Sex differences in lower extremity biomechanics during single leg landings

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Abstract:

Background. Females have an increased incident rate of anterior cruciate ligament tears compared to males. Biomechanical strategies to decelerate the body in the vertical direction have been implicated as a contributing cause. This study determined if females would exhibit single leg landing strategies characterized by decreased amounts of hip, knee, and ankle flexion resulting in greater vertical ground reaction forces and altered energy absorption patterns when compared to males.

Methods. Recreationally active males (N = 14) and females (N = 14), completed five single leg landings from a 0.3 m height onto a force platform while three-dimensional kinematics and kinetics were simultaneously collected.
Findings. Compared to males, females exhibited (1) less total hip and knee flexion displacements (40% and 64% of males, respectively, $P < 0.05$) and less time to peak hip and knee flexion (48% and 78% of males, respectively, $P < 0.05$), (2) 9% greater peak vertical ground reaction forces ($P < 0.05$), (3) less total lower body energy absorption (76% of males, $P < 0.05$), and (4) 11% greater relative energy absorption at the ankle ($P < 0.05$).

Interpretation. Females in this study appear to adopt a single leg landing style using less hip and knee flexion, absorbing less total lower body energy with more relative energy at the ankle resulting in a landing style that can be described as stiff. This may potentially cause increased demands on non-contractile components of the lower extremity. Preventative training programs designed to prevent knee injury may benefit from the biomechanical description of sex-specific landing methods demonstrated by females in this study by focusing on the promotion of more reliance on using the contractile components to absorb impact energy during landings.

1. INTRODUCTION

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It is well known that females are at a greater risk than males to rupture the anterior cruciate ligament (ACL) (Arendt et al., 1999; Arendt and Dick, 1995). Based upon a scientific review by leading experts in the area, it has been suggested that neuromuscular and biomechanical factors are crucial to help explain the injury rate differential (Griffin et al., 2000). Current theory suggests that females perform athletic tasks in a manner that exposes the knee joint to greater amounts of ligamentous strain (Chappell et al., 2002; Colby et al., 2000; Malinzak et al., 2001; Hewett et al., 2005).

Landing from a jump has often been implicated in the description of ACL injury mechanisms (Kirkendall and Garrett, 2000; Chappell et al., 2002) as well as other lower extremity injuries (Dufek and Bates, 1991; Chappell et al., 2002). As such, current research has investigated sex-specific kinematic patterns during maneuvers commonly associated with ACL injury. Most often cutting and landing from a jump have been used as injury models. General consensus of this research reveals that females typically land or move with a more upright or erect posture typically characterized by decreased amounts of knee flexion (Lephart et al., 2002; Chappell et al., 2002; Cowling and Steele, 2001; McLean et al., 1999; Huston et al., 2001). This observation of decreased knee flexion may affect how the lower extremity joints function and interact together to safely reduce or redirect the body's momentum.

The internal and external forces on the joints of the lower extremity can be modulated by changing the kinematic patterns (i.e. more or less joint flexion) of lower extremity joint function (Zhang et al., 2000; Devita and Skelly, 1992). There is limited evidence of how sex-specific kinematic patterns interact with and influence energy absorption of the hip, knee, and ankle during landings. Energy absorption during landing can be described as work done on the extensor muscles (McNitt-Gray, 1993). Of the one report we found comparing males and females on kinematic and energetic patterns, females demonstrated a more erect landing posture and greater energy absorption from the knee extensors and ankle plantar flexors during a 60 cm double leg drop landing (Decker et al., 2003). It was hypothesized that this female energy absorption strategy is related to the greater risk of ACL injury risk in females, as it may be associated with a more upright landing style often associated with ACL injury (Decker et al., 2003) or a more "ligament dominant" style in which there is a lack of muscular control of landing (Hewett et al., 2002). In turn, this may impair the ability of the large hip and/or knee extensor musculature to absorb the energy of landing thus impacting the integrity of the lower extremity (Zhang et al., 2000).

Landing on a single leg is a common activity in sports that requires sudden stops and changes in direction. While previous work of double leg landings suggest that sex-specific joint energetics may help explain the ACL injury bias (Decker et al., 2003), it is important to determine if similar sex differences occur during a single leg landing. Therefore the purpose of this study was to determine sex differences in hip, knee, and ankle kinematics; hip, knee, and ankle energetics, and vertical ground reaction forces during a single leg landing task. We hypothesized that when compared to males, females would (1) make ground contact with the hip and knee in a more extended position, (2) use less flexion displacements during the landing process, (3) use less joint energy absorption during landing, and (4) have greater peak vertical ground reaction forces.

2. METHODS

2.1. ***Subjects***

Twenty-eight recreationally active, healthy college students [Means(Standard Deviations)] (14 males, age = 23.9(6.3) yr, mass = 79.0(16.2) kg, ht = 181.5(9.6) cm) (14 females, age = 22.5(3.8) yr, mass = 53.5(5.6) kg, ht = 164.5(7.6) cm) volunteered to participate in this study. Recreationally active was defined as participation in some form of physical exercise for 30 min a day at least 3 times per week. Healthy was defined as having no previous orthopedic injury or neurological disorder of the lower extremity that impaired performance during recreational activity. These data were obtained through a medical history and activity questionnaire. Prior to participation, informed written consent was obtained from each subject according to the university institutional review board policy.

2.2. ***Instrumentation***

Kinematic data for the foot, shank, thigh, and pelvis were collected at 140 Hz using the Motion Monitor (Innovative Sports Training, Chicago, IL, USA) electromagnetic tracking system. Six-degree of freedom position sensors (Ascension Technologies, Burlington, VT, USA) were attached to each subject's dominant limb, identified as the preferred limb used to kick a ball, with double-sided tape and elastic wrap over the anterior mid-shaft of the third metatarsal, the mid-shaft of the medial tibia, and the lateral aspect of the mid-shaft of the femur. Two additional sensors were also placed on the sacrum, and over the C7 spinous process. Vertical ground reaction force data were obtained with a Bertec Force Plate, Type 4060-nonconducting (Bertec Corporation, Columbus, OH, USA) at 1000 Hz.

2.3. ***Design***

Subjects attended one 45 min testing session. During the session, subjects completed five single leg drop landings. Practice repetitions were performed until the subject appeared and reported to be comfortable with the task (typically 3–6 repetitions) to reduce the potential for learning effects. Subjects completed all landings barefoot.

2.3.1. **Landing protocol**

Subjects landed bare footed from a wooden platform, measuring 0.30 m in height (McNair and Marshall, 1994) and placed 0.1 m behind the rear edge of the landing target (the force plate). For all landings, subjects began in a standardized take-off position in which the hands were placed on the iliac crests and the toes of the dominant foot were aligned along the leading edge of the wooden platform. Subjects were then instructed to jump down and land with the dominant foot centered on the force plate. Subjects were not given any special instructions with regards to their landing mechanics to prevent experimenter bias. The hands remained on the iliac crests throughout the task to eliminate variability in jumping mechanics due to arm-swing. Subjects were also instructed not to allow the non-dominant limb to touch down during the landing. Trials in which the hands came off of the iliac crests, the foot did not land centered on the force plate, or the non-dominant foot touched down during the landing were discarded.

2.4. Data processing

Ground reaction force data were offline low-pass filtered at 60 Hz using a 4th order, zero-lag Butterworth filter. Ground contact was defined as when vertical ground reaction force exceeded 8 N. Peak vertical ground reaction forces (vGRF) were normalized to body weight.

Hip joint centers were calculated using the Leardini method (Leardini et al., 1999). Knee joint centers were calculated as the centroid of the medial and lateral femoral epicondyles and ankle joint centers were calculated as the centroid of the medial and lateral malleoli (Madigan and Pidcoe, 2003). A segmental reference system was defined for all body segments with the positive Z-axis defined as the medial to lateral axis; the positive Y-axis defined as the distal to proximal longitudinal axis; and the positive X-axis defined as the posterior to anterior axis. Three-dimensional hip, knee, and ankle flexion angles were calculated using Euler angle definitions with a rotational sequence of Z Y0 X00 (Kadaba et al., 1989). Raw kinematic data were linearly interpolated to force plate data and were subsequently low-pass filtered at 12 Hz using a 4th order, zero-lag Butterworth filter.

Total flexion displacements for the hip, knee, and ankle were defined as the difference between the joint angle at ground contact, and the peak joint angle. Time to peak flexions for the hip, knee, and ankle were defined as the time from ground contact to peak joint angle. For consistency purposes increasing hip, knee, and ankle flexion are reported as positive values.

Hip, knee, and ankle moments were calculated using an inverse dynamics analysis (Gagnon and Gagnon, 1992). Net joint powers were calculated as the product of the joint moment and joint angular velocity at each time point. Then, work done on the extensor muscles was calculated by integrating the negative portion of the joint power curve as this represented energy absorption by the extensor muscles (McNitt-Gray, 1993). The end of the interval measured was defined by the respective peak joint flexion. Work was then normalized to body weight. For consistency purposes, energy absorption of hip, knee, and ankle extensors are reported as negative values.

Total energy absorption was calculated by summing the normalized hip, knee, and ankle energy absorption values. Relative hip, knee, and ankle energy absorption were calculated as a percentage of their respective value to total energy absorption.

2.5. *Statistical analyses*

All dependent variables were calculated for each trial then averaged across the five trials. Repeated measures ANOVAs (joint by sex) were used to test for differences in joint angle at ground contact, total flexion displacement, time to peak flexion, absolute energy absorption, and relative energy absorption. A one-way ANOVA was used to test for sex differences in peak vertical ground reaction forces. The alpha level was set at $P < 00.05$. Post hoc testing was performed by using Tukey's HSD test.

The between-day measurement consistency of the testing protocol was established in our laboratory as part of concurrent investigation of landing styles (Kulas et al., 2005). Four males and four females that were recreationally active (3 times per week for at least 30 min per day) and free from injury twice completed the single leg landing protocol with at least 24 h between testing sessions. Intraclass correlation coefficients ($ICC_{2,k}$) and standard errors of measurement (SEM) were calculated to determine measurement consistency.

3. RESULTS

3.1. *Between-day measurement consistency*

Acceptable ICC values were established for total flexion displacements (0.85–0.99), absolute energy absorption (0.69–0.95), and vGRF (0.97). While knee joint flexion angle at ground contact was highly reliable (0.95), lower reliability values were established for the hip (0.56) and ankle (0.52) flexion angles at ground contact (Table 1).

3.2. *Kinematics*

There was a significant joint by sex interaction for total flexion displacement (P = 0.037) with females exhibiting 60% less hip and 36% less knee flexion range of motion than males during landing (Table 2). Additionally, there was a significant joint by sex interaction for time to peak flexion (P = 0.018) with females exhibiting 52% shorter hip and 22% shorter knee times to peak flexion than males

Table 1
Between-day measurement reliability $ICC_{2,k}$ and standard error of the mean (SEM) of kinematic and kinetic variables

	$ICC_{2,k}$	SEM
Joint flexion angle at ground contact (deg)		
Hip	0.56	2.6
Knee	0.95	0.8
Ankle	0.52	4.0
Total flexion displacements during landing phase (deg)		
Hip	0.90	1.4
Knee	0.99	4.2
Ankle	0.85	3.1
Absolute energy absorption ($(J\ N^{-1})\ x\ 10^{-2}$)		
Hip	0.95	1.1
Knee	0.69	1.1
Ankle	0.69	4.1
Vertical ground reaction force (% body weight)	0.97	0.05

Table 2
Means (SD), between sex effect sizes, and between sex observed power of joint flexion angle at foot contact, total joint flexion, time to peak flexion, and joint energetics during the energy absorption phase

	Males	Females	Effect size	Observed power
Joint flexion angle at ground contact (deg)				
Hip	16.7 (7.6)	21.6 (6.3)	0.67	0.46
Knee	38.9 (7.1)	42.5 (9.4)	0.43	0.21
Ankle	65.7 (6.3)	65.0 (5.6)	0.12	0.06
Total flexion displacements during landing phase (deg)				
Hip	4.0 (4.4)	1.6(1.9)[a]	0.67	0.47
Knee	12.9 (6.9)	8.3(5.9)[a]	0.68	0.48
Ankle	26.7 (5.7)	27.1 (6.0)	0.07	0.05
Time to peak flexion (ms)				
Hip	240.4 (133.2)	116.5 (113.2)[a]	0.91	0.76
Knee	285.5 (48.1)	223.4 (76.7)[a]	0.88	0.73
Ankle	334 (43.6)	323.5 (73.1)	0.18	0.08
Absolute Energy absorption ($(JN^{-1})\ x\ 10^{-2}$)				

Hip	-5.7(5.0)	-2.5(2.7)	0.76	0.56
Knee	-2.0(2.0)	-0.5(1.8)	0.75	0.55
Ankle	-24.6 (6.5)[b]	-21.7 (7.3)[b]	0.42	0.20
Total summed hip, knee, and ankle)	-32.3(9.5)	-24.7 (8.1)[c]	0.81	0.63
Relative joint work percent of total energy absorption (JN^{-1})				
Hip	16.2 (13.6)	9.7 (10.0)	0.54	0.42
Knee	5.7 (4.6)	5.7 (4.0)	0.00	0.04
Ankle	78.2 (12.9)	88.3 (12.3)[d]	0.75	0.56

a Significantly less than males' total flexion displacements and time to peak flexions for the hip and knee; **P** < 00.05.

[b] Significantly greater than absolute hip or knee energy absorption; **P** < 0.05.

[c]Significantly less than males' total energy absorption; **P** < 0.05.

[d] Significantly greater than males' relative ankle energy absorption; **P** < 0.05.

during landing. There were no significant sex differences in joint angles at ground contact (P = 0.148) (Table 2).

3.3. *Kinetics*

Females [3.56(0.28) body weights] landed with 9% greater peak normalized vertical GRFs compared to males [3.21(0.29) body weights] (P = 0.004).

3.4. *Energetics*

Males exhibited significantly greater (24%) amounts (P = 0.029) of total (summed hip, knee, and ankle) energy absorption per unit of body weight compared to females (Table 2). Absolute energy absorption revealed a main effect for joint (P S 0.001) with the ankle absorbing more work than either the hip or knee (Table 2). Additionally, there was a significant joint by sex interaction for relative energy absorption (P = 0.050), with females exhibiting a greater percentage of ankle energy absorption than males during landing (Table 2).

4. DISCUSSION

In our investigation of sex differences in single leg landing mechanics the hypotheses of females using less flexion displacements during landing and less joint energy absorption during landing were partially accepted. Additionally the hypothesis of females having greater vertical ground reaction forces was accepted. The discussion of these results will first focus on the uniqueness of the single leg landing mechanism and will be followed by a discussion of the measurement consistency and interrelationships of these significant biomechanical findings as they relate to sex differences and potential injury risk.

During landing the lower extremity musculature must function in concert to dissipate the kinetic energy and bring the body's downward momentum to zero (Devita and Skelly, 1992; Decker et al., 2003). Single leg landings are performed primarily in the sagittal plane, hence controlled flexion of the joints is likely the primary mechanism through which the impulse is applied. There is a lack of current literature to address the role of the combined joint energetics of a single extremity to control the body's momentum in a single leg landing. Although current focus is on the cause of knee injuries through applied forces, it is also important to consider the role of all lower extremity joints in controlling the body as the joints of the lower extremity act in concert to modulate the transfer of mechanical energy absorption during the landing process (Prilutsky and Zatsiorsky, 1994).

The single leg landing performed in the study would best be classified as a “stiff’’ landing using terminology most often associated with double leg landings (Devita and Skelly, 1992). Stiff landings have been described as having the muscular and passive tissue structures of the ankle joint absorb the greater shares of energy than during soft landings (Zhang et al., 2000; Devita and Skelly, 1992). Thus, we generically labeled this maneuver to be a “hard’’ or “stiff’’landing as compared to the more knee and hip dominant “soft’’ landings reported in the literature (Zhang et al., 2000).

It is important to note that the single leg landings performed in the current investigation did not produce the characteristic bimodal vertical ground reaction force curve commonly reported in double leg landing maneuvers (Fig. 1) (Zhang et al., 2000; Dufek and Bates, 1990; McNitt-Gray, 1993; Riemann et al., 2002). The demands of the current task resulted in a smoother increase to peak vertical force. A single leg landing task from 0.30 m has previously reported somewhat similar findings in a representative figure (Hargrave et al., 2003). Thus it seems as though kinetic and kinematic comparisons to the numerous double leg landing protocols in the literature are limited due to the unique nature of the single leg landing task. Thus, throughout this discussion we will attempt to

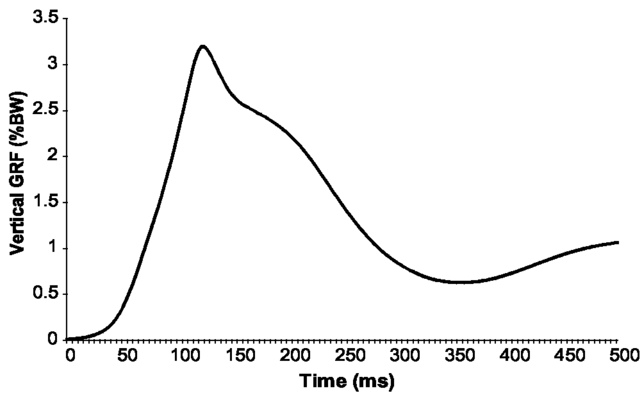

Fig. 1. Representative single trial vertical ground reaction force curve for single leg landing.

highlight differences and similarities between the current single leg landing task and the more commonly reported double leg landing.

4.1. *Kinematics*

There has been speculation that knee injuries often occur in shallow sagittal flexion angles (Boden et al., 2000; Griffin et al., 2000; Olsen et al., 2004). However the reports of initial joint flexion angles during landing have been unequivocal as there are reports of females having both lesser (Huston et al., 2001) and similar (Kernozek et al., 2005) joint flexions at landing compared to males during double leg landings, and greater joint flexion at landing (Fagenbaum and Darling, 2003) during single leg landings. Much of this disparity is likely due to the task differences, the range of subject population studied (ranging from recreational athletes to collegiate athletes), and the relatively small sample sizes of these studies (between 14 and 30). It is important to note that all these factors impact the generalizability of the work. Due to the lack of studies examining initial joint angles during a single leg landing, and the considerable biomechanical differences observed between single leg and double leg landings, we are unable to completely compare our findings to previous comparable work.

Mixed results have also been reported for sex differences in total knee flexion displacement during the landing phase. Some authors have reported that females use more knee range of motion during double and single leg landings (Fagenbaum and Darling, 2003; Decker et al., 2003), while others have reported that females use less range of motion during single leg landings (Lephart et al., 2002). Our data concur with latter. The combination of less knee and hip flexion during the landing phase in females relates well to the concept of adopting a "stiffer" landing mechanism to decrease their downward momentum (Zhang et al., 2000; Self and Paine, 2001). These stiffer landings (i.e. less knee and hip flexion) were also associated with shorter times to peak hip and knee flexion (Table 1). A previous study of single leg landings also reported shorter time to peak knee flexion in females (Lephart et al., 2002). The implications of decreased range motion during the landing phase on injury will be discussed later in conjunction with the energetics as it may be important to look at the variables together to ascertain a mechanism of how males and females differed in landing styles.

The use of range of motion to describe landing styles has been used previously (McNitt-Gray, 1993). A comparison of gymnasts and recreational athletes that performed double leg landings ranging from 0.32 to 1.28 m revealed that increases in landing height resulted in greater hip and knee flexion values. When combined with the current findings that for a fixed height males use more total hip and knee flexion displacements than females, this suggests that males may be more likely to decrease the body's momentum through a mechanism of coordinated joint actions regardless of the absolute demands placed on the system (i.e. the fixed landing height 0.30 m).

4.2. ***Vertical ground reaction forces***

The impulse–momentum relationship tells us that a given change in momentum (i.e. the momentum change from initial contact to the body's downward center of mass velocity reaching zero) is equal to the product of the force and the time that the force is applied. Our current data demonstrate that the times to peak hip and knee flexion are smaller for females. Thus, it is expected that greater forces would be acting on the system to reach the desired change in momentum. The finding of increased peak vertical GRFs in females is important as a previous prospective study of ACL injury risk demonstrated that athletes who went on to subsequently tear their ACL had 20% greater vertical GRFs during a drop vertical jump (Hewett et al., 2005). Previous work investigating peak vertical GRF has reported no sex differences during single leg landing (Lephart et al., 2002) while studies of double leg landings have reported greater female GRFs (Kernozek et al., 2005) as well as no sex differences in GRFs (Decker et al., 2003). Our findings of increased peak vertical GRFs in females may in part be a function of the relatively shorter time intervals over which the impact was attenuated in the hip and knee. The implications of these processes will be further explained in the discussion of the system energetics.

4.3. ***Energetics***

Energetics of the lower extremity during double leg landings have been previously used to compare athlete type, landing height, landing technique, and sex (Zhang et al., 2000; McNitt-Gray, 1993). Investigations of energy absorption strategies during landing may provide insight into the global strategy that males and females use to control the body's momentum (Decker et al., 2003).

There appear to be differences in the relative energy absorption of lower extremity joints during the 0.30 m single leg landing used in the current study when compared to the more prominent double leg 0.60 m landing in the literature. Table 2 demonstrates that less than 6% of total relative energy absorption occurred in the knee joint for males as well as females during a single leg landing. When this value is compared to the literature associated with "natural" 0.60 m double leg landing values that range from 33% to 47% (Zhang et al., 2000; Decker et al., 2003; McNittGray, 1993), it becomes apparent that the single leg landing strategy of energy absorption is quite different at the knee.

The ankle joint was the largest contributor to energy absorption during the single leg landing maneuver. For males and females, the ankle joint contributed between 78.2% and 88.3% of the total energy absorption in the lower extremity, respectively. Once again, when these ankle values are compared to the literature associated with "natural" 60 cm double leg landing values that range from 21% to 43% (Zhang et al., 2000; Schot et al., 1994), it becomes apparent that the energy absorption strategy is quite different at the ankle when comparing double versus single leg landings. This finding may be due to the fact that with a smaller base of support during the single leg landing, the body adapts a tactic to attenuate the impact distally, thereby decreasing the work demands of the more proximal joints. This in turn could result in a more stable system in which the body's center of mass is kept closer within the base of support. Although the proximal segments of the body were not measured in the current investigation it is theorized that the hip and knee joint extensor musculature may do less energy absorption and stiffen to contribute to postural control of the more proximal segments (i.e. head arms and trunk) while the muscles of the distal segments (i.e. gastrocnemius and soleus) attenuate the vertical ground reaction impulses. Future work should also investigate the biomechanical demands of the frontal and transverse plane during such a task.

The current study supports the notion that females land using a mechanism in which there is less total energy absorption done by the extensor muscles when normalized to body mass (Table 2). This finding relates well to the decreased hip and knee total flexion displacements and greater vertical GRF exhibited by females. Together, the energetic, GRF, and kinematic data indicate that females adopt a strategy using less of the available range of motion at the hip and knee joints where less work is absorbed by the extensor muscles during landing which is likely related to the decreased time to peak flexion and greater GRF. Other authors have suggested that the strategy of absorbing more work at the ankle during a double leg drop landing leads to a more upright position throughout the landing cycle at the knee and hip placing the females in a position that may be more at risk for knee injury (Decker et al., 2003). This idea is supported in the current study as females performed a greater relative percentage of ankle joint extensor energy absorption during landing than males (Table 2), suggesting a more ankle dominated strategy to attenuate the impact. This more upright, higher peak verti cal GRF ankle dominated strategy of females may put the non-contractile structures of the more proximal lower extremity joints (such as the ACL) at risk for injury as the large extensor muscles are absorbing less energy, as has been previously been suggested to be a "ligament dominant" strategy of landing (Hewett et al., 2002). The males may have a lesser chance for joint injury risk as they used less of an ankle strategy, allowing the more proximal joints to go through a larger, slower range of motion which is directly related to the lesser peak vertical ground reaction forces. As the current study did not measure ACL strain (or any other non-contractile structure), this is conjecture at the current time.

It is important to keep in mind that energy absorption in the current study was calculated as the integral of entire negative power curve from foot contact to peak flexion angle and may limit direct comparison to previous studies. Previous work in this area has only used the integral of the power curve during the first 100 ms after foot contact (Decker et al., 2003) as well as the entire flexion motion (Devita and Skelly, 1992; McNitt-Gray, 1993), which in the current study typically occurred well after 100 ms (Table 2). The decision to use the entire flexion motion was predicated by the thought that the negative power curve represents energy absorption by the extensor muscles (McNittGray, 1993) thus it would allow a better representation of muscular energy absorption during the entire task.

A secondary analysis of our data revealed a significant correlation between total absolute energy absorption and time to peak knee flexion ($r = —0.37$, $P = 0.052$) (energy absorption was not significantly correlated with hip or knee times to peak), demonstrating that as total energy absorption increased in magnitude, there was a corresponding increase in time to peak knee flexion. Thus it appears as though the easily clinically observed variable of a longer total landing phase at the knee greatly impacted the total energy absorption in the lower extremity and likely contributed to observed sex differences in total energy absorption.

4.4. ***Limitations***

With the exception of hip and ankle joint flexion angles at ground contact, the measures were stable across testing days (Table 1). A detailed examination of variances used to calculate the ICC values revealed a higher relative error variance in hip and ankle joint flexion angles at ground contact. This in part may be due to a small shifting of the ankle and sacral sensors at ground impact. However being that the total displacements of these joints during landing were highly reliable (0.85–0.90), we obtained representative measures of total joint action in the sagittal plane.

The authors acknowledge some limitations associated with the methods utilized in the current investigation. The greatest limitation of the study is that both males and females landed from a height of 0.30m, when the males were slightly taller (0.17 m) and of larger mass (15.5 kg) on average. This may have resulted in the task being slightly more difficult for females, thus altering their landing style. We feel as though this concern is minimal as qualitative observations revealed that the task was well below the threshold of physical abilities for all subjects. Although the same instructions were given to all subjects, the instructions may have been interpreted differently. We purposefully did not want to "over coach" the landing task as we wanted the single leg landing to be a general representation of how the subject would individually perform the task. Future studies of landing styles should include an exit interview to help determine how subjects individually interpreted the directions given to them. This would improve the methods of subsequent investigations. Additionally with subjects not wearing footwear during the landings, we cannot be sure if the results would be similar if subjects wore uniform footwear. Another limitation of the current study is the activity level of the subject population. Although activity level was defined quantitatively to be a minimum of 30 min of exercise at least 3 times per week, the type of physical activity was not controlled. It is possible that either the male or female population may have had more experience with tasks similar to the methods used in the study. Future studies should attempt to control not only type but also amount of activity when attempting to classify sex differences. Finally, a relatively small sample size (N = 28) may have hindered our ability to detect energetic differences. Medium effect sizes (0.55–0.56) present for hip and knee absolute energy absorption (Table 2) would necessitate 11 additional subjects of each sex to reach 80% power.

5. CONCLUSION

Collectively this study demonstrates that females use less total hip and knee flexion during single leg landings as well as having a shorter time to peak flexion values when compared to males of similar training levels. These kinematic variables, through the impulse–momentum relationship, likely explain the increased vertical ground reaction forces seen in females. The sex differences in the kinematics in concert with the energetics support the notion that females utilized an ankle dominant strategy to attenuate the vertical ground reaction impulse.

Although literature has reported sex differences in landing kinematics and energetics, it is still unknown as to how these differences contribute to the ACL injury discrepancies reported in the literature. Future studies aimed at studying the relationships between the biomechanics measured during functional tasks and the in vivo ACL biomechanics (i.e. strain) could provide the research community with better information with which to interpret sex differences in biomechanics.

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