Original Article

Gender differences in intra-limb coordination during single limb landings on dominant and non-dominant legs

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ABSTRACT

This study investigated the effects of gender and landing limb on intra-limb coordination during single limb drop landings. Fourteen females and eight males performed drop landings while lower limb kinematics were recorded in the sagittal plane. Discrete relative phase (DRP) and standard deviation of DRP were calculated for hip-knee, knee ankle and hip-ankle joint couplings. Mixed between-within ANOVA showed no significant gender effects for DRP of joint couplings ($p > 0.05$). Females showed significantly greater standard deviation of DRP for the hip-knee ($p = 0.03$) and hip-ankle ($p = 0.04$) joint couplings. There were no significant effects for limb in DRP of joint couplings ($p > 0.05$). Knee-angle standard deviation of DRP was significantly greater for the dominant limb compared to the non-dominant limb ($p = 0.04$). These findings suggest males and females adopt similar intra-limb coordination strategies when landing, however, females exhibit greater variability in coordination which may indicate greater adaptation in coordination patterns in an attempt to mitigate the effects of fatigue or compensate for gender differences in landing kinematics and kinetics identified in previous research. **Keywords:** ACL injury; Discrete relative phase; Kinematics; Biomechanics.

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INTRODUCTION

Anterior cruciate ligament (ACL) injury is a commonly occurring sports injury which can result in knee instability and further damage to the passive support structures, such as the menisci and articular surfaces (Irvine & Glasgow, 1992; Smith, Livesay, & Woo, 1988). Females are reportedly between 6 to 8 times more likely to sustain an ACL injury when compared to males (Arendt & Dick, 1995) and the majority of ACL injuries have been shown to occur during non-contact situations, which includes movements such as landing and rapid change of direction (Griffin et al., 2000). This gender difference in the incidence of non-contact ACL injury has been associated with a number of biomechanical risk factors. These include reduced knee flexion at ground contact (Yu, Lin, & Garrett, 2006), greater maximum knee valgus angle (Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005) greater frontal plane knee moments (Hewett et al., 2005) and greater normalized peak ground reaction force (Kernozek et al., 2005; Yu et al., 2006) in females compared to males. Previous research has also investigated the effect of factors such as volume, intensity and type of drop landing on landing biomechanics and found lower limb loading increases as drop height increases (Dickin, Johann, Wang, & Popp, 2015; Yeow, Lee, & Goh, 2010) and that fatigue induced through repeated landings can alter landing biomechanics (Madigan & Pidcoe, 2003). Furthermore, previous literature suggests that single-limb landings present a greater risk of ACL injury compared to double-limb landings due to increased ground reaction force and knee valgus angle combined with reduced knee flexion at initial ground contact (Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007; Yeow et al., 2010).

Whilst previous studies have shown gender differences in lower limb kinematics and kinetics during landing, there has been little investigation into the relationships between movements of each joint within the lower limb. Coordination refers to the relative timing of motion between body segments (Jensen, Phillips, & Clark, 1994). The concept of timing is of particular interest since the timing of movements of one joint within a kinetic chain is likely to influence resulting loading of the other joints within the kinetic chain (Watkins, 1999). Therefore, examining the relative timing of movement of two joints with respect to each other may provide greater understanding of the relationship between lower limb joints.

One way of assessing coordination between lower limb joints during a discrete movement, such as a landing task, is discrete relative phase (DRP) (Hughes & Watkins, 2008). DRP assesses the relative timing of the two key events during a discrete movement, such as the peak angle of two joints within the kinetic chain. Previous research has examined inter-limb DRP (i.e. coupling between the same joint in left and right legs) during a two footed landing and found females to be less symmetrical than males and to exhibit greater variability in coordination between left and right knee joints during landing (Hughes & Watkins, 2008). However, no previous research has presented data for intra-limb coordination (i.e. coupling between the different joints in the same leg) during landing manoeuvres. Examining the coordination strategies and variability within coordination strategies during landing may provide greater insight into the gender differences in landing biomechanics that have associated with ACL injury. Therefore, the purpose of the current study was to investigate the effect of gender and landing limb on intra-limb coordination during single-leg drop landings in recreational athletes. It was hypothesised that females would exhibit reduced intra-limb coordination and greater variability of intra-limb coordination compared to males when conduction single-leg drop landings. Also, it was hypothesised that the non-dominant limb would exhibit reduced coordination and greater variability of coordination compared to the dominant limb.

MATERIALS AND METHODS

Participants

Fourteen female (mean age 21.2 ± 1.7 years, mass 61.1 ± 6.1 kg and height 1.67 ± 0.05 m) and eight male (mean age 21.5 ± 0.8 years, mass 73.5 ± 4.2 kg and height 1.78 ± 0.06 m) recreational athletes volunteered to take part in the study. To be considered a recreational athlete, participants were required to take part in some form of recreational sporting activity at least 3 times per week which involved regularly performing landing tasks (i.e. basketball, volleyball and soccer). None of the participants had previously suffered an ACL injury and all participants were free of lower limb injury at the time of participating in the study and wore minimal tight-fitting clothing. Institutional ethical approval was granted for the study and written consent forms were signed by all participants prior to data collection. Prior to performing the experimental tasks, participants performed a standardised 10 minute warm up consisting of dynamic stretching of the lower limbs and moderate intensity cycling at 60 Watts for 5 minutes.

Equipment

37 retro-reflective markers were placed on various anatomical landmarks of the participants in accordance with the Cleveland Clinic Marker Set. Markers locations were as follows: three markers on head (top, front and back), left scapula, sacrum, right and left acromion process, lateral epicondyle of humerus, between styloid processes of radius and ulna, anterior superior illiac spines, three thigh cluster markers, three shank cluster markers, lateral and medial knees, lateral and medial ankles, heels and toes. Markers placed on the lateral and medial ankles and knees were only recorded during static trials and were then removed for all dynamic trials. The reason that all markers in the full Cleveland Clinic marker were placed on the body was to allow for the identification of the whole-body centre of gravity (CG) which was used to define the end of the landing period, as outlined later. The three-dimensional coordinates of the markers were tracked using a 10 camera Motion Analysis (Motion Analysis Corp., Santa Rosa, CA) system at a sampling rate of 500 Hz. To identify the point of initial ground contact during the landing, ground reaction force was recorded from a force plate (OR6-7 model, Advanced Mechanical Technology Inc, New York) sampling at 2000 Hz. This was recorded simultaneously with the video data using the Cortex software (version 4.0).

Procedure

To perform the landing tasks, participants held on to a metal bar suspended from the ceiling. The metal bar had previously been adjusted so that the participant's feet were 45 cm above the ground when hanging from the bar with the ankle held in a neutral position (i.e. neither plantarflexed nor dorsiflexed). Upon instructions from the investigators, the participant let go of the metal bar and landed in single limb stance on the force plate located directly below the participant when in the suspended position. Each participant repeated this task 5 times for each leg (dominant and non-dominant) in a randomised order with 60-90 seconds rest in between trials. Dominant leg was determined by asking participants which leg they would use to kick a ball when kicking for maximum distance. This suspension method has been proposed to be a more reliable procedure for performing a drop landing task compared to stepping off a box (Kernozek et al., 2005).

Data analysis

Marker trajectories were filtered at 6 Hz using a fourth order Butterworth filter. The location of the whole-body CG was determined based on a 15 segment model defined by the Cleveland Clinic marker set (right and left hand, right and left forearm, right and left upper arm, right and left foot, right and left shank, right and left thigh, head and neck, torso, pelvis) incorporating the anthropometric data of De Leva (De Leva, 1996). Joint angles were measured as the Euler angle of the distal segment relative to the proximal segment. DRP analysis of the hip, knee and ankle in the sagittal plane was carried out to quantify coordination between hip

– knee, knee – ankle and hip – ankle joint couplings. We considered the completion of the landing as when the body's momentum has been reduced to zero (i.e. the point where the body's centre of gravity velocity is zero). During the period from initial ground contact to zero momentum, the hip and knee joints flex and the ankle dorsiflexes to attenuate the ground reaction force. It was therefore chosen to use the timing of maximum angles of each joint as the points of interest in each trial. The DRP angle was calculated using the following equation, in accordance with Hamill, Haddad, & McDermott (2000):

$$\text{DRP angle } \Phi = \frac{t_2 - t_1}{t_f - t_s} \times 360^{o}$$

where t_2 = time of maximum angle of proximal joint, t_1 = time of maximum angle of distal joint, t_f = time of zero velocity of the whole-body CG and t_s = time of initial ground contact (IC).

The DRP angle therefore indicates the relative timing between the maximum angle of two coupled joints during the landing. This value may range between -360^{o} and $+360^{o}$, where 0^{o} indicates the two joints reach their maximum angle at the same time (i.e. are perfectly in-phase) and the greater the DRP angle the greater the extent to which the timing of the two maximum angles are out of phase. Where the proximal joint takes longer to reach its maximum angle than the distal joint (e.g. the hip reaches its maximum angle after the knee) this is indicated by a positive DRP angle and where the distal joint takes longer to reach its maximum angle than the proximal joint (e.g. the knee reaches its maximum angle before the ankle) this is indicated by a negative DRP angle. The standard deviation of the DRP angle over the five trials performed by each participant was also calculated and provides an indication of the variability whereby a small standard deviation of DRP angle indicates low variation and a large standard deviation of DRP angle indicates high variation.

Statistical analysis

Initially data were examined for normality using Shapiro-Wilk tests where all data were shown to be normally distributed. Mixed between-within ANOVA determined the effects of gender (males v females) and landing limb (dominant v non-dominant) on DRP and standard deviation of DRP for hip-knee, knee-ankle and hip-ankle joint couplings. A priori alpha level was set at 0.05. Effect sizes (η_p^2 values) were reported as small = 0.01, medium = 0.06 and large = 0.14, based on recommendations by Cohen (2010).

RESULTS

There were no significant landing limb by gender interactions ($p > 0.05$) for any of the dependent variables examined, indicating that both males and females responded in a similar way to changing the landing limb.

Gender effects on coordination

There were no significant effects for gender in DRP for hip-knee ($F_{(1, 21)} = 0.08$, $p = 0.78$, $\eta_p^2 = 0.004$), knee-ankle ($F_{(1, 21)} = 0.67$, $p = 0.42$, $\eta_p^2 = 0.03$) or hip-ankle joint couplings ($F_{(1, 21)} = 0.34$, $p = 0.57$, $\eta_p^2 = 0.02$), with all showing small effect sizes (Figure 1). There was a significant effect for gender in standard deviation of DRP for the hip-knee ($F_{(1, 21)} = 5.73$, $p = 0.03$, $\eta_p^2 = 0.21$) and hip-ankle ($F_{(1, 21)} = 4.29$, $p = 0.04$, $\eta_p^2 = 0.17$) joint couplings with both displaying large effect sizes (Figure 2). However, there was no significant effect for gender in standard deviation of DRP of knee-ankle joint coupling ($F_{(1, 21)} = 2.14$, $p = 0.16$, $\eta_p^2 = 0.09$), with a moderate effect size observed.

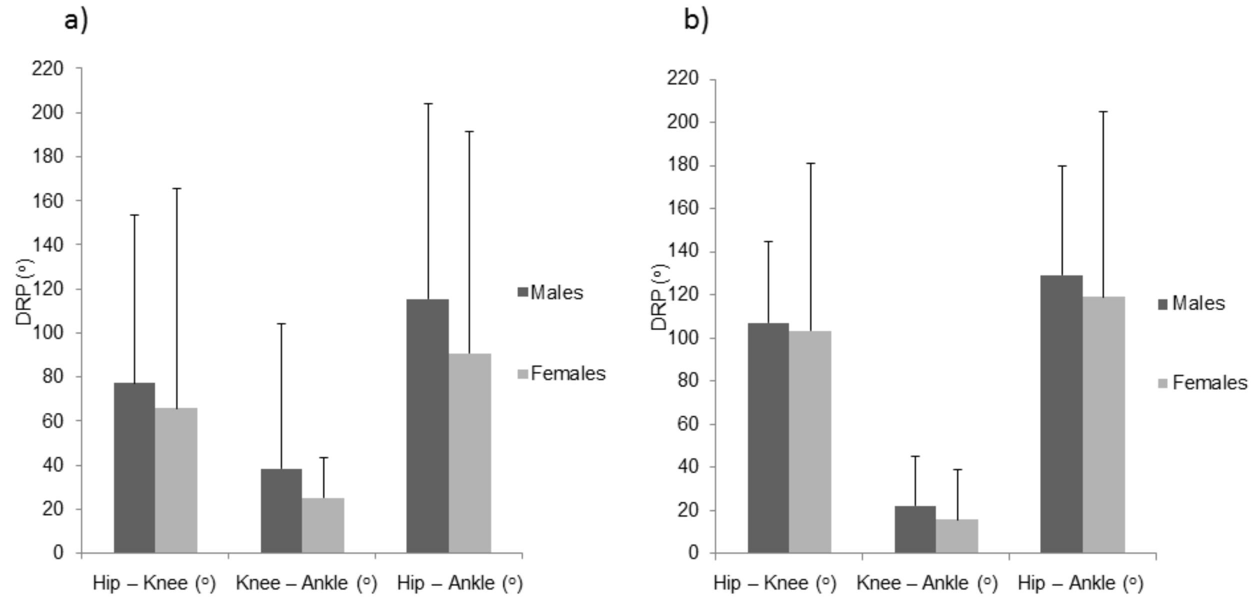
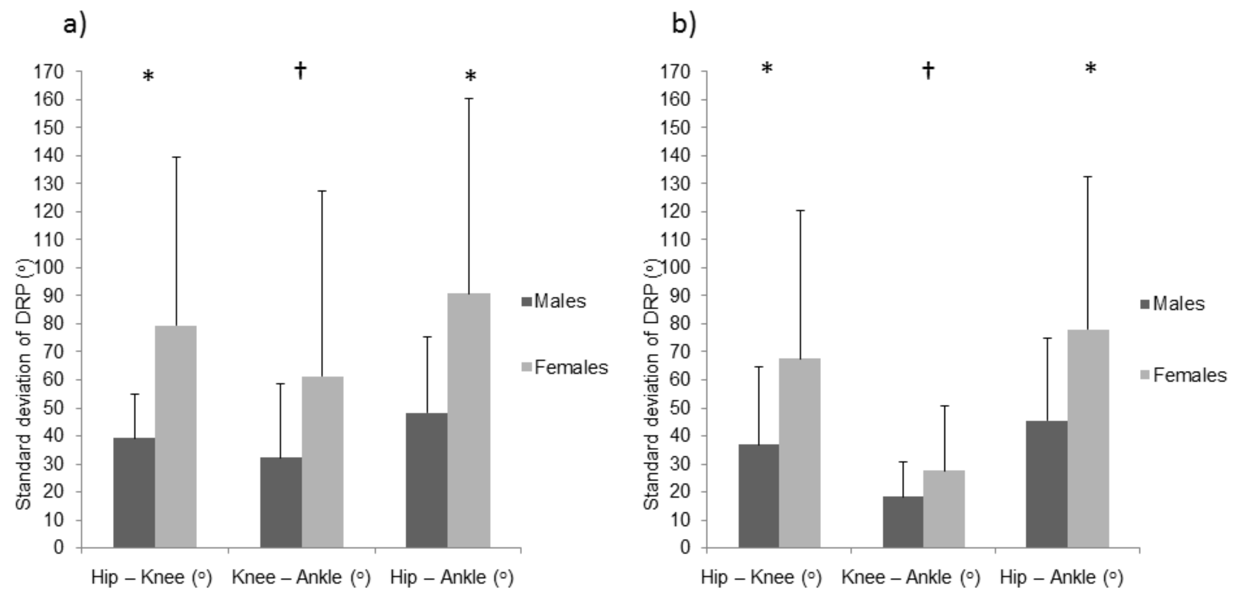


Figure 1. Discrete relative phase (DRP) for a) dominant and b) non-dominant single leg landings in males and females



** = significant effect for gender. † = significant effect for landing limb.*

Figure 2. Standard deviation of discrete relative phase for a) dominant and b) non-dominant single leg landings in males and females

Landing limb effects on coordination

There were no significant effects for landing limb in DRP for hip-knee ($F_{(1, 21)} = 2.70$, $p = 0.12$, $\eta_p^2 = 0.11$), knee-ankle ($F_{(1, 21)} = 2.23$, $p = 0.15$, $\eta_p^2 = 0.10$) or hip ankle joint couplings ($F_{(1, 21)} = 1.03$, $p = 0.32$, $\eta_p^2 = 0.05$), with all showing either moderate or small effect sizes (Figure 1). Both hip-knee ($F_{(1, 21)} = 0.28$, $p = 0.60$, $\eta_p^2 = 0.01$) and hip-ankle ($F_{(1, 21)} = 0.36$, $p = 0.56$, $\eta_p^2 = 0.02$) standard deviation of DRP showed no significant effect for landing limb with small effect sizes. There was a significant main effect for landing limb in knee-ankle standard deviation of DRP ($F_{(1, 21)} = 4.26$, $p = 0.04$, $\eta_p^2 = 0.17$) with a large effect size, showing greater variability in joint coupling for the knee-ankle in the dominant landing limb compared to the non-dominant landing limb.

DISCUSSION

The aim of the study was to investigate the effect of gender and landing limb on intra-limb coordination during single-leg drop landings in recreational athletes. There were no significant effects for gender with small effect sizes in DRP for hip-knee, knee-ankle or hip-ankle joint couplings therefore our hypothesis that females would exhibit reduced intra-limb coordination compared to males is rejected. This suggests that males and females adopt similar intra-limb coordination strategies during landing despite previous research showing differences in kinematics of joints when analysed independently (Decker, Torry, Wyland, Sterett, & Steadman, 2003; James, Sizer, Starch, Lockhart, & Slauterbeck, 2004; Yu et al., 2006). Therefore, while there may be gender differences in the movements of the lower limb joints during landing, the relative timing between these movements may not differ between the sexes. Positive DRP values were found for all joint couplings, indicating that on average the proximal joint reached its maximum angle prior to the distal joint. This is perhaps to be expected since the ground reaction force is applied to the end of the kinetic chain and confirms that both males and females adopt a distal to proximal joint coordination strategy when attenuating the impact of landing from a jump.

Significant effects for gender with large effect sizes were observed in standard deviation of DRP for the hip-knee and hip-ankle joint couplings, where females displayed greater standard deviation of DRP than males. Our hypothesis that females would exhibit variability of intra-limb coordination compared to males is therefore accepted. This finding suggests that whilst on average there were no significant differences between males and females in the relative timing of peak angles of the lower limb during single limb landings (i.e. the DRP angles), females exhibited greater variability in coordination strategies during landing. Since landing manoeuvres result in considerable eccentric loading of the muscles, effective landing strategy requires substantial eccentric muscle strength. It may be that a lack of eccentric muscle strength in females contributed to the increased variability in intra-limb coordination in that females used more variable coordination strategies in an attempt to avoid fatigue. In particular, this greater variability was evident for the joint couplings which involved the hip joint. The relationship between hip muscle function and knee positioning has been proposed to be of great importance (Homan, Norcross, Goerger, Prentice, & Blackburn, 2013) whereby the gluteus maximus acts eccentrically during landing manoeuvres to control hip flexion and internal rotation of the femur (Zazulak et al., 2005). The results of this study suggest that females utilise more variable movement patterns of the hip joint when coupled with either the ankle or knee compared to males which again could be in an attempt to limit the repeated loading on certain tissues in an attempt to either reduce the risk of injury or limit the effects of fatigue.

There were no significant effects for limb in DRP angle in any joint coupling, therefore our hypothesis that the non-dominant limb would exhibit reduced coordination is rejected. This suggests a similar coordination strategy during single limb landings on both dominant and non-dominant legs. Differences in kinematics between dominant and non-dominant limbs during landing manoeuvres have been shown in previous research (Hughes, Owen, & Watkins, 2007) but these findings were only found in the frontal plane. Since the DRP angles in the present study were only calculated for joint angles in the sagittal plane, the findings agree with the previous research examining differences in sagittal plane kinematics between dominant and non-dominant limbs.

The results showed knee-ankle standard deviation of DRP to be significantly greater for the dominant limb compared to the non-dominant limb, but both hip-knee and hip-ankle standard deviation of DRP showed no significant effect for limb. Our hypothesis that the non-dominant limb would exhibit greater variability in coordination is therefore rejected. This increased variability in the dominant leg may reflect the greater adaptability required to respond to complex dynamic sport environments (Bradshaw & Aisbett, 2006). However further research is required to verify this finding since this study utilised relatively controlled task demands and a more complex task may provide a greater requirement for demonstration of adaptability. Furthermore, it should be noted that the participants in the study were recreational athletes rather than athletes participating regularly in sports involving a high level of exposure to landing tasks.

The limitations regarding the use of DRP as a method of assessing coordination between joints are that it only evaluates relative timing of discrete points (i.e. at maximum angle for the two joints) during a movement. Also, the DRP angles calculated in the present study were only calculated for the sagittal plane. Since it has been suggested that combined movements in the sagittal and frontal planes are likely to contribute more to ACL injury than sagittal plane biomechanics alone (Kernozek et al., 2005) future research should investigate the coordination between different planes of motion as well as between different limbs during landing. This study included a relatively small sample size with unequal samples in each group (14 females and 8 males). Larger samples generally result in greater variance which therefore may have also contributed to the larger variance in the female group. Finally, there may be limitations in the question used to identify dominant limb. Since the task employed required the participants to control their landing eccentrically while maintaining balance during closed kinetic chain, whereas participants were asked which leg would you use to kick for maximum distance (i.e. open kinetic chain), this question may not be the most appropriate for determining limb dominance in this sense despite being commonly in previous literature (Hanson, Padua, Troy Blackburn, Prentice, & Hirth, 2008; McLean, Borotikar, & Lucey, 2010; Sigward & Powers, 2006; Zazulak et al., 2005).

CONCLUSIONS

The main findings of the current study were that whilst there were no significant gender effects in DRP angles for hip-knee, knee-ankle or hip-ankle joint couplings, females showed significantly greater standard deviation of DRP for the hip-knee and hip-ankle joint couplings in comparison to males. These results suggest that males and females adopt similar intra-limb coordination strategies when landing on dominant and non-dominant limbs but females exhibit greater variability in coordination. This greater variability in females may be an attempt to reduce the effects of fatigue brought on by the repeated eccentric loading of muscles when performing repeated landing trials, however further research is required to verify this finding during more complex tasks. There were no significant effects for limb in DRP for hip-knee, knee-ankle or hip ankle joint couplings or standard deviation of DRP for hip-knee and hip-ankle joint couplings but a significant effect for limb was only found in knee-ankle standard deviation of DRP. This increased variability in the knee-ankle joint coupling of the dominant leg may demonstrate increased adaptability of the kinetic chain in comparison to the non-dominant limb when landing.

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