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Using trunk kinematics to predict kinetic asymmetries during double-leg jump-landings in collegiate athletes following anterior cruciate ligament reconstruction☆

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A R T I C L E I N F O

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A B S T R A C T

Background: Bilateral vertical ground reaction force (VGRF) and knee extension moment asymmetries are commonly observed during jumping and landing tasks following anterior cruciate ligament (ACL) reconstructions (ACLR) in collegiate athletes. Kinetic asymmetries during landings are associated with increased ACL re-injury risk. Efforts have been made to predict bilateral kinetic asymmetries using trunk kinematics during squats but not during jump-landings.
Research question: To determine the correlations between trunk kinematics (medial-lateral shoulder positions, medial-lateral hip positions, and lateral trunk bending angles) and bilateral kinetic asymmetries (VGRF and knee extension moments) during double-leg jump-landings in collegiate athletes following ACLR.
Methods: Fifteen National Collegiate Athletic Association Division I athletes who had ACLR in the past 24 months participated. Eleven of them performed two assessments over the study period for a total of 26 assessments for data analyses. Athletes performed three double-leg countermovement jumps. Kinematics and kinetics data were collected. Medial-lateral shoulder and hip positions relative to ankle positions, lateral trunk bending angles, and kinetic asymmetries were calculated during the jumping (the lowest hip position until takeoff) and landing (the first 100 ms after initial contact) phases.
Results: Medial-lateral shoulder positions correlated with VGRF ($r = 0.63$, $p < 0.001$) and knee moment asymmetries ($r = 0.53$, $p = 0.006$) in the jumping phase. Medial-lateral hip positions correlated with VGRF ($r = 0.61$, $p < 0.001$; $r = 0.52$, $p = 0.006$) and knee moment asymmetries ($r = 0.55$, $p = 0.004$; $r = 0.61$, $p < 0.001$) in both jumping and landing phases.
Significance: Medial-lateral hip positions correlated with kinetic asymmetries during double-leg jump-landings in collegiate athletes following ACLR. A 2D assessment using a standard video camera might be used as a low-cost and clinically applicable tool to assess bilateral kinetic asymmetries by quantifying medial-lateral hip positions during jump-landings following ACLR.

1. Introduction

Anterior cruciate ligament (ACL) injuries are among the most prevalent severe injuries in National Collegiate Athletic Association (NCAA) athletes [1]. ACL injuries result in a long absence from playing [2], abnormal neuromuscular control [3], deficits in psychological health [4], and increased risks of knee osteoarthritis [5]. ACL reconstructions (ACLR) with post-surgery rehabilitation are a common process to help athletes return to their pre-injury performance level and prevent secondary injuries [6,7]. A study showed that 92% of NCAA athletes were able to return to play following ACLR [2]. However, among the athletes who returned to play, more than 20% of them may sustain ACL re-injuries [8]. Therefore, assessments to effectively monitor the rehabilitation process are needed to minimize the risk factors associated with ACL re-injuries.

Bilateral kinetic asymmetries in vertical ground reaction forces

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(GRF) and knee moments have been observed during jump-landings in individuals following ACLR [3,9,10]. One study has identified bilateral asymmetries in knee extension moments during landings with increased loading on the uninjured leg as a risk factor for future ACL re-injuries [11]. While the ACL is usually torn during the landing phase [12], the jumping phase also contains meaningful information for assessing knee strength and the overall rehabilitation progress [3,10,13,14]. As such, the kinetic asymmetries during both jumping and landing phases can be targeted to improve knee function and movement patterns and potentially reduce ACL re-injury risk. However, the standard equipment to assess the bilateral knee moment asymmetries involves two force platforms and one motion capture system [15]. The synchronized force and motion data, complicated inverse dynamic approach, and equipment cost might restrict their use in a clinical and training environment. Therefore, it is crucial to develop low-cost and clinically applicable assessments for identifying kinetic asymmetries during the jumping and landing phases following ACLR. Such assessments can help monitor post-surgery rehabilitation progress with the goal of decreasing ACL re-injury risk in a clinical and training setting.

Previously, researchers attempted to predict knee moment asymmetries using only force platforms in patients following ACLR. Read et al. (2020) [10] reported that vertical GRF (VGRF) impulse asymmetries during the jumping phase of countermovement jumps (CMJs) were the strongest predictor for ACLR status in patients 3–15 months following ACLR. Dai et al. (2014) [16] demonstrated that VGRF impulse asymmetries predicted 78% and 86% of the variance in the peak and average knee moment asymmetries during the landing phase of stop-jumps in patients 5–7.6 months following ACLR, respectively. Although the force data might be used as a surrogate variable to predict knee moment asymmetries, force platforms are still required. And the use of force platforms might be inconvenient for daily life training settings. It is unknown whether jump-landing kinetic asymmetries could be predicted from motion data alone.

Recently, a study showed that asymmetries in medial-lateral hip positions predicted more than 70% and 38% of the variance in VGRF and knee moment asymmetries during bilateral squats in athletes within 12 months following ACLR, respectively [15]. The authors explained that as the trunk region composed the largest portion of the whole-body mass [17], shifting the hip position to the uninjured leg was used as a compensatory strategy to modulate the whole-body center of mass (COM) to unload the injured leg [15]. Although ACL re-injures are unlikely to occur during squats, kinetic asymmetries in VGRF and knee moments during bilateral squats have been shown to be correlated with kinetic asymmetries in double-leg jump-landings [18]. Therefore, it is speculated that trunk kinematics alone might predict kinetic asymmetries during double-leg jump-landings in athletes following ACLR. Using trunk kinematics to monitor bilateral jump-landing kinetic asymmetries in athletes following ACLR will allow practitioners to apply a 2D assessment using a standard video camera to potentially assess kinetic asymmetries for ACL re-injury risk in a training environment.

Therefore, the purpose of the current study was to determine the correlations between trunk kinematics (medial-lateral shoulder and hip positions and lateral trunk bending angles) and bilateral kinetic asymmetries (VGRF and knee extension moments) during the jumping and landing phases of CMJs in collegiate athletes following ACLR. Based on a previous study [15], it was hypothesized that the medial-lateral shoulder and hip positions would be correlated with and used to predict bilateral kinetic asymmetries in VGRF and knee moments during the jumping and landing phases.

2. Methods

2.1. Participants

Based on a correlation coefficient of 0.62 between medial-lateral hip positions and kinetic asymmetries in squats [15], a sample size of 15 was needed to achieve a power of 0.8 at a type-I error level of 0.05. Fifteen NCAA Division I athletes who had ACLR in the past 24 months participated (Appendixes). Eleven of them performed two assessments over the study period with a sample size of 26 assessments for data analyses to increase the number of samples for analyses (Table 1). The average time between two assessments for these 11 participants was 3.00 ± 1.79 months, which likely resulted in noticeable changes in jump-landing patterns to be considered as two independent assessments [3]. 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 CMJs at the time of testing. This study was approved by the University of Wyoming Institutional Review Board. Participants signed the informed consent form before participation.

2.2. Procedure

Participants wore spandex pants and t-shirts and their athletic shoes or running shoes provided by the laboratory (Ghost 5; Brooks Sports, Bothell, WA, USA). After self-selected warm-up activities, twenty-four retroreflective markers were placed on the participants' bony landmarks [15]. Synchronized three-dimensional coordinates of retroreflective markers and bilateral GRF data were collected using eight infrared cameras (100 Hz, Bonita 10, Vicon Motion Systems Ltd, Oxford, UK) and two force platforms (1000 Hz, 4060; Bertec, Columbus, OH, USA). During the double-leg CMJs tasks, participants were asked to stand with one foot on a force platform, approximately shoulder-width apart. Participants squatted down and then immediately jumped vertically as high as possible with their preferred arm swing motion [3]. During the data collection, at least one practice and three official trials were performed with a minimum of a 15-second break in between two trials.

2.3. Data analysis

A fourth-order, zero-phase Butterworth filter at a low-pass cut-off of 15 Hz was used to filter the marker coordinates and GRF data. The same cut-off frequency of 15 Hz for both markers and GRF data was recommended by a previous study [19]. The cut-off frequency was also consistent with other jump-landing and ACL injury risk studies [20,21]. The hip joint center was defined as a point located on the line between the two greater trochanters. The distance between the hip center and the ipsilateral greater trochanter was 23.4% of the inter-trochanter distance [22]. The definitions of knee and ankle joint centers, segment reference

Table 1
Participants' characteristics across 26 assessments (means ± standard deviations).

	The Time of Testing
Sex#	9 men, 6 women
Age (years)	20.4 ± 1.4
Body Height (m)	1.80 ± 0.11
Body Mass (kg)	81.8 ± 17.8
Injury Side#	3 right legs, 12 left legs
Injury Mechanisms# [14]	6 non-contacts, 5 indirect contacts, 4 direct contacts
Days Between ACL Injury and ACLR#	23.4 ± 18.2
Months Following ACLR	8.3 ± 2.6
Surgery Types#	12 patellar tendon grafts, 3 hamstring grafts
Concurrent Injuries#	11 meniscus repairs, 2 medial collateral ligament reconstructions, 1 lateral collateral ligament reconstruction
Sports#	five men's American football, three men's wrestling, three women's soccer, two women's basketball, one men's basketball, one women's volleyball
Injury Histories (previous ACLR)#	2 to the contralateral leg, 2 to the ipsilateral leg, 1 to each leg

Note: ACL: anterior cruciate ligament; ALCR: anterior cruciate ligament reconstruction; #: the information based on a sample size of 15 participants.

frames, and the calculation of internal knee extension moments using a bottom-up inverse dynamic approach have been previously described [15]. VGRF was normalized using body weight, and knee moments were normalized using the product of body height and body weight.

The kinetic asymmetries included peak VGRF and knee extension moment asymmetries ((uninjured leg – injured leg)/larger value of the two legs), with positive values indicating greater numbers on the uninjured leg [3]. A 0% asymmetry indicated equal magnitudes between legs, while a 100% asymmetry indicated the forces and moments were generated only by the uninjured leg. The trunk kinematic asymmetries included medial-lateral shoulder positions, hip positions, and lateral trunk bending angles (Fig. 1). The medial-lateral shoulder and hip positions relative to the ankle centers were calculated with a positive number indicating the shoulder and hip centers were located closer to the uninjured leg [15]. A 0% distance indicated the midpoint of the bilateral shoulders and hips was located above the midpoint of the bilateral ankle centers. A 100% distance indicated the midpoint of the bilateral shoulders and hips was located above the ankle center of the uninjured leg. The lateral trunk bending angle was calculated as the vector connected between midpoints of the bilateral shoulders and hips relative to the vertical axis in the frontal plane, with positive numbers indicating lateral bending to the uninjured leg. The jumping phase of CMJs was defined as the lowest hip position until takeoff, and the landing phase of CMJs was defined as the first 100 ms after initial contact [3]. All trunk kinematic asymmetry variables were calculated as the average value of the jumping or landing phase to represent the general movement pattern. Data reduction was performed in MATLAB 2017b (MathWorks, Inc., Natick, MA, USA).

2.4. Statistical analysis

The average of kinematic and kinetic variables among three official trials was calculated for statistical analyses using the SPSS Statistics 22 software (IBM Corporation, Armonk, NY, USA). Pearson correlation and linear regression analyses were performed between trunk kinematic and kinetic asymmetry variables. The Benjamini-Hochberg procedure was applied to all the Pearson correlation analyses to control the study-wide false discovery rate at 0.05 [23]. Correlation coefficients smaller than 0.3, between 0.3 and 0.5, and greater than 0.5 were considered weak, moderate, and strong, respectively [24].

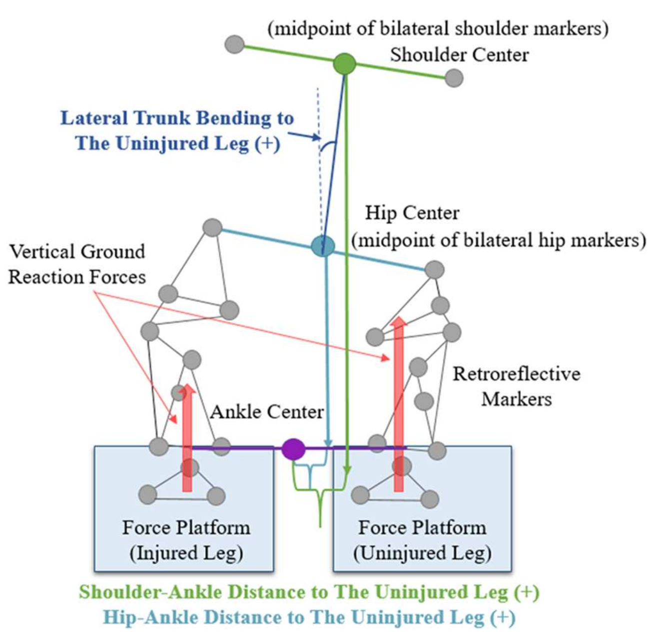

Fig. 1. Posterior view of the double-leg countermovement jump and description of trunk kinematic variables.

3. Results

The descriptive results (mean ± standard deviations) of trunk kinematics and kinetic asymmetry variables during the jumping and landing phases among participants are shown in Table 2. The largest p-value after the Benjamini-Hochberg procedure was 0.006 for statistical significance. Shoulder positions significantly correlated with peak VGRF ($r = 0.63$, $p < 0.001$) and knee extension moment ($r = 0.53$, $p = 0.006$) asymmetries in the jumping phase. Hip positions significantly correlated with peak VGRF ($r = 0.61$, $p < 0.001$; $r = 0.52$, $p = 0.006$) and knee extension moment ($r = 0.55$, $p = 0.004$; $r = 0.61$, $p < 0.001$) asymmetries in both jumping and landing phases, respectively. These significant correlations were considered between moderate and strong. The regression models between hip positions and bilateral kinetic asymmetries are reported in Fig. 2. No significant correlations were found between lateral trunk bending angles and kinetic asymmetries (Table 3).

4. Discussion

The purpose of this study was to determine the correlations between trunk kinematics (including medial-lateral shoulder and hip positions and lateral trunk bending angles) and bilateral kinetic asymmetries (VGRF and knee extension moments) during jumping and landing phases of CMJs in collegiate athletes following ACLR. More than 10% of bilateral VGRF asymmetries and approximately 30% of knee moment asymmetries were found during the jumping and landing phases of CMJs, with greater asymmetries shown in the landing phase compared to the jumping phase. Bilateral kinetic asymmetries in VGRF and knee moments are commonly observed in patients following ACLR with increased loading to the uninjured leg during the jumping and landing phases [3,10,13]. Decreased forces and knee moments of the injured leg during jumping are associated with decreased knee strength [13,14,25]. The increased knee moment asymmetry during landing has been identified as a risk factor for ACL re-injuries [11]. The current findings showed that more than 10% of bilateral kinetic asymmetries, particularly knee moment asymmetries, were observed during jump-landings in collegiate athletes following ACLR. The increased bilateral kinetic asymmetries might increase athletes' re-injury risk if they are not identified and corrected during the rehabilitation process prior to athletes' return to play.

The results supported the hypothesis that the medial-lateral hip position would correlate with VGRF and knee moment asymmetries during the jumping and landing phases. The results partially supported the hypothesis that the medial-lateral shoulder position would correlate with VGRF and knee moment asymmetries during the jumping phase. Knee moment asymmetries may result from the asymmetric VGRF and the redistribution of hip and knee moment ratio for the injured leg [26–28], while the asymmetric VGRF might result from the shifted whole-body COM [15]. As the trunk region is composed of more than half of the body mass [17], medial-lateral movements of the hip may move most body mass above the hip in the same direction. Moving the hip position laterally to the uninjured leg could be a compensatory strategy to move COM closer to the uninjured leg. On the other hand,

Table 2
Descriptive data (mean ± standard deviations) of trunk kinematics and kinetic asymmetry variables during the jumping and landing phases across 26 assessments (n = 26).

	Jumping Phase	Landing Phase
Medial-lateral Shoulder Position (%)	3.3 ± 8.6	5.5 ± 12.3
Medial-lateral Hip Position (%)	7.9 ± 9.1	6.0 ± 8.5
Lateral Trunk Bending angles (°)	-1.2 ± 2.8	-0.1 ± 2.2
Vertical Ground Reaction Force Asymmetries (%)	13.7 ± 7.3	19.6 ± 17.3
Knee Extension Moment Asymmetries (%)	29.7 ± 25.1	31.3 ± 24.8

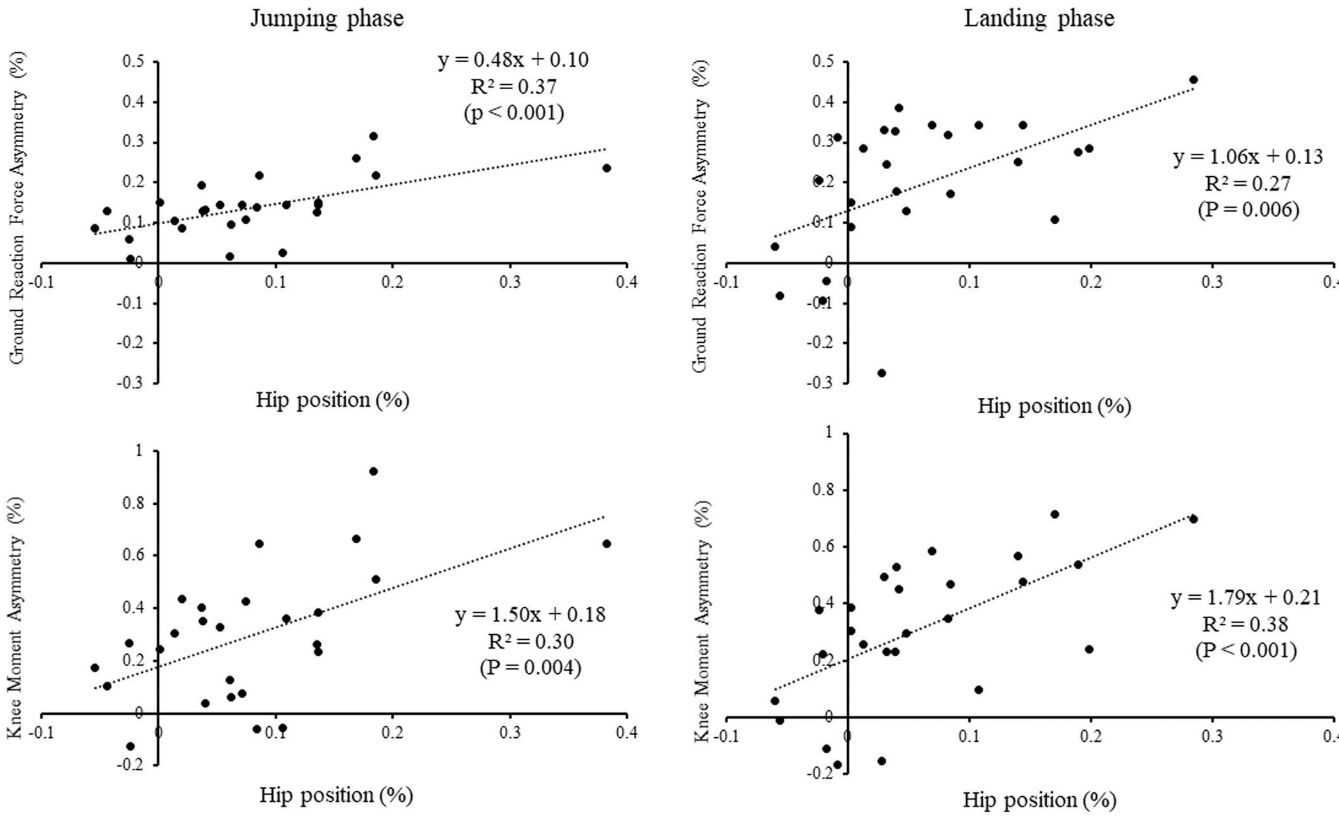

Fig. 2. Relationships between hip positions and bilateral vertical ground reaction force and knee moment asymmetries during the jumping and landing phases of double-leg countermovement jump.

Table 3
Coefficients of correlation (p-values) between kinematic and kinetic asymmetry variables during the jumping and landing phases across 26 assessments (n = 26).

		Shoulder Position	Hip Position	Lateral Trunk Bending Angle
Vertical Ground Reaction Force Asymmetries	Jumping Phase	**0.63 (<0.001)**	**0.61 (<0.001)**	-0.01 (0.972)
	Landing Phase	0.31 (0.123)	**0.52 (0.006)**	-0.02 (0.931)
Knee Moment Asymmetries	Jumping Phase	**0.53 (0.006)**	**0.55 (0.004)**	-0.02 (0.907)
	Landing Phase	0.30 (0.136)	**0.61 (<0.001)**	-0.10 (0.639)

moving the medial-lateral shoulder position might not be as effective in moving the whole-body COM compared to moving the medial-lateral hip position. Therefore, the hip positions showed the strongest correlations with VGRF and knee moment asymmetries during both the jumping and landing phases of CMJs. These findings were consistent with medial-lateral hip shifting as the primary strategy to unload the injured leg during bilateral squats following ACLR [15]. Meanwhile, the results did not show significant correlations between lateral trunk bending angles and bilateral kinetic asymmetries during the jumping and landing phases of CMJs. The lateral trunk bending angles observed in this study was around one degree, suggesting that patients did not use lateral trunk bending as a compensatory strategy to unload the injured leg. One possible reason might be that patients were instructed to minimize trunk lateral leaning in jump-landings during post-surgery rehabilitation. In summary, the medial-lateral hip position showed the strongest correlations with VGRF and knee moment asymmetries during both the jumping and landing phases of double-leg CMJs in collegiate athletes following ACLR.

The R-Squared (variance being explained) of the prediction between hip positions and kinetic asymmetries during double-leg jump-landings was between 27% and 38% in the current study. The R-Squared appeared to be less than the R-Squared (38%–72%) during double-leg squats observed in a previous study [15]. The squat had relatively slow and balanced movements, which allowed the COM and COP to be closely aligned with each other [15]. On the other hand, for the jumping phase, the hip positions may not represent the COM as accurately as the squat due to the fast movements of other body segments [26]. As such, the hip position may not closely align with the COP during jumping compared to the squat. Also, participants might take off with a certain amount of body lateral bending in the frontal plane. Additionally, possible compensatory strategies may happen during the mid-flight. Participants could land with the uninjured leg first to unload the injured leg, resulting in greater kinetics asymmetries. Therefore, the medial-lateral hip positions had less strength in predicting kinetic asymmetries during jump-landings compared to squatting.

The intercepts of the regression lines for predicting kinetic asymmetries also provided meaningful information to further understand the results. The positive intercepts (10%–20%) between hip position and bilateral kinetic asymmetries indicate that a neutral hip position (0%) could not guarantee symmetrical VGRF and knee moment between legs during jumping and landing. These findings further supported additional factors other than the hip positions that could contribute to the kinetic asymmetries. A more anteriorly located COP could result in a smaller knee moment and greater hip moment and contribute to knee moment asymmetries in addition to medial-lateral hip positions [27]. Sharafoddin-Shirazi et al. [28] reported that the hip extension moment was greater for the injured leg than the uninjured leg of athletes following ACLR. Meanwhile, the knee extension moment of the injured leg was smaller compared to the uninjured leg. Therefore, redistributing joint moments through modulating COP locations was another self-selected compensatory strategy to unload the injured knee following

ACLR. Although such a compensatory strategy could not be fully detected by medial-lateral hip positions, the medial-lateral hip position might be an easy-to-use tool to monitor bilateral kinetic asymmetries in a clinical and training setting during the early phase following ACLR.

Several practical implications can be made based on the current findings. Medial-lateral hip positions might be used to identify kinetic asymmetries in VGRF and knee moments during double-leg jump-landings. Compared to standard equipment, a 2D assessment using a standard video camera might be an option to use as an easy-to-use and low-cost tool to quantify hip positions to monitor the bilateral kinetic asymmetries in a clinical and training setting, particularly during the early phase of post-ACLR rehabilitation when athletes demonstrate great asymmetries. However, more evidence is needed to support the use of a 2D assessment. In addition, the 27%–38% predictive value of hip positions suggested additional assessments such as anterior-posterior COP locations, hip positions in the sagittal plane, and timing of landing are needed to better determine kinetic asymmetries when the asymmetries become less in laboratory testing. Furthermore, if the medial-lateral hip position can be quantified in real-time such as visual biofeedback [29], the feedback regarding hip positions might be used in training to decrease kinetic symmetries in athletes following ACLR.

Several limitations exist in the current study. First, the statistical analysis was conducted with a sample size of 26 assessments from 15 participants within two years following ACLR. Eleven of the participants performed two assessments, which might create a bias in the data analysis. However, statistical analyses with 15 participants' first assessments showed similar results (Appendixes). Second, sexes, ACLR histories, injury mechanisms, and types of grafts might affect the jump-landing mechanics. A more homogeneous group with a greater sample size is needed in the future. Third, the current study recruited collegiate athletes. Patients from other populations might demonstrate different compensatory strategies and warrant further investigation. Fourth, the kinetic asymmetries were assessed in double-leg vertical CMJs. Future studies might consider drop-landing and medial-lateral landing tasks. Fifth, kinetic asymmetries were extracted as peak values, while kinematic asymmetries represented the average values during the jumping and landing phases. Continuous data analyses might be performed to reveal more information during the entire jumping and landing phases in future studies. Last, a control group without ACLR was not included. Previous studies have shown that uninjured NCAA athletes mostly demonstrate less than 10% peak jumping VGRF asymmetries [30]. Future studies are needed to quantify the relationships between trunk kinematics and bilateral kinetic asymmetries in uninjured populations.

5. Conclusion

Medial-lateral hip positions correlated and predicted 27%–38% of the variance in VGRF and knee moment asymmetries during the jumping and landing phases of double-leg jump-landings in collegiate athletes following ACLR. A 2D assessment using a standard video camera might be used as a low-cost and clinically applicable tool to quantify the medial-lateral hip positions to assess bilateral kinetic symmetries during jump-landings in athletes following ACLR, particularly during the early phase of post-ACLR rehabilitation when athletes demonstrate great asymmetries.

Ethical approval

The current study was approved by the University of Wyoming Institutional Review Board (Protocol #20160202BD01031). The University of Wyoming's agreement to abide by The Belmont Report and 45 C.F.R. Part 46 is approved by the federal agency that oversees ethical issues in human research.

Conflict of interest statement

The authors have no financial or personal conflicts of interest to declare.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2023.03.003.

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