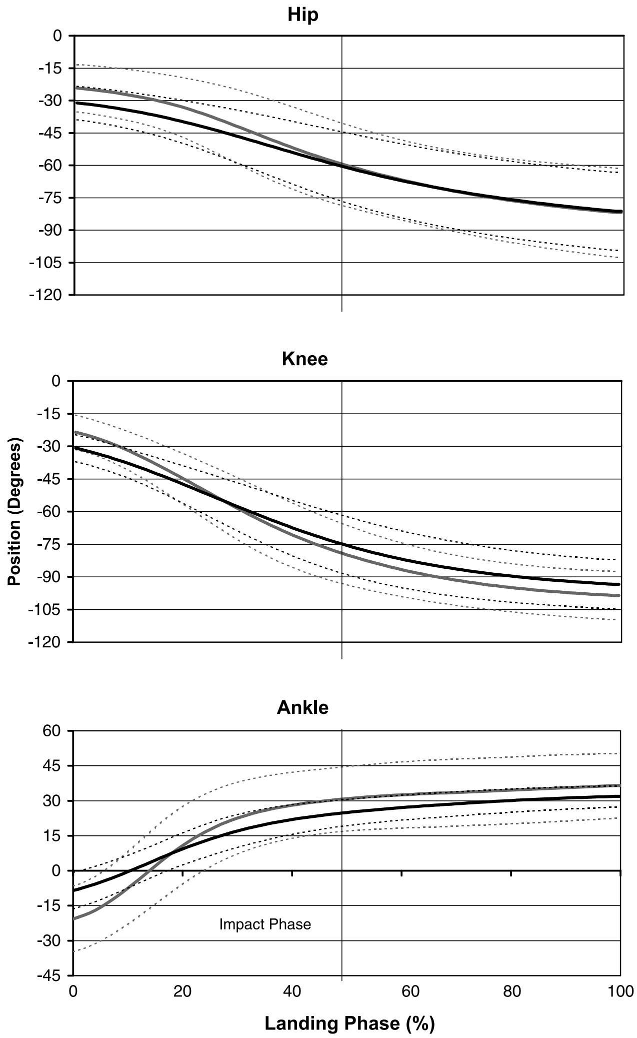

Fig. 1. Group mean hip, knee and ankle position curves and standard deviations from females (gray lines) and males (black lines) normalized to 100% of the landing phase. Negative values indicate hip and knee flexion and ankle plantar-flexion. Vertical line represents the ending of the impact phase defined as the first 100 ms of the landing phase.

Table 2
Means (SD) of magnitude, time and loading rate for the first (F1) and second (F2) peak vertical ground reaction forces

	Males	Females
Magnitude (BW)		
F1	1.51	1.58
	(0.41)	(0.33)
F2	3.67	3.39
	(0.92)	(0.89)
Time (ms)		
F1	10.35	11.34
	(3.49)	(3.60)
F2	40.00	44.38
	(10.27)	(13.78)
Loading rate (BW/s)		
F1	162.11	156.63
	(60.84)	(75.66)
F2	102.09	96.18
	(48.08)	(79.26)

$^{*}P < 0.05$; BW = body weight; ms = milliseconds.

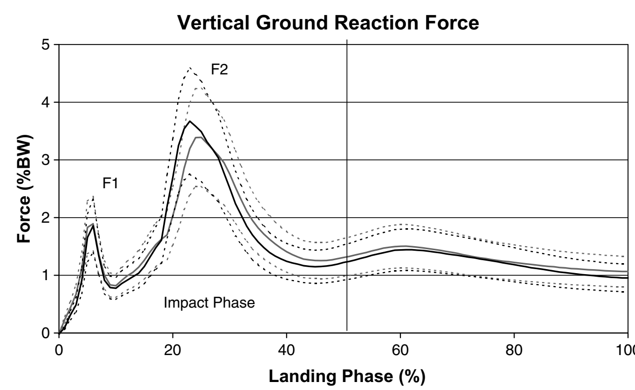

Fig. 2. Group mean vertical ground reaction force curves and standard deviations from females (gray lines) and males (black lines). Bi-modal force peaks from forefoot (F1) and rear-foot (F2) impacts with the ground during landing were evident from all subjects. Vertical line represents the ending of the impact phase defined as the first 100 ms of the landing phase.

no energy absorption differences between the lower extremity joints (all $P > 0.05$). The female group revealed greater total energy absorption during the impact phase compared to the males (males, −16.2 (SD, 1.6 %BW * ht); females, −18.3 (SD, 2.1 %BW * ht)); $P < 0.05$). Both groups utilized the knee as the primary joint to absorb energy, however, the female group performed 34% less negative hip work ($P < 0.05$); and 30% and 52% more negative knee and ankle work (both $P < 0.05$) compared to the male group.

4. Discussion

During landing, the lower extremity joints function to reduce and control the downward momentum acquired during the flight phase through joint flexion. A maximum knee flexion angle greater than and less than 90° has traditionally defined the landing technique as soft or stiff, respectively (Devita and Skelly, 1992). According to this criterion, both groups in the present study demonstrated the soft landing technique with the lower extremities in slight flexion at initial ground contact followed by large joint RoM. Within this landing technique, however, distinct kinematic performance differences were exhibited between genders. At initial ground contact the females were in a more erect position compared to the males similar to the results of other authors (Huston et al., 2001). Despite the initial kinematic landing differences, males and females demonstrated similar landing phase times. Thus, while the female

Table 3
Means (SD) for peak lower extremity joint moments and powers during the impact phase

	Males	Females
*Peak internal joint moments (%BW * ht)*		
Hip extensor	38.87	25.42
	(13.41)	(19.36)
First knee extensor	17.69	14.59
	(4.57)	(2.01)
Second knee extensor	13.24	15.31
	(3.42)	(3.30)
Ankle plantar-flexor	11.31	10.71
	(3.08)	(2.39)
*Peak internal joint powers (%BW * ht/s)*		
Negative hip power	−252.25	−200.48
	(80.78)	(166.17)
First negative knee power	−144.42	−133.86
	(44.15)	(16.05)
Second negative knee power	−135.35	−183.15*
	(39.43)	(58.02)
Negative ankle power	−94.15	−151.43*
	(29.47)	(23.26)
*Negative joint work (%BW * ht)*		
Hip work	−4.86	−3.20*
	(1.45)	(1.92)
Knee work	−6.59	−8.58*
	(2.07)	(2.15)
Ankle work	−4.74	−6.42*
	(1.40)	(1.71)

$*P < 0.05$; %BW * ht = product of percent body weight and height.

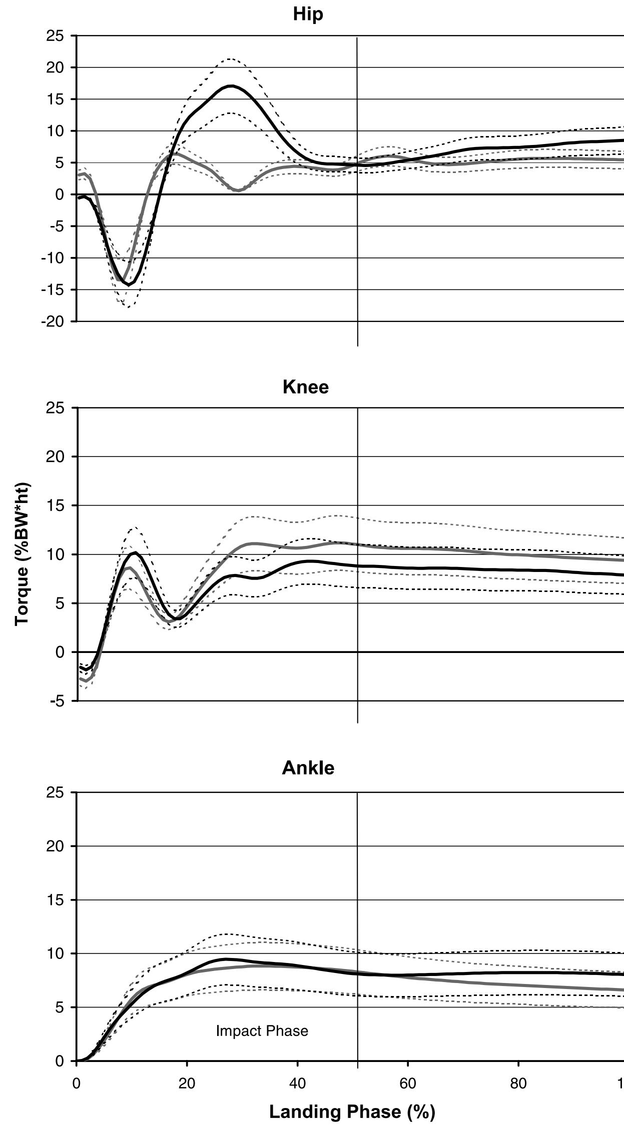

Fig. 3. Group mean hip, knee and ankle internal joint moment curves and standard deviations from females (gray lines) and males (black lines) normalized to 100% of the landing phase. Positive values indicate net hip and knee extensor and ankle plantar flexor moments and negative values indicate net hip and knee flexor moments. Vertical line represents the ending of the impact phase defined as the first 100 ms of the landing phase.

group landed more erect at ground contact, they subsequently exhibited greater knee and ankle RoM and angular velocities throughout the landing phase suggesting females may attempt to dissipate the large external forces over a wider range of joint motion.

The magnitude and timing of the bi-modal VGRF force peaks for both genders are similar to the results of other studies (Zhang et al., 2000; Schot et al., 1994; Dufek and Zhang, 1996; Liebermann and Goodman, 1991). Although the female group demonstrated a more erect position at contact compared to the male group, no differences in the magnitude or timing of the bi-modal peak VGRF were observed. These findings were surprising and in contrast to previous researchers that have found progressively greater peak VGRF with straighter knee positions at ground contact (Nigg, 1985; Stacoff et al., 1988). However, Self and Paine (2001) studied landings with four different ankle strategies and found the strategy with the largest ankle plantar-flexion position at ground contact demonstrated the most shock absorption and reduction of the peak VGRF. Thus preplanned muscular landing strategies and the position of the lower extremity joints at ground contact may collectively influence the magnitude of the peak VGRF (review by Schot and Dufek (1993)). Compared to the male group, therefore, the female group may have compensated for a more erect landing posture at ground contact by employing a muscular strategy by the ankle plantar-flexor muscles resulting in similar peak VGRF values. Further, these results are interpreted to indicate that the general external loading conditions between the male and female groups were equal.

Although no gender differences were noted for the peak hip and knee extensor and ankle plantar-flexor joint moments, the females delayed the time to the occurrence of the peak, knee extensor joint moment. The

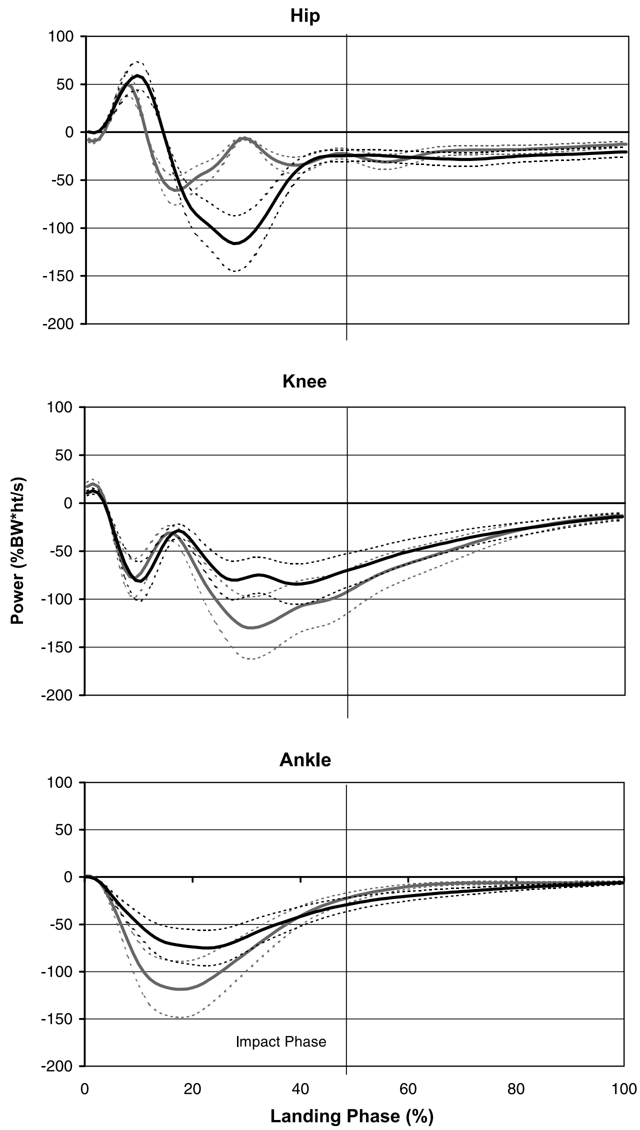

Fig. 4. Group mean hip, knee and ankle internal joint power curves and standard deviations from females (gray lines) and males (black lines) normalized to 100% of the landing phase. Positive values indicate energy production through concentric muscular contractions and negative values indicate energy absorption through eccentric muscular contractions. Vertical line represents the ending of the impact phase defined as the first 100 ms of the landing phase.

fact that both groups had similar peak joint moments was most likely due to the performance of soft landings with similar ground reaction forces. However, the timing delay to the peak knee extensor joint moment suggests the presence of a muscular strategy that was aimed at reducing the muscular tension of the knee extensor musculature during the early phase of landing (<50 ms). This muscular strategy also promotes greater knee flexion and ankle plantar-flexion angular velocities that in turn requires significantly larger peak muscular powers from the knee extensor and ankle plantar-flexor muscles to decelerate the body and bring the joints to rest. The subsequent effect of this landing technique on ACL force is unknown from the data presented in the current study. It is reasonable to suggest that although the female group landed with greater knee extension at ground contact, increasing the speed and RoM of knee flexion and ankle plantar-flexion may delay the time and increase the knee flexion position of the occurrence of the peak knee extensor power and therefore provide an ACL loading environment similar to their male counterparts.

Investigation of the preferred energy absorption strategy during landing may provide an understanding for the commonly observed gender differences in knee contact position. Previous studies that have calculated lower extremity, energy absorption contributions during either soft or natural landing styles from a height near 60 cm are located in Table 4 (Zhang et al., 2000; McNitt-Gray, 1993; Devita and Skelly, 1992; Schot et al., 1991). The pooled shock absorption contributions for the males reveals the ankle plantar-flexor and knee and hip extensor muscle groups to contribute 22%, 41% and 38% to the total energy absorption (Zhang et al., 2000; McNitt-Gray, 1993), whereas the females used 40%, 41% and 19% (Devita and Skelly, 1992; Schot et al., 1991). From these pooled results, and similar to the results of the current study, the knee was the primary shock absorber for both genders, whereas the ankle plantar-flexors muscles was the second largest contributor to energy absorption for the females and the hip extensors muscles for the males. Collectively, these data may indicate that females prefer to land in a more erect position than their male counterparts due to their selection of the muscular landing strategy that emphasizes energy absorption from the ankle plantar-flexor muscles.

It is plausible to assume that this gender-specific landing strategy may place female athletes at a greater risk of ACL injury. Despite the performance of a soft landing, the females preferred to utilize the ankle musculature for impact attenuation more than the males but required them to be in a contact position with greater knee extension and ankle plantar-flexion. A more erect landing strategy may become potentially harmful during the presence of muscular fatigue or during an unbalanced landing performance. In either case a more erect landing strategy with a decrement in shock absorption may provide a mechanical disadvantage to the hamstring muscles and allow the quadriceps muscles to pull the tibia anterior resulting in larger values of ACL force (Pandy and Shelburne, 1997). Conversely, it was clear that the male group did not use the full capacity of the ankle plantar-flexors, and demonstrated greater knee flexion and less ankle plantar-flexion at ground contact. This lower extremity configuration at ground contact may indicate that the knee is more prepared to transfer energy up the kinetic chain to the larger and more proximal muscles such as the hip extensors (Self and

Table 4
Literature review of gender-specific lower extremity shock absorption contributions during soft or normal landings from a height near 60 cm

Authors	Subjects	Landing height (cm)	Landing style	Ankle %	Knee %	Hip %
Female landers						
Schot et al. (25)[a]	5 female, 4 male intercollegiate athletes	60	Natural	43	45	12
Devita et al. (5)	8 female intercollegiate athletes	59	Soft	37	37	25
Current Study	9 female recreational athletes	60	Natural	35	47	18
Male landers						
McNitt-Gray et al. (17)	6 male recreational athletes	72	Natural	30	33	37
Zhang et al. (30)	9 male recreational athletes	62	Soft	14	44	42
Zhang et al. (30)	9 male recreational athletes	62	Natural	21	46	34
Current Study	12 male recreational athletes	60	Natural	29	41	30

[a] Predominantly female subject population.

Paine, 2001). Although the final knee position is generally emphasized during ACL injury prevention programs for landing (Hewett et al., 1999), instructing athletes to achieve greater knee flexion positions at initial ground contact may be an important addition for training the soft landing technique.

5. Summary

This study provides an increased understanding for the commonly observed gender difference in knee contact position noted throughout the literature. It was noted that the preferred shock absorption strategy for the females required the ankle and knee to be in a more extended position to fully utilize the capacity of the ankle plantar-flexor muscles. Under certain landing conditions, this shock absorption strategy was proposed to provide a greater potential risk for non-contact ACL injury for females compared to males and increased knee flexion at initial ground contact was advocated to be a part of future ACL injury prevention programs. This study highlights the need to investigate lower extremity positions and muscular strategies when determining whether performance is a primary factor in the gender disparity of non-contact ACL injury rates.

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