Original Research

Hop Distance Symmetry Moderately Reflects Knee Biomechanics Symmetry During Landing But Not For Controlled Propulsions

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Background

Landing with poor knee sagittal plane biomechanics has been identified as a risk factor for Anterior Cruciate Ligament (ACL) injury. However, it is unclear if the horizontal hop test battery reflects knee function and biomechanics.

Hypothesis/Purpose

To investigate the correlation between clinical limb symmetry index (LSI) and landing and propulsion knee biomechanics during the hop test battery using markerless motion capture.

Study Design

Cross-sectional biomechanics laboratory study

Methods

Forty-two participants with and without knee surgery (age 28.0 ± 8.0 years) performed the hop test battery which consisted of a single hop for distance, crossover hop, triple hop, and 6-m timed hop in the order listed. Eight high speed cameras were used to collect simultaneous 3D motion data and Theia 3D (Theia Markerless Inc.) was used to generate 3D body model files. Lower limb joint kinematics were calculated in Visual3D. Correlation (Spearman's ρ) was computed between clinical LSI and symmetry in peak and initial contact (IC) knee flexion angle during propulsion and landing phases of each movement.

Results

In the single hop, clinical LSI showed positive correlation with kinematic LSI at peak landing ($\rho = 0.39$, $p=0.011$), but no correlation at peak propulsion ($\rho = -0.03$, $p=0.851$). In the crossover hop, non-significant correlations were found in both propulsion and landing. In the triple hop, positive correlation was found at peak propulsion ($\rho = 0.38$, $p=0.027$), peak landing ($\rho = 0.48 – 0.66$, $p<0.001$), and last landing IC ($\rho = 0.45$, $p=0.009$). In the timed hop, peak propulsion showed positive correlation ($\rho = 0.51$, $p=0.003$).

Conclusions

Single hop and triple hop distance symmetry reflected landing biomechanical symmetry better than propulsion symmetry. Poor scores on the hop test battery reflect

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asymmetrical knee landing biomechanics, emphasizing the importance of continuing to use the hop test battery as part of clinical decision making.

Level of Evidence

3b

INTRODUCTION

Limb symmetry index (LSI) from the horizontal hop test battery[1] is widely used by clinicians for return to sport (RTS) decision making after knee, and particularly anterior cruciate ligament (ACL), injury.[2,3] The battery involves four single-leg hop tests: single hop for distance (SLH), crossover hop for distance (COH), triple hop for distance (TRH), and timed 6-meter hop (TIH). The hops for distance must be completed with a controlled landing for the distance score to count. With the advancement of technology (e.g., motion capture, inertial measurement units, force plates), biomechanical data during athletic maneuvers, such as the hops, are becoming more available in clinical practice and may ultimately guide better care.[4,5] Landing with poor knee sagittal plane biomechanics has been identified as a part of the ACL injury mechanism in several sports.[6-8] It is unclear, however, if the more easily and commonly implemented hop test battery reflects knee function and biomechanics.

Researchers have suggested that horizontal hop distance poorly reflects propulsion (e.g., take-off) knee biomechanics, but rather captures a greater degree of involvement from the ankle and hip joint.[9] Some researchers also advocate using the vertical hop test as a better indicator of biomechanical deficits, as there is a higher knee contribution during a vertical hop compared to a horizontal hop.[9,10] These studies, however, mostly investigate vertical hop propulsive phase, while non-contact ACL injuries almost always occur during landing.[6] While performance in vertical hop may capture an athlete's ability to move faster and further, it does not capture the athlete's ability to land safely after the maneuver is complete. Moreover, there has been no evidence to date quantifying the influence of vertical hop performance on secondary injury. Moderate evidence does exist for including the horizontal hop tests as part of a test battery for secondary injury reduction.[11,12]

Clinically, while the use of these tests assumes that scores in the horizontal hop test battery captures the ability for an athlete to land, no work has quantified the LSI scores obtained during the hop test battery and compared it to propulsion and landing biomechanics symmetry. Thus, whether the current performance metrics are related to propulsion and/or landing biomechanical asymmetries are unknown.

The present study aimed to investigate the potential correlation between horizontal hop test battery LSI and sagittal plane knee kinematics during propulsion and landing using markerless motion capture technology. It was hypothesized that hop battery LSI and kinematics would correlate better during the hop landing phase compared to propulsion phase. Ultimately, this is an investigation of the validity of the horizontal hop test battery symmetry outcome as described by Noyes and colleagues[1] against a 3D biomechanics symmetry outcome measure. In addition, this is the first study, to the authors' knowledge, that has investigated biomechanics during the hop test battery without impeding with participant attire/movement by attaching retroreflective markers or IMUs.

MATERIALS AND METHODS

Written informed consent was received from all participants before inclusion and all study procedures were approved by the University of Delaware Institutional Review Board (n. 1770974-3).

PARTICIPANTS

Forty-two participants (n=12) with and (n=30) without previous lower extremity surgery were recruited for the study (Table 1). Patients without injury were included to ensure a range of values for the correlational analysis. Participants with previous knee surgery had been cleared to return to sport and/or activity by a qualified healthcare provider (average time from surgery: 81.9 ± 43.2 months, minimum 42 months).

DATA COLLECTION

Participants provided basic demographic information and surgery/injury history, in addition to completing questionnaires that assessed physical activity levels (Physical Activity Scale [PAS], Marx Activity Rating Scale [MARS]), and Patient-Reported Outcomes Measurement Information System [PROMIS]).

Participants performed a five-minute warm-up on a treadmill at a comfortable pace prior to testing. Each participant performed the hop test battery which consisted of a SLH, COH, TRH, and TIH in the order listed.[1] Participants were asked to hop as far as possible (or as fast as possible for the TIH), starting with their toes behind a marked point on the ground. Two practice trials preceded two successful hop trials. As is the practice in the authors' clinics and laboratory since 1991, hops for distance were only considered valid if participants were able to maintain their landing posture (at last landing) without shifting the foot from the initial landing position, excessive leaning of the trunk or arms, and were able to be determined to have complete control over their body as determined by the physical therapist in charge.[1] If a hop was deemed invalid, participants repeated the hop until a successful trial was achieved. Participants were provided as much rest as desired between hop trials. Hops were performed first on the uninvolved limb then involved limb. The involved limb was defined as the non-dominant limb for participants without previous injury. The dominant limb was defined as the pre-

Table 1. Participants demographics.

	All	Knee surgery	Healthy	p-value
Population (Non-injured:injury history) [a]	30:12			
Age (years)	28.0 ± 8.0	30.4 ± 9.3	27.1 ± 7.4	0.282
Sex (male:female)	20:22	5:7	15:15	0.738
Weight (kg)	72.5 ± 12.0	72.7 ± 11.5	72.4 ± 12.4	0.942
Height (m)	1.7 ± 1.0	1.7 ± 0.9	1.7 ± 1.0	0.699
Time from surgery (years) [b]		6.9 ± 3.6		
PAS score (pt)	4.9 ± 1.1	5.3 ± 0.8	4.7 ± 1.2	0.043
Marx score (pt)	6.6 ± 3.6	6.5 ± 2.9	6.6 ± 3.9	0.904
PROMIS Pain Interference score (pt)	42.4 ± 5.8	44.6 ± 6.5	41.5 ± 5.3	0.119
PROMIS Physical Function score (pt)	60.0 ± 6.0	59.3 ± 6.6	60.3 ± 5.9	0.639

Note: Data are presented as mean ± standard deviation or number and frequency; involved limb: non-dominant (healthy participants), surgical (knee surgery participants). a. Injury history included ACL reconstructive surgery (n=7), any other knee surgery (n=5). b. time from surgery is intended for knee surgery participants only.

ferred leg to kick a ball.[13] Starting position of the toe and landing position of the heel over the tape measure on the ground was used to measure the distance hopped. A stopwatch was used to measure time from heel lift to when the participants center of mass crossed the six-meter line. The two successful hop trials were used for data processing and analysis. Eight high speed cameras (Sony RX0-II, Sony Corp., Minato, Japan, 120Hz) were used to collect simultaneous three-dimensional (3D) motion data. All hop tests were administered by a licensed PT.

DATA PROCESSING

Theia 3D (Theia Markerless Inc., Kingston, Canada) was used to generate 3D body model files for each trial. The model files were processed in Visual3D (v6, C-Motion Inc., Germantown, USA) (Figure 1). Lower limb (hip, knee, ankle) joint kinematics were calculated using the Visual3D models with a Cardan XYZ rotation sequence.[14]

Hop event detection was performed in Visual3D. A “propulsion phase” and one (SLH) or more (COH, TRH, TIH) “landing phases” were identified. Toe-off and landing events were identified for each hop through the peak foot segment velocity. Peak knee flexion angle was extracted from each propulsion and landing phase and averaged between the two successful trials for each participant. Knee flexion angle at initial contact (IC) of each landing phase was also extracted and averaged.[15] In tests with multiple hops (all but SLH), the landing peak and IC knee flexion angles were also averaged and reported. For the TIH, participants took three to six hops to reach the 6-meter line. The TIH landing biomechanics are presented only as the average of the hops.

The average performance (distance for SLH, COH, and TRH; time for TIH) of two trials was computed for each participant and each limb. Clinical LSI was computed as the percentage of the involved limb divided by the uninvolved limb. Kinematic LSI was computed as the percentage of the supplementary knee flexion angle of the uninvolved limb divided by the supplementary knee flexion angle of the involved limb. The choice to use the supplementary angle (180° - actual angle) was made to address the small knee flexion angle values occurring at IC: dividing by a number close to 0° would have, indeed, generated non-physiologically high LSI. Additionally, knee flexion angle interlimb difference (ILD = involved limb – uninvolved limb) was computed. ILD values were also calculated for ease of interpretation, as it is more common for clinicians to reference a certain degree of knee joint angle asymmetry than a percentage of asymmetry.

STATISTICAL ANALYSIS

The categorical variables were presented as a percentage of the total, while the continuous variables were presented as the mean ± standard deviation. Normal distribution of the data was tested through a Shapiro-Wilk test. Since distribution was found to be non-normal ($p<0.05$), Spearman’s rank correlation coefficient ρ (with 95% confidence interval) was used to assess the correlation between clinical LSI and kinematic LSI. Correlation was considered weak, moderate, and excellent for $\rho < 0.40$, 0.40-0.75, and > 0.75, respectively.[16] Significance level was set at $\alpha=0.05$. Statistical analyses were performed in Matlab (v9.13, R2022a, The MathWorks Inc., USA).

RESULTS

For the SLH, clinical LSI showed a weak positive correlation with kinematic LSI at peak landing (ρ= 0.39), but no correlation at peak propulsion or knee angle at IC was seen (Figure 2). For the COH, no correlations were found in propulsion or landing (Figure 3). For the TRH, a weak positive correlation was found at peak propulsion (ρ= 0.38) and a moderate positive correlation at first, last, and average peak landing (ρ= 0.48 – 0.66), as well as a moderate positive correlation at last landing IC (ρ= 0.45) (Figure 4). For the TIH, peak propulsion showed a moderate positive correlation with clinical LSI (ρ= 0.51, Figure 5). In those without correlation, while the range of hop LSI was broad, the range of values for kinematic LSI had a truncated range centered around 100%.

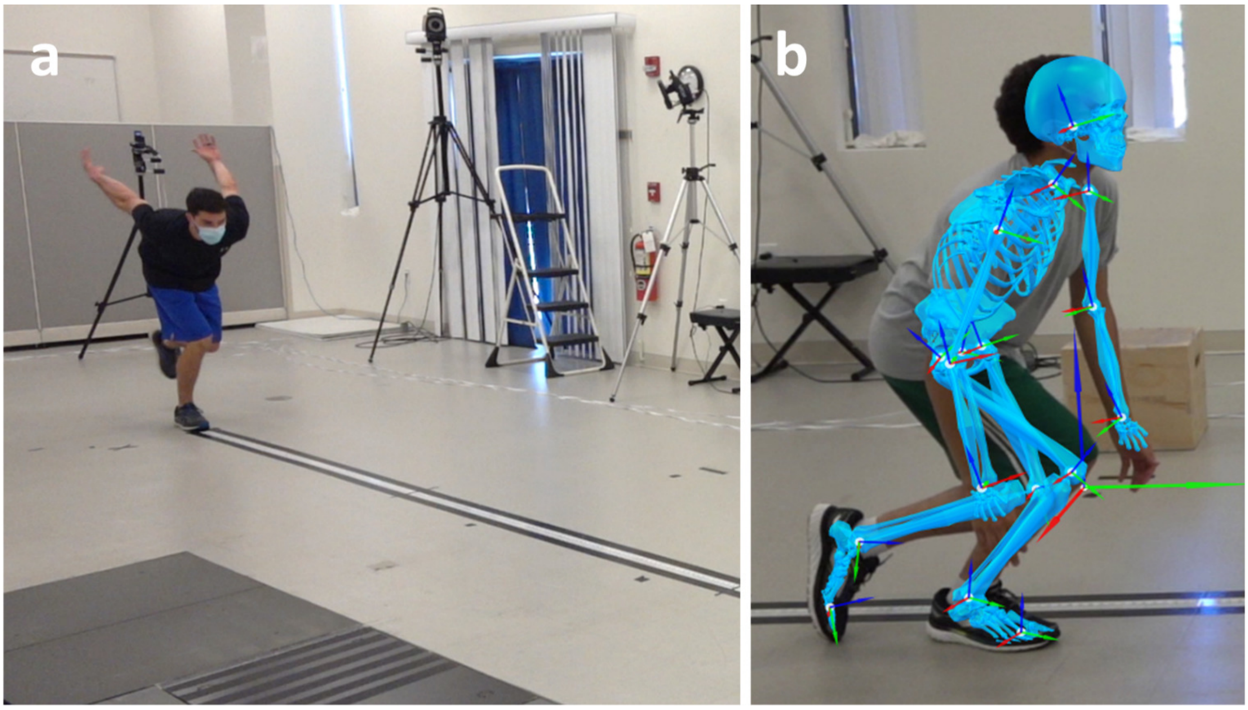

Figure 1. Example of hop test battery measured with the markerless motion capture setup.

Participants started with their toes behind a marked point on the ground (a) and hopped in the acquisition volume of the markerless motion capture, where 3D reconstruction of joint centers and bony segments was automatically performed (b).

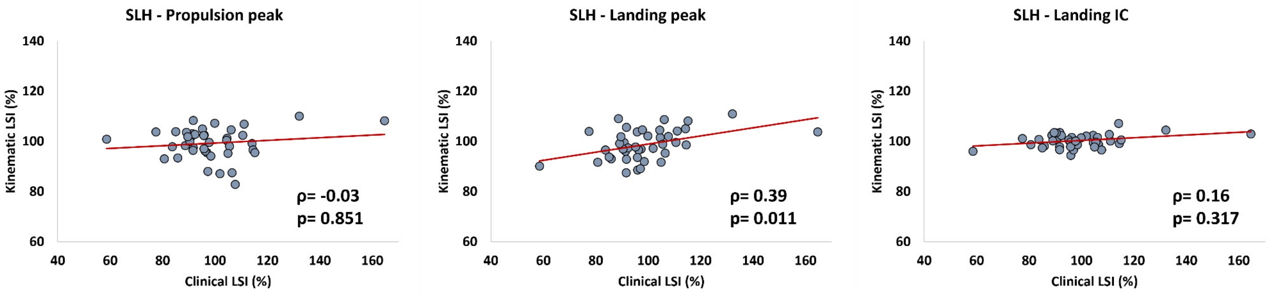

Figure 2. Correlation plot for clinical (x-axis) vs kinematic LSI (y-axis) in single leg hop for distance.

Descriptive and correlation data for all clinical vs kinematic LSI are presented in Appendices 1-4. Descriptive kinematic ILD are presented in Appendix 5. Descriptive knee flexion angle curves are presented in Appendix 6.

DISCUSSION

The present study investigated the correlation between clinical LSI and both knee propulsion and landing kinematic symmetry during the hop test battery. This is the first study presenting biomechanical data for the hop test battery evaluated clinically and simultaneously measured with markerless motion capture.

Symmetry in hop distance during the SLH and TRH was more representative of landing (ρ= 0.39 – 0.66) compared to propulsion (ρ= -0.03 – 0.38) knee biomechanical symmetry (i.e., knee flexion angle LSI and ILD). The effects were most clear in the SLH, where participants had one attempt to successfully land their hop, compared to the TRH, where participants were able to accumulate distance over the first two hops without controlling their landings. This is also reflected in the current data, as the TRH's last landing had the strongest clinical-to-biomechanical symmetry correlation amongst the three hops. This confirms the authors' hypothesis that while propulsion biomechanics matter in acquiring horizontal hop distance, symmetry in hop distance may be limited by the ability to control the landing. Hence, the asymmetry in landing ability is reflected in the horizontal hop test battery score.

Null findings for the COH compared to the SLH and TRH (which are more strictly sagittal plane movements), was not surprising, as sagittal plane biomechanics were only considered in this study due to the questionable reliability and validity of markerless motion capture in other planes of movement.[17,18] During the COH test, participants must adjust the direction of progression at each landing and propulsion; stronger knee frontal/transverse plane control

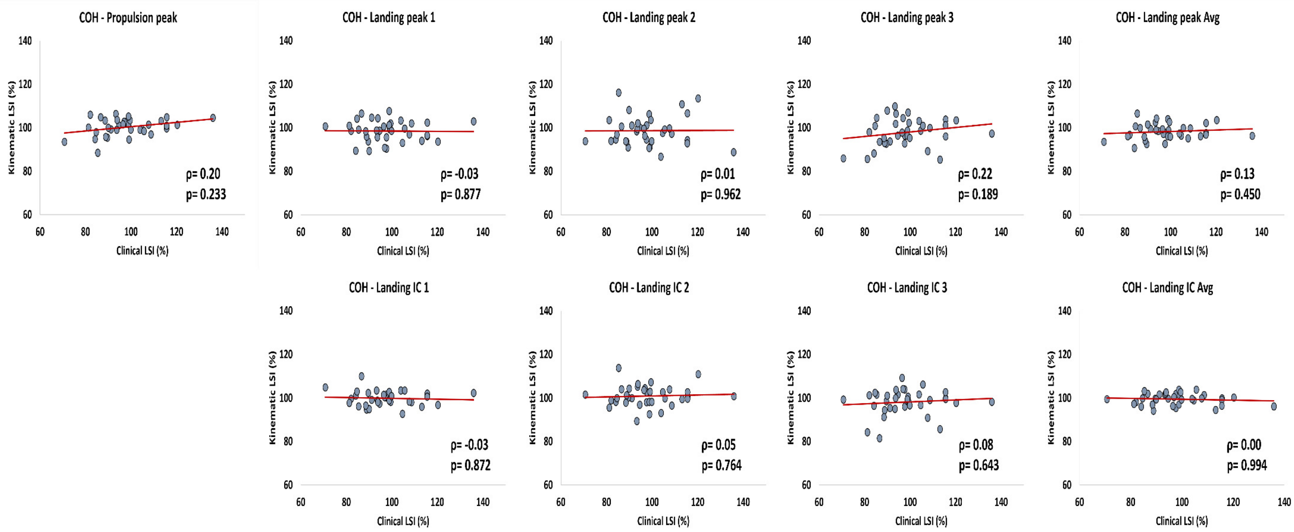

Figure 3. Correlation plot for clinical (x-axis) vs kinematic LSI (y-axis) in crossover hop.

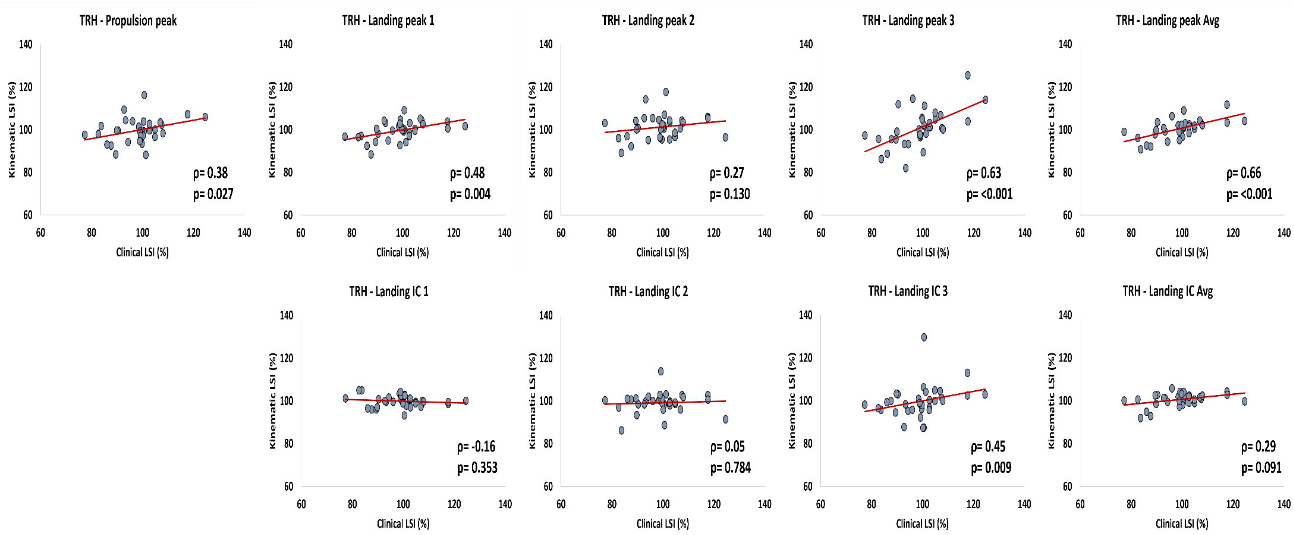

Figure 4. Correlation plot for clinical (x-axis) vs kinematic LSI (y-axis) in triple hop.

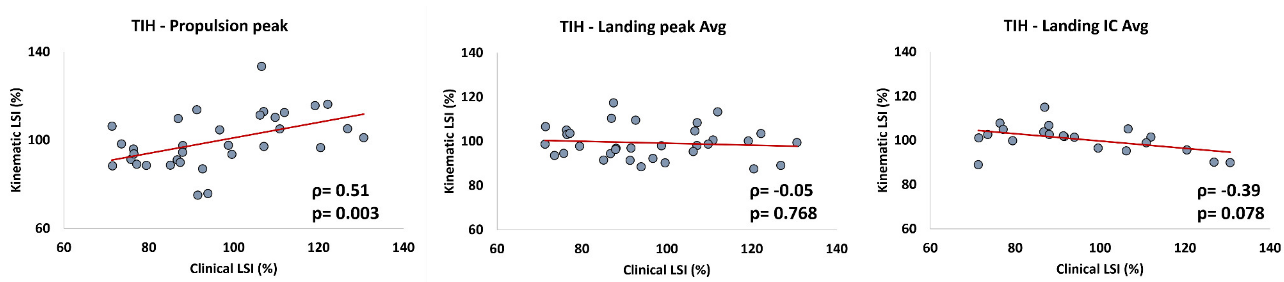

Figure 5. Correlation plot for clinical (x-axis) vs kinematic LSI (y-axis) in 6-m timed hop.

is therefore required. Future studies should aim to see if the addition of frontal plane biomechanics may better explain the relationship between hop distance LSI and COH biomechanical LSI.

The TIH showed contrasting results compared to the other three hops; clinical LSI was positively correlated with propulsion but not landing peak knee biomechanics and negatively correlated with landing IC biomechanics. The latter was the only statistically significant negative correlation found in the study. Such differences compared to other hops are likely related to the biomechanical strategy adopted in TIH; since participants have a time goal and no limit to the number of hops, they might choose to do shorter – but quicker – or longer hops. Thus, greater intra- and inter-subject variability in knee flexion angle can be expected (Appendix 4).

Recent literature questioned the use of hop for distance tests, suggesting that clinical LSI could overestimate knee function and mask residual deficits during the propulsion phases of hopping.[9] In the present study, hop distance symmetry was correlated to landing movement symmetry better than propulsion movement symmetry. Landing with proper knee flexion angle is crucial to distribute the impact forces on lower limb muscles and avoid excessive stress on knee ligaments.[19] Thus, proper landing mechanics and joint loading are crucial to address during rehabilitation after knee injury and surgery, where knee underloading and muscle weakness are common.[20] When hopping in the horizontal direction, symmetrical distance reflected symmetrical knee sagittal plane kinematics in landing. Therefore, poorer clinical LSI during the hop test battery can inform asymmetries in knee function and allow clinicians to focus on further landing movement quality training. In addition, the range of kinematic LSI was truncated in many cases, while the hop LSIs were not, suggesting that the clinical LSIs uncovered more asymmetry.

In the present study, knee biomechanics from markerless motion capture was used to improve the understanding of the hop test battery. Metrics such as peak knee flexion angle could be integrated in clinical practice to offer precious insights on hopping quality and knee function while maintaining ease of interpretation for clinicians and patients. Currently, the need for dedicated training and time required for data collection, analysis and processing are the most prominent barriers to the use of biomechanics metrics in daily clinical practice.[21,22] Markerless motion capture technology may soon be integrated into clinics due to the reduced testing time required of patients and the simplified equipment.[18]

The present cross-sectional study has one of the largest and heterogeneous (both healthy and surgery participants) cohorts investigating a clinical test battery designed for RTS clearance decision making through markerless motion capture technology.[17] Knee biomechanics quantified from markerless motion capture may provide information beyond current clinical symmetry metrics. Further research is required to assess if markerless motion capture could provide additional insight into knee function in patient populations to improve clinical RTS decision making.[23]

This study has some limitations. First, knee sagittal plane was the only kinematic variable investigated given the current limitation of markerless motion capture. Knee frontal and transverse plane kinematics might have been of interest to assess the overall knee motion and identify risk factors for biomechanically-driven knee injuries, e.g., non-contact ACL injury. This choice was made due to the more straightforward interpretation and greater applicability in the clinical setting of knee sagittal plane kinematics compared to frontal and transverse plane data.[17] Since the study's primary outcome was to assess the correlation between clinical and kinematic LSI, the cohort studied included both healthy and knee surgery participants to enhance the inter-subject variability. Future investigations should focus on possible residual biomechanical deficits in the homogeneous cohorts (e.g., ACL reconstructed athletes) and consider their implications in the use of clinical and kinematic LSI.

CONCLUSION

Clinical hop LSI distances correlated with landing biomechanics, while hop times correlated with propulsion knee biomechanics. Moderate positive correlation was found in purely horizontal hop tests, such as the single and triple hop. No correlation was found when more frontal plane movement was introduced, as seen in the crossover hop. Indeed, poorer clinical LSI scores during hop for distance tests implies greater knee landing biomechanics asymmetry.

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CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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SUPPLEMENTARY MATERIALS

Appendices

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