Sex- and Limb-specific Relationships Exist Between Triple Flexion Landing Patterns and Estimates of Knee Joint Stress During a Triple Forward Hop Task Between 9- and 12-months Post Anterior Cruciate Ligament Reconstruction: a Cross-Sectional Study

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INTRODUCTION:

Landing biomechanics form a core component of ACL reconstruction (ACLR) rehabilitation and return to sport testing, given its validated comparability to sport-specific movement demands. During landing, the lower-limb is subject to considerable compressive forces and acceleration transients. Of these, tibial acceleration is one of the main indicators of dynamic knee stability and joint stress given its strong relationship with *in vivo* ACL force. A 'triple flexion' landing pattern, characterized by coordinated flexion at the hip, knee and ankle (dorsiflexion), from foot contact to the point of peak tibial acceleration is encouraged to reduce limb impact loading and associated knee stress. However, current ACLR biomechanical studies of landing tasks have largely focused on kinematics at single joints (e.g., peak knee flexion angle), which may ignore secondary multi-joint compensatory strategies to accommodate impaired post-ACLR knee mechanics. Measures of inter-joint coordination, which examines the synergies between two joint movements may better classify clinically relevant movement patterns post ACLR.

While some studies argue the limited role female sex has on graft rupture rates, there is abundant literature displaying higher subsequent ACL injuries and worse outcomes for females compared to males following ACL injury and ACLR. However, no studies to date have examined sex-specific differences in landing strategies following ACLR and whether these relate to the magnitude of impact loading and knee stress. It is important to identify sex- and limb-specific landing strategies, so that targeted interventions can be developed to improve outcomes in male and female ACLR patients. Thus, this study aimed to (i) determine the frequency by sex and limb of triple flexion landing patterns during a triple forward hop task in males and females at late phase (9-12 months) ACLR; and (ii) examine the sex- and limb-specific relationships between landing patterns and knee joint stress quantified by resultant peak tibial acceleration.

METHODS:

A cross-sectional study was conducted on 112 participants (50 females, 62 males) who had undergone unilateral ACLR and who were at late phase (9-12 months) rehabilitation. Eight Inertial Measurement Units (IMUs) (Xsens, Netherlands) were secured on each patient's trunk, pelvis, and bilateral thigh, tibia and foot to obtain kinematic motion capture data. For the operative and non-operative limbs, participants performed three trials of a triple forward hop-for-distance test, with the best hop distance obtained (m). Our primary biomechanical region of interest was the final land from initial foot contact to peak tibial acceleration, as this is where peak ACL force and loading rate occurs. Inter-joint coordination in the sagittal plane was determined by coupling joint angles (e.g., hip angle vs knee angle; knee angle vs ankle angle) across landing chronological time points. Landing strategies at each time point were then categorized using a binomial approach (i.e., hip/knee/ankle flexion vs hip/knee/ankle extension). We also reported joint dominance for each joint couple (i.e., knee flexion > hip flexion is a knee dominant strategy, while hip flexion > knee flexion is a hip dominant strategy). Resultant tibial acceleration (*g)* was obtained from the IMU sensor fixed to the tibial tuberosity, and time integrated to provide a measure of cumulative knee joint load across the analysis region. Baseline characteristics and hop distance limb symmetry (%) were compared between sex using parametric and non-parametric tests as appropriate. A mixed effect model with Bonferroni correction was used to compare the frequency of an 'optimal' landing strategy (i.e., both joints flexing, knee dominant) to cumulative tibial acceleration (*g),* with sex (male/female), and limb (operated/non-operated) modelled as interaction effects.

RESULTS:

Compared to males, females demonstrated a significantly lower frequency of the preferred triple flexion landing pattern in the surgical limb, as demonstrated by lower frequency of knee dominant hip/knee flexion ($p<0.001$) and knee dominant knee flexion/ankle dorsiflexion landing patterns ($p<0.001$). This relationship was not present in the non-operated limb. Females demonstrated several unique compensatory strategies compared to males, including landing with ankle dominance and/or an extending hip.

A significant main effect was found for tibial acceleration and knee dominant hip/knee flexion ($p<0.001$) and knee dominant ankle/knee flexion ($p<0.001$); where lower tibial acceleration occurred with a higher frequency when these patterns were observed (Fig 1). However, both sex and limb were shown to modify this relationship, as shown by significant interaction effects ($p<0.05$). Notably, the operated limb in females exhibited a larger slope (i.e., gradient of the linear regression line) than the operated limb in males, suggesting that tibial acceleration responds more sensitively to movement patterns in females (Fig 1).

DISCUSSION AND CONCLUSION:

Our primary findings demonstrated the frequency of triple flexion and knee dominant landing strategies was more prevalent in males than females, with both sex and limb significantly modifying this linear relationship (i.e., magnitude of slope). This higher frequency of triple flexion and knee dominancy landing strategies results in lower estimates of knee joint stress in patients performing a triple forward hop task at late phase ACLR. Secondarily, we observed several aberrant landing strategies in females compared to males which warrant further investigation. Collectively, these findings confirm the need to consider sex-specific landing biomechanics at late phase ACLR when devloping post-operative rehabilitation protocols.

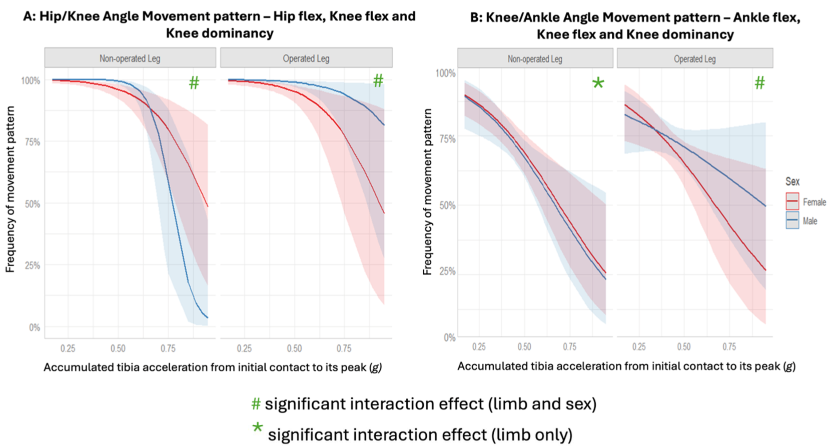

Fig 1. Frequency of optimal landing pattern, consisting of both joints flexing with knee dominancy (y axis) plotted against accumulated tibial acceleration from initial contact to peak acceleration (x axis) for (A) Hip/knee angle pairs and (B) Knee/Ankle angle pairs for males (blue line ± shaded standard deviation) and females (red line ± shaded standard deviation).