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# Medial-lateral hip positions predicted kinetic asymmetries during double-leg squats in collegiate athletes following anterior cruciate ligament reconstruction☆

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ABSTRACT

ACL re-injury rates are high in collegiate athletes, and double-leg squats have been used as a functional weight-bearing exercise to strengthen the lower extremities and assess bilateral kinetic asymmetries. The primary purpose was to quantify the correlations between medial–lateral shoulder/hip positions and lateral bending angles and bilateral asymmetries in vertical ground reaction forces (VGRF) and knee extension moments during double-leg squats in collegiate athletes at two assessments following anterior cruciate ligament reconstruction (ACLR). Seventeen National Collegiate Athletic Association Division I athletes performed double-leg squats between 0 and 6 months and/or between 6 and 12 months following their ACLR while kinematic and kinetic data were collected. Medial-lateral shoulder positions strongly and significantly correlated with VGRF asymmetries at both assessments ($p \leq 0.007$, $r \geq 0.68$). Medial-lateral hip positions strongly and significantly correlated with VGRF asymmetries and knee moment asymmetries at both assessments ($p \leq 0.018$, $r \geq 0.62$). Additionally, participants demonstrated decreased VGRF asymmetries and knee moment asymmetries, more neutral shoulder and hip positions, and increased knee moments for the injured leg at the second assessment compared to the first assessment with large effect sizes ($p \leq 0.008$, Cohen's $d \geq 1.06$). In conclusion, medial–lateral hip positions correlated and predicted VGRF and knee moment asymmetries during double-leg squats in collegiate athletes at two assessments (0–6 and 6–12 months) following ACLR. The bilateral asymmetries support the need for an individual approach for kinetic asymmetry assessments. A commercially available camera can be utilized as a low-cost and convenient tool to monitor and potentially train bilateral kinetic symmetries during double-leg squats in patients following ACLR.

## 1. Introduction

The anterior cruciate ligament (ACL) injury is one of the most frequent severe injuries in National Collegiate Athletic Association (NCAA) athletes (Kay et al., 2017), with a rupture rate of 32 per 10,000 athlete exposures (Gans et al., 2018). ACL injuries compromise athletes' sports careers and cause numerous functional and health consequences and increased risks of knee osteoarthritis (Barber-Westin and Noyes, 2020; Dai et al., 2020; Poulsen et al., 2019). ACL reconstruction (ACLR) and post-surgery rehabilitation are commonly performed to help athletes return to preinjury sports levels and prevent secondary injuries (Barber-Westin and Noyes, 2011; Kvist, 2004; Malempati et al., 2015). However, ACL re-injury rates were reported to be between 13% and 37% in NCAA Division I athletes (Kamath et al., 2014), positing an urgent need to develop effective and efficient assessment and training strategies to modify the risk factors associated with ACL re-injuries.

Double-leg squats have been used as a functional weight-bearing exercise to strengthen the lower extremities during the rehabilitation after ACLR (Malempati et al., 2015; Shelbourne and Nitz, 1990). Squats are convenient closed-chain exercises, which may result in increased knee muscle activation and less tibial translation compared to open-chain exercises in patients (Kvist and Gillquist, 2001). The standing

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posture of squats also facilitates an effective transfer of strength gain to other dynamic activities (Wirth et al., 2016). Additionally, the correlations between double-leg squat and landing mechanics may allow the use of squats as an alternative screening task for risky movement patterns with lower loading demands (Donohue et al., 2015). Furthermore, double-leg squats can be used to assess bilateral compensatory strategies and bilateral asymmetries (Chan and Sigward, 2020; Sigward et al., 2018). Indeed, patients following ACL injuries commonly demonstrate bilateral asymmetries in vertical ground reaction force (VGRF) and knee moments with increased loading to the uninjured leg during double-leg squats (Neitzel et al., 2002; Roos et al., 2014; Sanford et al., 2016; Webster et al., 2015). The asymmetric knee moments resulted from the asymmetric VGRF and the redistribution of the hip and knee moment ratio for the surgical leg (Chan and Sigward, 2020; Sigward et al., 2018). These kinetic asymmetries indicate insufficient recovery of the injured knee and are particularly concerning if they persist when athletes return to sports as increased bilateral asymmetries in landing have been identified as a risk factor for ACL re-injuries (Paterno et al., 2010). While it is imperative to identify and correct bilateral asymmetries during the rehabilitation following ACLR, the standard equipment to quantify bilateral VGRF asymmetries involved two force platforms. Synchronized force and motion data with an inverse dynamic approach were typically needed to calculate bilateral knee moment asymmetries (Chan and Sigward, 2020; Sigward et al., 2018). The limitations associated with the cost, testing locations, and sophisticated calculations have restricted their practical applications and warrant the development of alternative assessments for quantifying kinetic asymmetries during double-leg squats in patients following ACLR.

Efforts have been made to predict knee moment asymmetries in patients following ACLR. Dai et al. (2014) showed that bilateral VGRF impulse asymmetries predicted 78% of the variance in the peak knee moment asymmetries during jump-landing. Sigward et al. (2018) found that the combined bilateral VGRF ratio and hip-knee moment ratio of the injured leg predicted 85% of the variance in the bilateral knee moment ratio during double-leg squats in patients 3-month following ACLR. Chan and Sigward (2020) found that VGRF and anterior-posterior center of pressure (COP) asymmetries predicted 70% of the variance in the knee moment asymmetries during double-leg squats. Overall, decreased VGRF and VGRF impulse and anteriorly located COP of the injured leg correlated to the decreased knee moment of the injured leg after ACLR. Therefore, the VGRF and COP were measured from force platforms as a surrogate to estimate knee moment asymmetries. However, whether the kinetic asymmetries could be predicted from movement patterns captured from cameras is still unknown. Mechanically speaking, the center of mass (COM) and the COP are closely aligned during slow and balanced movements (Caron et al., 2000). The bilateral VGRF asymmetries could represent the shifted COP resulting from patients' control of their COM. As the upper body composed more than half of the body mass (de Leva, 1996), and the two feet were fixed to the ground during double-leg squats, the movement of the trunk became essential in modulating the COM. Consistently, Jean and Chiu (2020) found that by raising up the non-injured leg and shifting the COM toward the injured leg, patients following ACLR demonstrated improved symmetries in knee moments in double-leg squats. Another study found that expert workers were able to shift their hip positions to move their COP toward the opposite side during asymmetric lifting, decreasing the loading on the waist compared to novices (Jeong et al., 2016). These previous findings support the potential value of predicting bilateral VGRF and knee moment asymmetries from trunk movements in the medial–lateral direction.

The primary purpose was to quantify the correlations between medial–lateral shoulder/hip positions and lateral bending angles and bilateral asymmetries in VGRF and knee extension moments during double-leg squats in collegiate athletes at two assessments (0–6 and 6–12 months) following ACLR. It was hypothesized that medial–lateral shoulder/hip positions and lateral bending angles would be strongly correlated with bilateral asymmetries in VGRF and knee moments at both assessments. The secondary purpose was to quantify the changes in squatting kinematic and kinetic variables between the two assessments. It was hypothesized that the medial–lateral shoulder/hip positions and bending angles would be more neutral, and the kinetic asymmetries would decrease at the second assessment compared to the first assessment.

## 2. Methods

### 2.1. Participants

A previous study identified a coefficient of correlation of 0.79 between the inter-limb COP ratio and the hip-knee moment ratio during double-leg squats (Chan and Sigward, 2020). Another study reported a coefficient of correlation of 0.74 between bilateral VGRF impulse asymmetries and peak knee moment asymmetries during a jump-landing task (Dai et al., 2014). With a coefficient of correlation of 0.7 between the shoulder and hip kinematics and bilateral kinetic asymmetries, a sample size of 11 was needed to achieve a power of 0.8 at a type-I error level of 0.05.

Seventeen NCAA Division I athletes (≥18-year-old) who had an ACLR in the past year participated in the study. Twelve of them performed both assessments (0–6 and 6–12 months following ACLR). Three additional athletes only performed the first assessment, while two additional athletes only performed the second assessment. Participants' demographic information, injury mechanisms (Song et al., 2021), injury history, and surgery information are shown in Table 1. Participants were treated with a standard rehabilitation program under the guidance of their team doctors and athletic trainers and were cleared to perform double-leg squats at the time of testing. Individuals were excluded from this study if they were pregnant or allergic to adhesive tapes. The study was approved by the University of Wyoming Institutional Review Board. Participants signed informed consent forms prior to participation.

**Table 1**
Participants' information at two assessments (means ± standard deviations).

| | First Assessment (0–6 months following ACLR) | Second Assessment (6–12 months following ACLR) |
|---|---|---|
| Sex | 10 men, 5 women | 8 men, 6 women |
| Age (years) | 20.2 ± 1.1 | 21.0 ± 1.4 |
| Height (m) | 1.81 ± 0.13 | 1.79 ± 0.11 |
| Mass (kg) | 84.0 ± 19.1 | 82.1 ± 21.1 |
| Months Between ACL Injuries and ACLR | 0.54 ± 0.23 | 0.72 ± 0.51 |
| Months Following ACLR | 3.1 ± 0.8 | 8.7 ± 1.3 |
| Sports | 6 men's American football, 3 women's soccer, 3 men's wrestling, 1 men's basketball, 1 women's basketball, 1 women's volleyball | 4 men's American football, 3 women's soccer, 3 men's wrestling, 2 women's basketball, 1 men's basketball, 1 women's volleyball |
| Injury Side | 4 right legs, 11 left legs | 3 right legs, 11 left legs |
| Injury Mechanisms | 6 non-contact, 5 indirect contact, 4 direct contact | 7 non-contact, 3 indirect contact, 4 direct contact |
| Surgery Types | 13 patellar tendon grafts, 2 hamstring grafts | 11 patellar tendon grafts, 3 hamstring grafts |
| Concurrent Injuries | 12 meniscus repairs, 2 medial collateral ligament reconstruction, 1 lateral collateral ligament reconstruction | 12 meniscus repairs, 2 medial collateral ligament reconstruction, 1 lateral collateral ligament reconstruction |
| Injury Histories (previous ACLR) | 2 to the contralateral leg, 1 to the same leg, and 1 to both legs. | 1 to the contralateral leg, 2 to the same leg, and 1 to both legs. |

Note: ACL: anterior cruciate ligament. ACLR: anterior cruciate ligament reconstruction.

### 2.2. Procedure

Participants were tested between 0 and 6 months and/or between 6 and 12 months following their ACLR. The first time point was chosen as participants were typically in their rehabilitation and working towards returning to play, while most participants were expected to return to play at the second time point (Shelbourne and Nitz, 1990). Participants wore spandex pants and t-shirts and their own athletic shoes or running shoes provided by the laboratory (Ghost 5; Brooks Sports, Bothell, WA, USA). Participants performed self-selected warm-up activities. Twenty-four retroreflective markers were placed on the participants' bilateral acromioclavicular joints, greater trochanters, anterior mid-thighs, medial and lateral femoral condyles, tibial tuberosities, inferior anterior shanks, medial and lateral malleolus, calcaneus, first toes, and fifth metatarsal heads. The three-dimensional positions of retroreflective markers were collected using eight infrared cameras at a sampling frequency of 100 Hz (Bonita 10, Vicon Motion Systems Ltd, Oxford, UK). Bilateral GRF data were captured using two force platforms at a sampling frequency of 1000 Hz platforms (4060; Bertec, Columbus, OH, USA).

For the double-leg squat, participants started with each foot on a force platform with two feet approximately shoulder-width apart and looked straight ahead. Participants were instructed to keep the hands at their shoulder height and parallel to the ground throughout the squat (Glave et al., 2012). Participants then squatted as deep as possible and came back to the starting posture with their preferred movement speed (Sigward et al., 2018). This double-leg squat with elevated arm positions was selected because the elevated arm position was shown to increase peak knee flexion angles (Glave et al., 2012). A minimum of one practice and three official trials were performed.

### 2.3. Data reduction

Marker positions and ground reaction force data were filtered via a fourth-order, zero-phase Butterworth filter at a low-pass cut-off of 15 Hz (Kristianslund et al., 2012). The hip joint center was defined as a point located between the two greater trochanters and 23.4% to the ipsilateral greater trochanter (Bennett et al., 2016). The definitions of knee and ankle joint centers, lower extremity segment reference frames, and the calculation of three-dimensional joint angles were previously described (Gorsic et al., 2020). A bottom-up inverse dynamic approach was performed to calculate three-dimensional knee joint resultant moments, which were expressed in the tibia reference frame as internal joint moments (Kingma et al., 1996; Li et al., 2020). Anthropometric information was based on a previous study (de Leva, 1996). VGRF were normalized to body weight, and knee joint moments were normalized to the product of body height and body weight.

Kinetic asymmetry variables include VGRF asymmetries and knee extension moment asymmetries, which were calculated as follows: (non-injured leg - injured leg)/(greater number of the two legs), with positive values indicating greater values on the non-injured leg (Dai et al., 2020). Kinematic variables include medial–lateral shoulder/hip positions and shoulder/hip lateral bending angles (Fig. 1). The medial–lateral shoulder/hip positions were calculated as the distance between the midpoint of the bilateral shoulders/hips and the midpoint of the bilateral ankles projected in the medial–lateral axis. This distance was then normalized to half of the distance between the two ankles, with positive values indicating the midpoint of the shoulders/hips was located closer to the non-injured leg. The shoulder/hip lateral bending angles were calculated between the shoulder/hip vectors and the medial–lateral axis in the frontal plane with positive numbers indicating bending toward the non-injured leg. All kinematic and kinetic variables were extracted at the lowest position of the squat, defined by the mid-point of the two hips. The lowest position was selected because a previous study showed that knee extension moments and bilateral knee moment asymmetries were the greatest at the deepest knee flexion angle during double-leg squats in patients following ACLR (Jean and Chiu, 2020). Data reduction was performed using subroutines developed in MATLAB 2017b (MathWorks, Inc., Natick, MA, USA).

### 2.4. Statistical analysis

Variables were averaged across the three official trials for statistical analyses. Pearson correlation and linear regression analyses were performed between kinetic and kinematic asymmetry variables for both assessments, respectively. As a secondary analysis, independent t-tests were performed between the first and second assessments for kinematic and kinetic variables to identify potential changes as a function of time. The Benjamini-Hochberg procedure was applied to all the Pearson correlation analyses and independent t-tests to control the study-wide false discovery rate at 0.05 (Benjamini and Hochberg, 1995). Pearson correlation coefficients were considered "weak" (<0.3), "moderate"

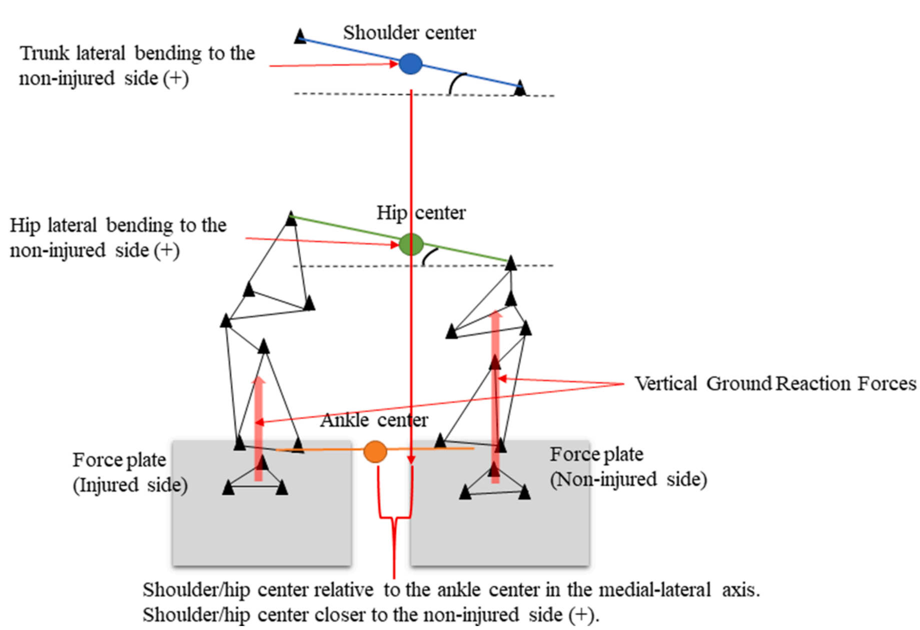


**Fig. 1.** Posterior view of the squat and description of dependent variables.

(0.3–0.5), or "strong" (>0.5) (Cohen, 1988). Cohen's d was calculated to evaluate the effect size of t-tests, which were considered "small" (<0.5), "medium" (0.5–0.8), and "large" (>0.8) (Cohen, 1988). Statistical analyses were conducted using the IBM SPSS Statistics 22 software (IBM Corporation, Armonk, NY, USA).

## 3. Results

The largest p-value for statistical significance was 0.018 after the adjustment for the false discovery rate. Shoulder position strongly and significantly correlated with VGRF asymmetries at both assessments (Table 2). Hip position strongly and significantly correlated with VGRF asymmetries and knee moment asymmetries at both assessments (Fig. 2). The regression lines nearly passed the origin for VGRF asymmetries but had positive intercepts for knee moment asymmetries (Fig. 2). No significant correlations were observed for shoulder and hip lateral bending angles. Additionally, participants demonstrated decreased VGRF asymmetries and knee moment asymmetries, more neutral shoulder and hip positions, and increased knee moments for the injured leg at the second assessment compared to the first assessment with large effect sizes (Table 3).

## 4. Discussion

Regarding the primary purpose, the findings support that medial–-lateral hip positions strongly correlated with VGRF and knee moment asymmetries at both assessments, while shoulder positions strongly correlated with VGRF asymmetries at both assessments. Previous studies have shown that bilateral VGRF asymmetries contributed to bilateral knee moment asymmetries during squats (Chan and Sigward, 2020; Sigward et al., 2018). Bilateral squats involved relatively slow and balanced movements, so the person had minimal whole-body rotation in the frontal plane. The COM was located closer to the side with greater VGRF and further away from the side with less VGRF to result in minimal whole-body resultant moments in the frontal plane. The shifted COM toward the uninjured leg reflected the self-selected strategy to unload the injured leg. The midpoint of the hips was likely located closer to the whole-body COM than the shoulders. Moving the hips could more effectively shift the whole-body COM since it would have a direct effect on the mass above the hips, which composed nearly 60% of the whole-body mass. As such, the hip positions demonstrated stronger correlations with VGRF and knee moment asymmetries compared to shoulder positions. Shoulder and hip lateral bending could also affect the whole-body COM, but these strategies did not appear to be used based on the close to zero bending angles and a lack of significant correlations. Lateral bending is more likely to be self-perceived and detected by rehabilitation specialists than medial–lateral hip and shoulder movements. As such, participants might have self-corrected or been instructed to maintain a straight trunk during squatting exercises. The current findings were aligned with a previous study showing the movement of hip positions was the primary strategy to shift the COP during asymmetric lifting tasks in expert workers (Jeong et al., 2016). The current results also suggested that previous findings of increased knee moments for the injured leg by raising up the non-injured leg during double-leg squats were likely due to the shifted hip and COM toward the injured leg (Jean and Chiu, 2020). In summary, medial–lateral hip positions appeared to be the most sensitive variable to correlate and predict VGRF and knee moment asymmetries during double-leg squats in collegiate athletes following ACLR.

The intercepts of the regression lines to predict kinetic asymmetries from hip positions provided further insight into the contributing factors to the kinetic asymmetries. For the VGRF asymmetry predictions, the intercepts were nearly 0, suggesting balanced VGRF between the two legs when the mid-point of the hips was right above the mid-point of the ankles. This close-to-zero intercept again supported that the midpoint of the hips gave a good representation of the whole-body COM. Furthermore, the predictions for knee moment asymmetries had positive intercepts, indicating greater knee moments for the non-injured side despite symmetric VGRF. Mechanically speaking, knee moments were primarily determined by the VGRF and the perpendicular distance between the knee joint and the VGRF vector. A more anteriorly located COP was likely to decrease the distance between the VGRF and the knee but increase the distance between the VGRF and the hip. In fact, previous studies have found that the injured leg had a more anterior COP and an increased hip to knee moment ratio during double-leg squats (Chan and Sigward, 2020; Sigward et al., 2018). In addition to VGRF asymmetries, the anterior-posterior COP location or hip to knee moment ratio was another significant contributor to knee moment asymmetries. Consequently, patients could achieve symmetric VGRF but still demonstrate asymmetric knee moments during double-leg squat, as shown in a previous study (Salem et al., 2003) and the current findings at the second assessment. In summary, while VGRF symmetries were expected with a neutral medial–lateral hip position, knee moment asymmetries could still exist due to the shift of the COP in the sagittal plane. Additional measurements such as the COP locations and sagittal plane squat motion might be needed along with medial–lateral hip positions to accurately predict 0% of knee moment asymmetries.

Regarding the secondary purpose, the findings supported that the medial–lateral shoulder and hip positions would be more neutral, and the kinetic asymmetries would decrease at the second assessment compared to the first assessment. The decreased kinetic asymmetries were primarily because of the increased values for the injured leg. The non-significant changes in knee flexion angles suggested similar squat depths between the two assessments. Previous studies have documented decreased VGRF and knee moments for the injured leg in double-leg squats in patients between several months and several years following ACLR (Chan and Sigward, 2020; Roos et al., 2014; Sanford et al., 2016; Webster et al., 2015), while fewer studies have evaluated the changes in kinetic asymmetries over time (Neitzel et al., 2002; Sigward et al., 2018). Sigward et al. (2018) did not observe significant changes in peak knee flexion, knee extension moments, or VGRF for both legs between the 3-month and 5-month assessments post ACLR. Neitzel et al. (2002) observed that the bilateral force asymmetries were greater during weighted double-leg squats for patients 1.5–4 months post ACLR and patients 6–7 months post ACLR compared to the control group, while patients 12–15 months post ACLR did not significantly differ from the control group. In the current study, kinetic asymmetries decreased between approximately three months and nine months following ACLR. The lack of consistent changes in kinetic asymmetries as a function of time in the current and previous studies highlighted that time alone was not likely a sufficient indicator of kinetic symmetries during double-leg squats. The current study included collegiate athletes who were highly motivated to perform rehabilitation protocols, which might contribute to the general improvements of kinetic symmetries. Additionally, a

**Table 2**
Coefficients of correlation (p values) between kinetic and kinematic asymmetries at the first and second assessments.

| | | Shoulder Position | Hip Position | Shoulder Lateral Bending Angle | Hip Lateral Bending Angle |
|---|---|---|---|---|---|
| Ground Reaction Force Asymmetry | First Assessment | 0.85 (**<0.001**) | 0.85 (**<0.001**) | 0.13 (0.66) | 0.26 (0.35) |
| | Second Assessment | 0.68 (**0.007**) | 0.72 (**0.004**) | −0.36 (0.21) | 0.39 (0.17) |
| Knee Moment Asymmetry | First Assessment | 0.58 (0.025) | 0.85 (**<0.001**) | −0.02 (0.93) | 0.14 (0.61) |
| | Second Assessment | 0.34 (0.23) | 0.62 (**0.018**) | −0.55 (0.043) | 0.48 (0.08) |

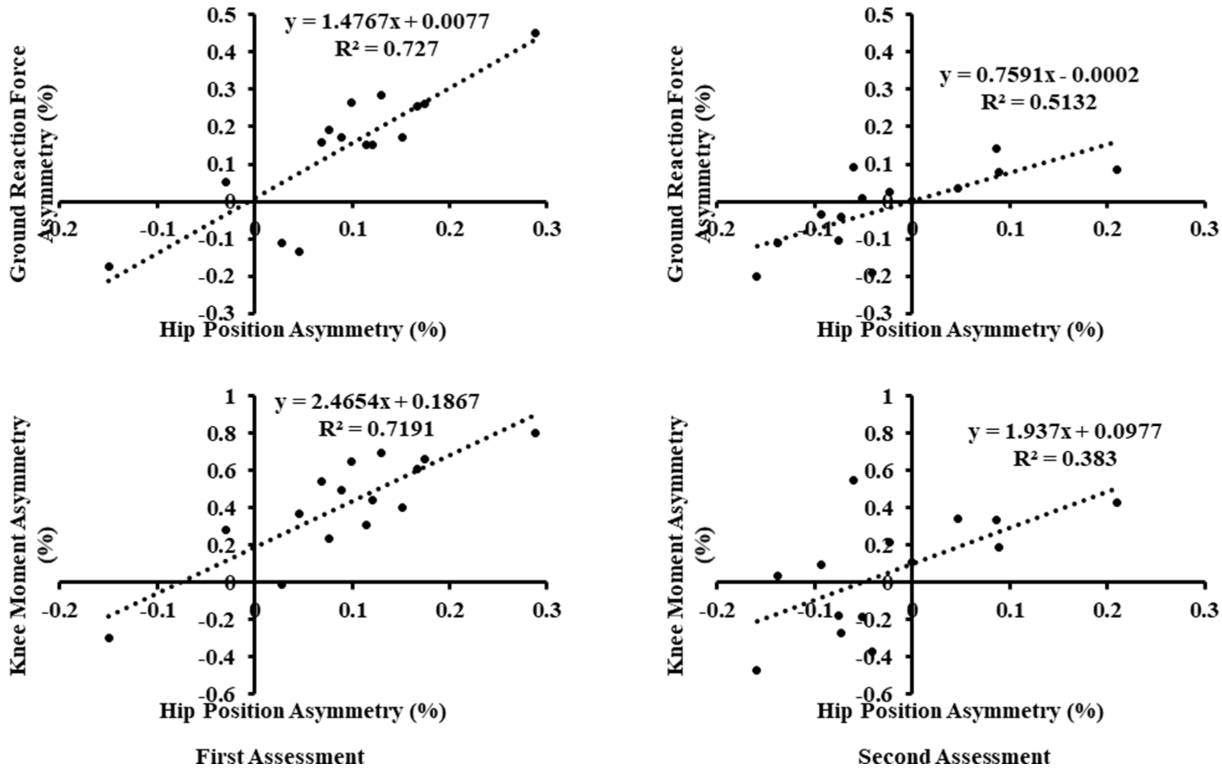


**Fig. 2.** Relationships between hip positions and bilateral vertical ground reaction force and knee moment asymmetries at two assessments.

**Table 3**
Means ± standard deviations of kinematic and kinetic variables and effect sizes (Cohen's d) and p values of independent t-tests between two assessments.

| | First Assessment | Second Assessment | Cohen's d (p values) |
|---|---|---|---|
| Ground Reaction Force Asymmetry (%) | 0.14 ± 0.17 | −0.02 ± 0.11 | **1.10 (0.006)** |
| Knee Extension Moment Asymmetry (%) | 0.41 ± 0.29 | 0.06 ± 0.31 | **1.18 (0.004)** |
| Shoulder Position (%) | 0.06 ± 0.12 | −0.06 ± 0.09 | **1.07 (0.008)** |
| Hip Position (%) | 0.09 ± 0.10 | −0.02 ± 0.09 | **1.16 (0.005)** |
| Shoulder Lateral Bending Angle (deg) | 1.3 ± 2.6 | −0.12 ± 1.8 | 0.64 (0.10) |
| Hip Lateral Bending Angle (deg) | 0.9 ± 2.4 | −0.7 ± 2.6 | 0.64 (0.10) |
| Non-injured Side Ground Reaction Force (Body Weight) | 0.63 ± 0.12 | 0.61 ± 0.11 | 0.18 (0.62) |
| Injured Side Ground Reaction Force (Body Weight) | 0.54 ± 0.12 | 0.62 ± 0.10 | 0.77 (0.05) |
| Non-injured Side Knee Extension Moment (Body Weight * Body Height) | 0.05 ± 0.02 | 0.04 ± 0.01 | 0.66 (0.09) |
| Injured Side Knee Extension Moment (Body Weight * Body Height) | 0.026 ± 0.010 | 0.035 ± 0.007 | **1.06 (0.008)** |
| Non-injured Side Knee Flexion Angle (deg) | 103.2 ± 14.8 | 101.8 ± 10.3 | 0.10 (0.78) |
| Injured Side Knee Flexion Angle (deg) | 101.8 ± 14.4 | 102.3 ± 11.1 | 0.04 (0.92) |

portion of athletes still demonstrated significant VGRF and knee moment asymmetries at the second assessment, indicating the importance of objective assessments for each patient. Meanwhile, medial–-lateral hip positions demonstrated significant changes along with the changes in kinetic asymmetries and showed strong correlations with kinetic asymmetries at both assessments. These findings further support the feasibility of using the hip position to predict kinetic asymmetries during various phases of the rehabilitation with different magnitudes of kinetic asymmetries.

The current study has several practical implications. First, kinetic asymmetries generally decreased during double-leg squats between the two assessments. However, kinetics asymmetries, particularly knee moment asymmetric, still existed for a portion of athletes. The bilateral asymmetries strongly support the need for an individual approach for kinetic asymmetry assessments in contrast to using time alone to guide the rehabilitation process. Second, the current findings suggested that medial–lateral hip positions could be used to predict VGRF and knee moment asymmetries. Compared to a pair of force platforms and synchronized motion capture systems, a commercially available camera can be used as a low-cost and convenient tool to monitor bilateral kinetic asymmetries during double-leg squats in patients following ACLR. However, it should be noted that a neutral hip position was a good indicator of VGRF symmetries but not necessarily knee moment symmetries. While the hip position might be used to help restore VGRF symmetries during the early phase of rehabilitation, additional measurements such as the anterior-posterior COP locations and sagittal plane squat motion may be needed to determine knee moment symmetries. Third, the cause-effect relationships between the hip positions and kinetic asymmetries were not directly assessed, but the mechanical relationship between them and their consistent changes between the two assessments suggested that real-time feedback of the hip positions might be used as a training strategy to restore kinetic symmetries. This feedback could be provided visually by a screen or a mirror or verbally by the therapists and trainers during double-leg squats.

The current study had several limitations. Firstly, participants had different histories of ACLR, injury mechanisms, and types of grafts, which might have introduced confounding effects on their squat mechanics. Future studies with larger sample sizes and more homogeneous groups with separate sex groups might quantify how these factors might affect squat kinematics and kinetic asymmetries. Second, the current participants were limited to collegiate athletes. Other populations might demonstrate different changes in kinetic asymmetries as a function of time, and their compensation strategy to unload the injured leg might be different. Third, the two assessments were performed within one year following ACLR. A longer follow-up time might provide more information regarding the changes in kinetic asymmetries over time and the sensitivities of the prediction when more athletes demonstrate kinetic symmetries. Last, only the double-leg squat was examined. While double-leg squats are commonly used for training, future studies are warranted to identify kinematic predictors of kinetics asymmetries in athletic maneuvers such as jumping and landing tasks.

In conclusion, medial–lateral hip positions correlated and predicted VGRF and knee moment asymmetries during double-leg squats in collegiate athletes at two assessments (0–6 and 6–12 months) following ACLR. While VGRF symmetries were expected with a neutral medial–-lateral hip position, knee moments asymmetries could still exist due to other factors. The bilateral asymmetries support the need for an individual approach for kinetic asymmetry assessments. A commercially available camera can be utilized as a low-cost and convenient tool to monitor and potentially train bilateral kinetic symmetries during double-leg squats in patients following ACLR.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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