MEDIAL-LATERAL HIP POSITIONS PREDICTED KINETIC ASYMMETRIES DURING BILATERAL SQUATS IN COLLEGIATE ATHLETES FOLLOWING ACLR

Yu Song[1], Ling Li[1], Elizabeth E. Albrandt[1], Boyi Dai[1]

[1]Division of Kinesiology and Health, University of Wyoming, Laramie, WY, USA

Anterior cruciate ligament (ACL) re-injury rates are high in collegiate athletes, and double-leg squats are commonly used following ACL reconstruction (ACLR). The purpose was to quantify the correlations between the medial-lateral shoulder/hip kinematics and bilateral kinetic asymmetries during double-leg squats in collegiate athletes at two assessments. Seventeen collegiate athletes performed three double-leg squats 0-6 months and/or 6-12 months following ACLR. Medial-lateral shoulder/hip positions and bending angles were calculated. Medial-lateral hip positions were significant and strongly correlated with ground reaction force and knee moment asymmetries. A commercially available camera may be used to capture the frontal plane motion as a low-cost and more convenient tool to monitor bilateral kinetic asymmetries during double-leg squats in patients following ACLR.

KEYWORDS: Kinematics; Kinetics; ACL; Re-injury; Rehabilitation

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). ACL reconstruction (ACLR) and post-surgery rehabilitation are commonly performed to help athletes return to preinjury sports levels and prevent secondary injuries. Bilateral vertical ground reaction force (VGRF) and knee extension moment asymmetries are commonly observed following ACL injury with increased loading to the non-injured leg during double-leg squats (Clark et al., 2014). Such kinetic asymmetries have been identified as a risk factor for ACL re-injury (Paterno et al., 2010). While it is imperative to identify and correct bilateral asymmetries, the standard equipment to quantify bilateral kinetic asymmetries involved force platforms and synchronized force and motion data with an inverse dynamic approach (Chan & Sigward, 2020; Sigward et al., 2018). The logistics of equipment have restricted their applications. Alternative assessments for quantifying kinetic asymmetries are needed. Efforts have been made to predict knee moment asymmetries following ACLR. Previous studies identified that shifting weight distribution in the medial-lateral and anterior-posterior directions could affect the bilateral knee moment asymmetries (Chan & Sigward, 2020; Sigward et al., 2018). As the upper body composed more than half of the body mass (de Leva, 1996) and two feet were fixed to the ground during double-leg squats, the trunk movement became essential in modulating the weight distribution. But whether the kinetic asymmetries could be predicted from trunk movement patterns is still unknown. Jean and Chiu (Jean & Chiu, 2020) found that improved knee extension moments have been observed when elevating the non-injured leg and shifting the centre of mass (COM) towards the injured leg during squats following ACLR. It supports the potential value of predicting bilateral kinetic asymmetries from trunk movements in the medial-lateral direction during squats.

The purpose of the current study was to quantify the correlations between the medial-lateral shoulder/hip positions and lateral bending angles in bilateral VGRF and knee moment asymmetries during double-leg squats in collegiate athletes at 0-6 months (athletes during rehabilitation) and 6-12 months (athletes were returned to sports) following ACLR. It was hypothesized that medial-lateral shoulder/hip positions and lateral bending angles would be strongly correlated with bilateral kinetic asymmetries at both assessments.

METHODS: Based on the coefficient of correlation from a previous study (Chan & Sigward, 2020), the coefficient of correlation of 0.7 is identified between the shoulder/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 collegiate athletes (≥ 18 years) who had an ACLR in the past year participated in the study (age: 20.03 ± 1.29 years, height: 1.80 ± 0.12 m, mass: 82.28 ± 20.14 kg). Twelve of them performed both assessments (0-6 months and 6-12 months following ACLR). Three additional athletes only performed the first assessment, while two additional athletes only performed the second assessment. Three double-leg squats were performed approximately shoulder-width apart and shoulder-height hands parallel to the ground. Participants squatted as deep as possible and came back to the starting posture with their preferred movement speed (Sigward et al., 2018). Twenty-four retroreflective markers were placed on the bony landmarks. Synchronized force and motion data were collected via a pair of force platforms (4060; Bertec, Columbus, OH, USA) and eight infrared cameras (Vicon Motion Systems Ltd, UK).

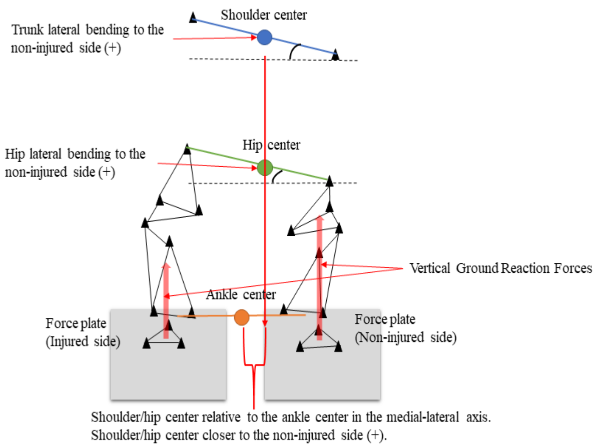

Figure 1: Posterior view of the squat and independent variables

The dependent variables were kinetic asymmetries, including VGRF and knee extension moment asymmetries, which were calculated as follow: (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). The independent variables were kinematic asymmetries, including medial-lateral shoulder/hip positions and lateral bending angles (Figure 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 ankle centres projected in the global medial-lateral axis. This distance was then normalized to half of the distance between the two ankle centres. The shoulder/hip lateral bending angles were calculated between the shoulder/hip vectors and the horizontal axis in the frontal plane. All variables were extracted at the lowest position of the squat, defined by the mid-point of the two hips. Data reduction was performed using subroutines developed in MATLAB 2017b (MathWorks, Inc., Natick, MA, USA).
Pearson correlation analyses were performed between dependent and independent variables for both assessments. The Benjamini-Hochberg was applied to the Pearson correlation analyses to control the study-wide false discovery rate at 0.05. Pearson correlation coefficients were considered “weak,” (< 0.5) “moderate,” (0.5-0.8) or “strong” (> 0.8) (Cohen, 1988).

RESULTS: After the Benjamini-Hochberg adjustment for the false discovery rate, the p-values not greater than 0.018 were considered as statistical significance. Shoulder position strongly and significantly correlated with VGRF asymmetries at both assessments (Table 1). Hip position strongly and significantly correlated with VGRF asymmetries and knee moment asymmetries at both assessments (Figure 2). The regression lines nearly passed the origin for VGRF asymmetries but had positive intercepts for knee moment asymmetries (Figure 2). No significant correlations were observed for shoulder and hip lateral bending angles.

Table 1: Coefficient of correlation (p values) between kinetic and kinematic asymmetries at the first and second assessments.

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

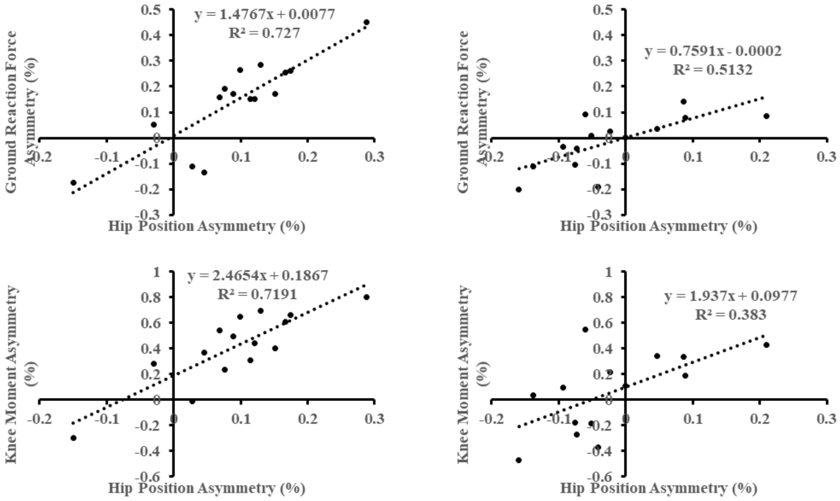

Figure 2: Relationships between hip positions and bilateral ground reaction force and knee moment asymmetries at first (left column) and second (right column) assessments.

DISCUSSION: The results support the hypothesis that medial-lateral shoulder/hip positions would strongly positively correlate with bilateral kinetic asymmetries during double-leg squats in collegiate athletes at two assessments following ACLR. The results do not support the hypothesis that shoulder/hip lateral bending angles correlated with bilateral kinetic asymmetries at both assessments. Previous studies have shown that bilateral VGRF asymmetries contributed to bilateral knee moment asymmetries during squats (Chan & Sigward, 2020; Sigward et al., 2018). Double-leg squats involved relatively slow and balanced movements. 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 medial-lateral direction. The shifted COM toward the non-injured 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 (de Leva, 1996). 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 results suggested that previous findings of increased knee moments for the injured leg by elevating the non-injured leg during squats were likely due to the shifted hip and COM toward the injured leg (Jean & 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. Besides, COM and the centre of pressure (COP) are closely aligned during slow and balanced movements (Caron et al., 2000). A more anteriorly located COP was likely to decrease the distance between the VGRF and the knee but increase the distance between the knee and hip. Previous studies have found that the injured leg had a more anterior COP and an increased hip-knee moment ratio during squats (Chan & Sigward, 2020; Sigward et al., 2018). In addition to VGRF asymmetries, the anterior-posterior COP location or hip-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 squats (Salem et al., 2003). 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.

CONCLUSION: Medial-lateral hip positions could be used to predicted VGRF and knee moment asymmetries. A commercially available camera can be used as a low-cost and convenient tool to monitor bilateral kinetic asymmetries during double-leg squats following ACLR. In addition, the mechanical relationships and consistent changes between hip positions and kinetic asymmetries in 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.

REFERENCES

Caron, O., Gelat, T., Rougier, P., & Blanchi, J. P. (2000). A comparative analysis of the center of gravity and center of pressure trajectory path lengths in standing posture: an estimation of active stiffness. *Journal of Applied Biomechanics, 16*(3), 234-247. 10.1123/jab.16.3.234 [doi]

Chan, M., & Sigward, S. M. (2020). Center of pressure predicts Intra-limb compensatory patterns that shift demands away from knee extensors during squatting. *Journal of Biomechanics, 111*, 110008.

Clark, R. A., Howells, B., Feller, J., Whitehead, T., & Webster, K. E. (2014). Clinic-based assessment of weight-bearing asymmetry during squatting in people with anterior cruciate ligament reconstruction using Nintendo Wii Balance Boards. *Archives of Physical Medicine and Rehabilitation, 95*(6), 1156-1161.

Cohen, J. (1988). *Statistical power analysis for the behavioural sciences*. Lawrence Erlbaum Associates.

Dai, B., Layer, J. S., Bordelon, N. M., Critchley, M. L., LaCroix, S. E., George, A. C., Li, L., Ross, J. D., & Jensen, M. A. (2020). Longitudinal assessments of balance and jump-landing performance before and after anterior cruciate ligament injuries in collegiate athletes. *Research in Sports Medicine,* , 1-12.

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics, 29*(9), 1223-1230. 0021929095001786

Jean, L. M. Y., & Chiu, L. Z. F. (2020). Elevating the Noninvolved Limb Reduces Knee Extensor Asymmetry During Squat Exercise in Persons With Reconstructed Anterior Cruciate Ligament. *Journal of Strength and Conditioning Research, 34*(8), 2120-2127. 10.1519/JSC.0000000000003682 [doi]

Kay, M. C., Register-Mihalik, J. K., Gray, A. D., Djoko, A., Dompier, T. P., & Kerr, Z. Y. (2017). The Epidemiology of Severe Injuries Sustained by National Collegiate Athletic Association Student-Athletes, 2009–2010 Through 2014–2015. *Journal of Athletic Training, 52*(2), 117-128. 10.4085/1062-6050-52.1.01

Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., Huang, B., & Hewett, T. E. (2010). Biomechanical Measures during Landing and Postural Stability Predict Second Anterior Cruciate Ligament Injury after Anterior Cruciate Ligament Reconstruction and Return to Sport. *The American Journal of Sports Medicine, 38*(10), 1968-1978. 10.1177/0363546510376053

Salem, G. J., Salinas, R., & Harding, F. V. (2003). Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction. *Archives of Physical Medicine and Rehabilitation, 84*(8), 1211-1216.

Sigward, S. M., Chan, M. M., Lin, P. E., Almansouri, S. Y., & Pratt, K. A. (2018). Compensatory strategies that reduce knee extensor demand during a bilateral squat change from 3 to 5 months following anterior cruciate ligament reconstruction. *Journal of Orthopaedic & Sports Physical Therapy, 48*(9), 713-718.