JUMP-LANDING KINETIC ASYMMETRIES PERSISTED DESPITE SYMMETRIC SQUAT KINETICS IN COLLEGIATE ATHLETES FOLLOWING ACL RECONSTRUCTION

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Anterior cruciate ligament (ACL) re-injury rates are high in collegiate athletes. Squats and countermovement jumps (CMJ) are commonly used for assessments and training after ACL reconstruction (ACLR). The purpose was to quantify the differences and correlations in kinetic asymmetries between squats and CMJs in collegiate athletes following ACLR. Fourteen athletes performed 1-2 squats and CMJs within 24-month following ACLR for a total of 25 assessments. Greater kinetic asymmetries showed in CMJs than squats. Kinetic asymmetries strongly correlated between the ascending and descending phases in squats and moderately between the jumping and landing phases in CMJs. Two phases of squats moderately correlated with the jumping phase of CMJs but the landing phase. CMJ kinetic asymmetries should be directly assessed and trained for mitigating ACL re-injury risk.

KEYWORDS: kinetics, asymmetry, biomechanics, re-injury, rehabilitation.

INTRODUCTION: Anterior cruciate ligament (ACL) injuries are considered one of the most frequent severe injuries in National Collegiate Athletic Association (NCAA) athletes (Kay et al., 2017). Although ACL reconstruction (ACLR) and postoperative rehabilitation have been often performed to help athletes return to play and prevent secondary injuries (Malempati, Jurjans, & Johnson, 2015), the incidence rate of ACL re-injuries is 15 times higher than the primary ACL injuries (Paterno, Rauh, Hewett, 2012). Bilateral asymmetries in knee extension moments (KEM) during double-leg landings with increased loading on the uninjured leg have been identified as a risk factor for ACL re-injuries (Paterno et al., 2010). In addition, the kinetic asymmetries in vertical ground reaction force (VGRF) and KEM were commonly observed during rehabilitation following ACLR (Dai et al., 2020; Hughes, Musco, Howe, 2020). Therefore, determining sensitive assessments to quantify bilateral kinetic asymmetries is an essential part of monitoring the rehabilitation progress and evaluating potential ACL re-injury risk.
Bilateral squats are often utilized as a safe and functional weight-bearing exercise to strengthen the lower limbs during the early phase of rehabilitation (Malempati et al., 2015). While ACL re-injury is not likely to occur during squats, bilateral squats with similar descending and ascending phases as jump-landings allow real-time feedback for abnormal movement corrections (Bonnette et al., 2020). The double-leg countermovement jump (CMJ) is a jump-landing manoeuvre often utilized to assess and monitor compensatory strategies during the later phase of rehabilitation following ACLR (Dai et al., 2020; Read, Michael Auliffe, Graham-Smith, 2020). Although significant differences have been found in peak KEM between the descending phase of squats and the landing phase of jump-landings (Donohue et al., 2015), the training effects of squat mechanics through real-time feedback could be transferred to jump-landing tasks in healthy athletes (Bonnette et al., 2020). Recently, a study found significant correlations in VGRF and KEM asymmetries between the descending phase of squats and the landing phase of stop-jumps in patients approximately 6-month following ACLR (Peebles, Williams III, & Queen, 2021), further supporting the potential transferring effect between two tasks in their eccentric phases. Previous studies have shown significant kinetic asymmetries in VGRF and KEM during both ascending and descending phases of squats and jumping and landing tasks in individuals even more than 24-month following ACLR (Hughes et al., 2020; Read et al., 2020). However, whether the mechanical relationships between squats and jump-landings persist in patients further away from ACLR is unclear. In addition, the ascending phase in squats and jumping tasks have been associated with the muscle force production capability affected by the injury status, knee strength, and rehabilitation progress

(Dai et al., 2020; Read et al., 2020). It is unknown whether the correlations would be similar between the concentric and eccentric phases in squats and CMJs. Understanding the differences and correlations in kinetic asymmetries between squat and CMJs can help identify effective and sensitive tasks for monitoring postoperative rehabilitation progress and designing training strategies following ACLR.
The purpose of the current study was to quantify the differences and correlations in VGRF and KEM asymmetries between the ascending and descending phases of squats and the jumping and landing phases of CMJs in collegiate athletes following ACLR. It was hypothesized that the kinetic asymmetries in VGRF and KEM would be greater in both phases of CMJs than squats. In addition, it was hypothesized that significant correlations would be found in both phases between squats and CMJs in VGRF and KEM asymmetries.

METHODS: Based on an estimated effect size of 1.6 in differences in KEM asymmetries and an estimated correlation coefficient of 0.595 in KEM asymmetries between squats and stop-jumps (Peebles et al., 2021), a sample size of 17 was needed to achieve a power of 0.8 at a type-I error level of 0.05. Fourteen NCAA Division I athletes who had ACLR in the past 24-month participated. Eleven of them performed two assessments over the study period with an average of 3-month (ranging from 1- to 6-month) in between assessments. Participants' age, height, mass, and months following ACLR across the 25 assessments were 20.40 ± 1.41 years, 1.80 ± 0.11 m, 80.83 ± 17.65 kg, and 7.60 ± 2.71 (ranging from 3- to 14-month) months following ACLR. Three squat and CMJ tasks were performed in each assessment session as previously described (Dai et al., 2020; Song, Li, & Dai, 2021). Twenty-four retroreflective markers were placed on the bony landmarks. Synchronized force and motion data were collected via two force platforms (4060; Bertec, Columbus, OH, USA) and eight infrared cameras (Vicon Motion Systems Ltd, UK).
The kinetic asymmetries in peak VGRF and KEM were calculated during the ascending and descending phases of squats and the jumping and landing phases of CMJs using (uninjured leg-injured leg)/greater number of the two legs (Dai et al., 2020). The VGRF was normalised by body weight, and the KEM was normalised by the product of body weight and body height. The ascending phase of the squat was defined as the lowest hip position until the highest hip position, while the descending phase of the squat was defined as the squat initiation until the lowest hip position. The jumping phase of the CMJ was defined as the lowest hip position until take-off, while the landing phase of the CMJ was defined as the first 100ms after initial contact. Data reduction was performed in MATLAB 2021b (MathWorks, Inc., Natick, MA, USA).
One by four (ascending phase of the squat, descending phase of the squat, jumping phase of the CMJ, and landing phase of the CMJ) repeated measure analysis of variance (ANOVA) was performed in kinetic asymmetries following paired t-tests between each pair of comparisons with a significant main effect. Pearson correlations were performed between both phases of squat and CMJ tasks in kinetic asymmetries. Pearson correlation coefficients were considered "weak," (≤0.3) "moderate," (0.3-0.5) or "strong" (≥0.5) (Cohen, 1988). The Benjamini-Hochberg procedure was applied to both paired t-tests and Pearson correlations to control the study-wide false discovery rate at 0.05.

Table1:Means ± standard deviations of kinetic asymmetries and main effect (p-value) of ANOVA

	Squat		Countermovement jump		P-values
	Ascending	Descending	Jumping	Landing	of ANOVA
VGRF asymmetry	-0.02±0.11[b]	-0.03±0.11[b]	0.14±0.07[a]	0.19±0.17[a]	**<0.001**
KEM asymmetry	0.09±0.29 [b]	0.06±0.29 [c]	0.30±0.25[a]	0.32±0.25[a]	**<0.001**

Note: VGRF: vertical ground reaction force; KEM: knee extension moment [a]: the greatest; [b]: the second greatest; [c]: the least based on paired t-tests results (all p-values <0.009).

RESULTS: The largest p-value after the false discovery rate adjustment was 0.009 for paired t-tests and Pearson correlations. Greater kinetic asymmetries in VGRF and KEM have been found in both phases of CMJs than squats (Table 1). The kinetic asymmetries in VGRF ($r=0.96$, $p<0.001$) and KEM ($r=0.98$, $p<0.001$) strongly correlated between the two phases in squats, while KEM asymmetry strongly correlated between the two phases in CMJs (r=0.62, p=0.001). The KEM asymmetry in the jumping phase of CMJ moderately correlated with both phases of squats (Figure 1). No significant correlations showed between either phase of squats and the landing phase of CMJs.

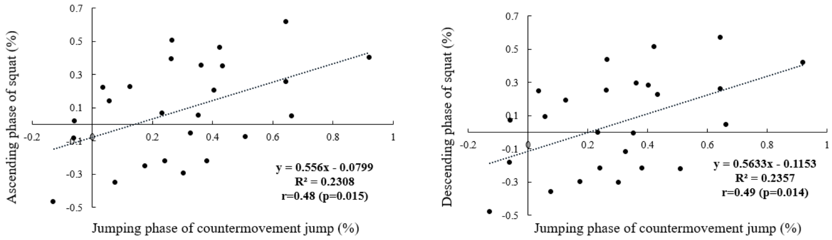

Figure 1: The correlations in knee extension moment asymmetries between squats and CMJs.

DISCUSSION: The current findings supported the first hypothesis that greater VGRF and KEM asymmetries would be observed in CMJs compared to squats with increased loading on the uninjured leg in collegiate athletes within 24-month following ACLR. These findings were consistent with a previous study that greater kinetic asymmetries have been reported in the landing phase of stop-jumps compared to the descending phase squats (Peebles et al., 2021). Recently, researchers suggested an expected goal of postoperative rehabilitation and a safe return to sports criterion as 10% bilateral asymmetries (Dai et al., 2020). Based on this criterion, greater than 10% of kinetic asymmetries in VGRF and KEM have been found in both squats and stop-jumps in patients approximately 6-month following ACLR (Peebles et al., 2021). In comparison, the current study found greater (>10%) kinetic asymmetries in VGRF and KEM during both jumping and landing phases of CMJ, when symmetrical VGRF and KEM (<10%) were achieved during squats. These findings were closely aligned with decreased kinetic asymmetries in VGRF and KEM from 3-month to 9-month during bilateral squats following ACLR in collegiate athletes (Song et al., 2021), while the kinetic asymmetries continued to be at a high level during jump-landings. Bilateral squats with relatively slow speed and a balanced motion were convenient for motor learning and movement corrections (Bonnette et al., 2020). Athletes could continuously adjust their movements and receive proprioceptive feedback throughout the squat to minimize uneven weight distribution. However, kinetic asymmetries persisted during a relatively fast jump-landing with airborne motion. Compared to squats, jump-landings required athletes to perform the task quickly, and slowing down the motion might affect the stretch-shortening cycle and compromise their jump height. The fast motion also imposed greater loading on the injured leg and exposed its muscle weakness. Athletes might also spontaneously unload their injured leg despite the ability to use it when the exercise is faster and unobvious to monitor (Chan & Sigward, 2019).

In addition, KEM asymmetries were greater than VGRF asymmetries in both phases and tasks. The KEM was determined via VGRF and the perpendicular distance between the knee and VGRF vector, which indicated that other compensatory strategies like the anteriorly located centre of pressure might also contribute to KEM asymmetries (Chan & Sigward, 2020). As the KEM asymmetry during landing is a risk factor for ACL re-injuries, the double-leg CMJ is a more sensitive assessment to monitor bilateral asymmetries and their associated ACL re-injury risk in collegiate athletes following ACLR compared to bilateral squats.

The current findings partly supported the second hypothesis that the kinetic asymmetries strongly correlated between phases in both tasks. However, only KEM asymmetry in the jumping phase of CMJs moderately correlated with both phases of squats. The jumping phase contains meaningful information for assessing the rehabilitation process, which reflects the ability of lower limbs for force production (Dai et al., 2020; Read et al., 2020). The force production during the jumping phase represented the active muscle contraction ability in jump-landings related to both phases of squats. Therefore, bilateral squat as a functional weight-bearing exercise to strengthen lower limbs contributed to jump-landing capability to a certain extent. On the other hand, the peak force experienced during the landing phase could be largely related to the landing strategies. A high landing force could be achieved by a stiff landing pattern despite weak muscles, as the landing forces could be absorbed by passive tissues. These findings indicated that the transferring effects in KEM asymmetries from squats to jump-landings might be limited and should be screened and trained with their own emphases. These findings did not support previously identified transferring effects from squatting to landing biomechanics in patients following ACLR (Peebles et al., 2021). One potential reason was the time of testing, which was a later phase of rehabilitation than in the previous study. Also, the current population included collegiate athletes, who were highly motivated to perform rehabilitation for return-to-play. In addition, the kinetic asymmetries have been found strongly correlated between phases in squats, while a less significant correlation was only found in KEM asymmetry between phases in CMJs. These results might indicate a need to assess both phases during jump-landings to monitor the rehabilitation progress and screen ACL re-injury risk.

CONCLUSION: Kinetic asymmetries persisted in CMJs (>10%), while kinetic symmetries were achieved in squats (<10%) in collegiate athletes within 24-month following ACLR. The CMJ is a more sensitive assessment to monitor the bilateral kinetic asymmetries in VGRF and KEM than squats in patients following ACLR. The limited correlations posed a need to assess and train different phases of squats and CMJs with their own emphases.

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