Original Research

Reliability of Markerless Motion Capture Systems for Assessing Movement Screenings

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Background: Movement screenings are commonly used to detect unfavorable movement patterns. Markerless motion capture systems have been developed to track 3-dimensional motion.

Purpose: To determine the reliability of movement screenings assessed using a markerless motion capture system when comparing the results of multiple systems and multiple collection periods.

Study Design: Descriptive laboratory study.

Methods: The inter- and intrarater reliability of a commercially available markerless motion capture system were investigated in 21 recreationally active participants aged between 18 and 22 years. A total of 39 kinematic variables arising from 10 fundamental upper and lower body movements typical of a screening procedure in sports performance were considered. The data were statistically analyzed in terms of relative error via the intraclass correlation coefficient (ICC) and absolute error via the residual standard error (RSE).

Results: Both inter- and intrarater reliability ICCs were at least moderate across all variables (ICC, >0.50), with most movements and corresponding variables having excellent reliability (ICC, >0.90). Although maximum knee valgus angles were the kinematic variables with the lowest interrater reliability (ICCs, 0.59-0.82) and moderate relative agreement, there was agreement in absolute terms with an RSE of <1.3°.

Conclusion: Findings indicated that markerless motion capture provides reliable measurements of joint position during a movement screen, which allows for a more objective evaluation of the direction and subsequent success of interventions. However, practitioners should consider relative and absolute agreements when applying information provided by these systems.

Clinical Relevance: Markerless motion capture systems may assist clinicians by reliably assessing movement screenings using different systems over different collection periods.

Keywords: interrater reliability; intrarater reliability; kinematic variables; markerless motion capture; movement screening

Movement screening assessments are routinely integrated into the support of athletes, most commonly as a precautionary measure to identify abnormal patterns of motion that adversely affect their performance in sports and predispose them to injury. The screens are typically best suited as a complimentary piece to an objective clinical assessment by a trained sports medicine practitioner, mainly because of the subjective nature of scoring and the inherent inter- and intrarater reliability issues.[26] Removing the rating subjectivity of movement screens may make these data more valuable and equip practitioners with objective information from both their clinical and functional assessments.

The collection of kinematic data during a movement screen or sporting action is hardly novel; nonetheless, the typical methods for obtaining these data require optical tracking of reflective markers.[25] The reflective markers are burdensome during the data acquisition process and force environmental constraints that reduce the construct

The Orthopaedic Journal of Sports Medicine, 12(3), 23259671241234339
DOI: 10.1177/23259671241234339

validity of the assessment itself. Hence, developing markerless motion capture systems to track 3-dimensional (3D) motion resolves the need for markers. This affords a collection of more simplistic biomechanical athletic movements (eg, movement screening) and has obvious potential to capture the complexity of the sporting action itself within its native context (eg, in competition). However, there is a lack of literature assessing the reliability of these systems and their underlying algorithmic models,[6,12,23] and the existing research compares with marker-based systems .[5,9,18] This is logical, considering that marker-based systems are the current benchmark; nevertheless, the models used to drive these systems are not without their limitations (eg, occlusion, skin artifacts) that may contribute to a biased interpretation compared with markerless systems.[4,11] Similarly, 2-dimensional (2D) markerless measurements of movement are prevalent, especially because of the increased processing capabilities of smartphones and tablets. These options have limitations with respect to simplicity (ie, 2D vs 3D modeling) that may limit practical utility and validity. Moreover, there is low agreement relative to marker-based systems with error magnitudes similar to those of manual techniques such as goniometry.[1,22] Weighing these limitations collectively, it may be more appropriate to establish repeatability within an individual markerless system and between 2 independent markerless systems. No such investigation exists, leaving a meaningful gap in the motion capture literature.

Therefore, the present study aimed to investigate the inter- and intrarater reliability of a commercially available markerless motion capture system and the respective algorithms used to derive whole-body and joint-specific kinematic variables. In particular, this study considered testing the hypothesis that such a markerless motion capture system and algorithms would be reliable under inter- and intrarater conditions for whole-body and joint-specific measurements typical of a screening procedure used in sports performance.

METHODS

The study protocol received institutional review board approval, and study participants signed written informed consent forms and attested that they had no current injuries that would influence their ability to perform the protocol. A total of 21 recreationally active participants (6 men, 15 women) volunteered to participate in the study—mean height, 174.53 ± 9.64 cm; mean weight, 68.64 ± 11.24 kg; and age range, 18-22 years. Reliability was assessed primarily using the intraclass correlation coefficient (ICC); thus, sample size planning was conducted in reference to this statistic. Specifically, the method provided by Bonett[3] was followed to obtain a sample size so that reasonably narrow confidence intervals for the ICC could be obtained. Because of the statistical properties of the ICC, a higher ICC requires fewer observations to obtain a narrow confidence interval. Thus, it was determined that a sample size of approximately 20 participants was adequate to identify the variables that were measured with high reliability.

TABLE 1
Movements Performed in the Study

Shoulder internal/external rotation
Shoulder flexion
Trunk rotation
Overhead squat
Lateral lunge
Unilateral squat
Vertical jump
Lateral bound
Unilateral vertical jump
Unilateral hop, 5 hops

After a self-selected warm-up lasting approximately 3 minutes, participants were asked to perform 2 sets of 3 repetitions of each movement, except for the unilateral hop, which had 5 hops each, within a series of fundamental upper and lower body movements that are typical of screening procedures in sports performance (Table 1). Each movement was separated by approximately 30 seconds of standing and passive rest, during which study staff shared standardized coaching instructions describing the subsequent movement. Each set was separated by 5 to 10 minutes of seated, passive rest.

Each repetition was simultaneously captured by two 8-camera markerless motion capture systems (DARI Motion; DARI Motion Inc), each collecting at 240 Hz (Figure 1). Postprocessing synchronization of the 2 systems was not necessary because of the repetition-level nature of the analysis and the native capabilities of the software's algorithms.

The selection of kinematic variables included both upper and lower body joints as well as the 3 cardinal planes of the body for a thorough assessment of the algorithm's capabilities. The lower body variables of interest were hip abduction, hip flexion, knee flexion, ankle dorsiflexion, and knee valgus; the upper body variables of

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Final revision submitted July 28, 2023; accepted September 6, 2023.
The authors have declared that there are no conflicts of interest in the authorship and publication of this contribution. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.
Ethical approval for this study was obtained from the University of Notre Dame (ref No. 22-09-7421).

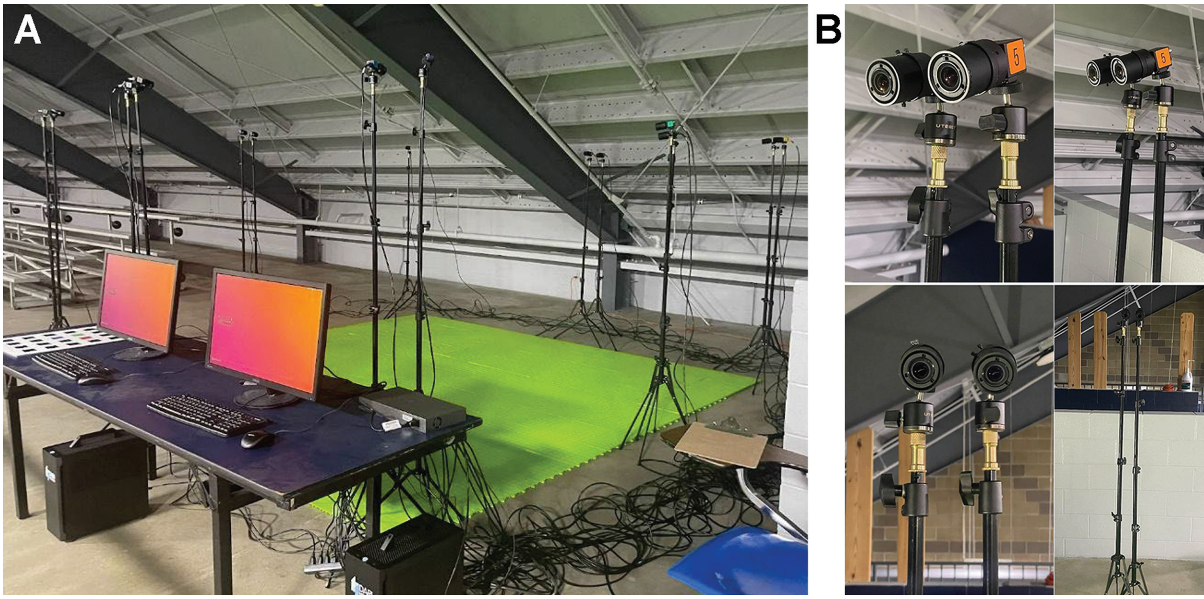

Figure 1. (A) The setup for data collection for the present study, with 8 pairs of cameras for each system positioned approximately at the vertices and edge midpoints of a green-tiled square where participants stood. (B) Details of the camera pairs used for each system.

TABLE 2
The 39 Kinematic Variables Assessed

Shoulder
• Maximum external rotation[a]
• Maximum internal rotation[a]
• Maximum flexion[a]
Thorax
• Maximum rotation[a]
Hip
• Maximum flexion, overhead squat[a]
• Maximum flexion, unilateral squat[a]
• Maximum flexion, lateral lunge[a]
• Maximum hip abduction, overhead squat[a]
Knee
• Maximum flexion, overhead squat[a]
• Maximum flexion, unilateral squat[a]
• Maximum flexion, lateral lunge[a]
• Maximum valgus angle, overhead squat[a]
• Maximum valgus angle, unilateral squat[a]
• Maximum valgus angle, lateral lunge[a]
Ankle
• Maximum flexion, overhead squat[a]
• Maximum flexion, unilateral squat[a]
• Maximum flexion, lateral lunge[a]
Jump height
• Vertical jump height
• Unilateral vertical jump height[a]
• Mean unilateral hop height, 5 hops[a]

[a]Assessed bilaterally.

interest were shoulder external rotation, shoulder internal rotation, shoulder flexion, and thoracic rotation. Jump height was also considered under the 3 relevant dynamic movements—ie, vertical jump, unilateral vertical jump, and unilateral hop. A total of 39 kinematic variables were included in the assessment (Table 2). Values of whole-body and joint-specific kinematic variables relevant to sports practitioners were processed using the motion capture system's algorithms and exported to a flat file for analysis. Peak values were used for all variables for each participant, with the exception of the unilateral hop movement, where the mean height of the 5 hops was used for subsequent analysis.

Statistical Analysis

Because each participant had performed the respective movements for 2 sets, with each set captured by 2 systems simultaneously, this resulted in data that could be used in 4 different reliability studies: 2 interrater reliability studies (ie, the agreement between the systems on each of the sets) and 2 intrarater reliability studies (ie, the agreement between the first and second set for each system). The reliability was assessed for the 39 kinematic variables using the ICC with 95% CI for measuring relative agreement and the residual standard error (RSE) for measuring absolute agreement. Specifically, the form of the appropriate ICC for all 4 studies is notated as the ICC (2,1), as determined using the flowchart and formulas provided in Table 3 by Koo and Li.[10] The RSE was computed as the RSE in a linear model with subjects and systems (for the interrater studies) and sets (for the intrarater studies) as effects.[7] All data cleaning and analyses were performed using the statistical software environment R.[20] In particular, *psych*[21] and *psr*[13] packages were used to compute the ICCs and RSEs, respectively.

Choosing a threshold value for a minimum acceptable ICC is subjective and may differ depending on the context.

TABLE 3
Inter- and Intrarater Reliability for Shoulder, Thorax, and Hip Kinematic Variables[a]

	Interrater		Intrarater	
Variable	ICC (95% CI)	RSE	ICC (95% CI)	RSE
Maximum shoulder external rotation	0.98 (0.94-0.99)	1.66°	0.90 (0.75-0.96)	4.39°
Maximum shoulder internal rotation	1 (0.99-1)	1.37°	0.59 (0.23-0.81)	13.69°
Maximum shoulder flexion	0.97 (0.89-0.99)	2.03°	0.83 (0.64-0.93)	5.42°
Maximum thoracic rotation	0.92 (0.68-0.97)	1.79°	0.78 (0.54-0.90)	3.86°
Maximum hip flexion, overhead squat	0.89 (0.75-0.95)	4.21°	0.78 (0.54-0.90)	5.90°
Maximum hip flexion, unilateral squat	0.91 (0.80-0.96)	4.80°	0.76 (0.51-0.90)	8.23°
Maximum hip flexion, lateral lunge	0.94 (0.86-0.97)	4.73°	0.55 (0.18-0.79)	11.21°
Maximum hip abduction, overhead squat	0.87 (0.05-0.97)	1.15°	0.80 (0.56-0.91)	2.04°

[a]ICC, intraclass correlation coefficient; RSE, residual standard error.

In the field of exercise science, Baumgartner and Chung[2] stated a minimally acceptable ICC value of 0.70, which has been used in subsequent research into the reliability of sports science technology.[8]

RESULTS

Missing values and outliers were examined first. Each kinematic variable was measured 84 times (21 participants × 2 systems × 2 sets), and vertical jump height and left unilateral and right unilateral vertical jump heights were missing 12, 21, and 30 times, respectively. Outliers were identified by standardizing each variable and filtering for values >4 or <–4. A total of 8 measurements were flagged as outliers—2 each for the left and right maximum knee valgus angle overhead squat and the left and right maximum knee valgus angle unilateral squat. No observations were removed from the analysis since outliers were only observed for these variables and the system operators did not report any irregularities in the testing procedure.

The full results for the 4 reliability studies consisting of 39 kinematic variables are provided in Appendix Tables A1 to A5. Here, we focus on the results for a subset of the variables to simplify the presentation. Since many variables had both "right" and "left" versions (eg, right and left maximum shoulder flexion), only the results for the right side are presented here. Since labeling the systems was arbitrary, we present the results of the first system for the intrarater study. Finally, since the participants were more familiar with the protocol after the first set and to account for a potential increase in tissue compliance or treatment effect that would be reflected in an increase in joint range in the subsequent trial, we present the results of the second set for the interrater study. Moreover, a previous study[19] examining reliability of dorsiflexion for a weightbearing lunge included 3 to 5 trials, consistent with being in the second set for this study.

Regarding interrater reliability, Table 3 shows that kinematic variables involving the shoulder were highly reliable (ICC, ≥0.97), and the confidence interval ranges for these ICCs were narrow. Examining Table 3 further, the variables concerning thoracic rotation and hip flexion all had an estimated interrater ICC of at least 0.89, and the lower bounds of all their respective confidence intervals were ≥0.68. Table 4 shows that the variables for knee flexion were highly reliable, with narrow confidence interval ranges of 0.98 to 1. However, the knee valgus variables showed lower interrater reliability, with the ICC for the maximum knee valgus angle during the lateral lunge being 0.59. The interrater ICCs for the ankle flexion variables were all ≥0.88, and the lower bounds for all the confidence intervals were >0.70. Finally, despite missing data, the variables for jump height showed high interrater ICCs and narrow confidence interval ranges (Table 4).

The ICCs for intrarater reliability were generally lower than those for interrater reliability. Of the 20 variables in this subset, 15 had lower bounds confidence intervals of <0.70. The jump height variables showed the closest correspondence between the intrarater ICCs (ie, ICC ≥ 0.91) and the corresponding interrater ICCs (ie, ICC > 0.98) than any other group of variables.

DISCUSSION

The present study aimed to investigate the inter- and intrarater reliability of a commercially available markerless motion capture system and the respective algorithms used to derive whole-body and joint-specific kinematic variables. The study findings showed that markerless motion capture is reliable when comparing the results of multiple systems or multiple collection periods. Specifically, regarding interrater reliability, the markerless motion capture system provided at least moderate agreement across all variables (ie, ICC, >0.50), with a vast majority demonstrating excellent reliability (ie, ICC, >0.90). In particular, interrater reliability was excellent across all upper body measurements, including multiplanar shoulder movements and thoracic rotation. Similarly, interrater reliability was largely good for lower body measurements (ie, ICC, >0.75), except for hip flexion during the overhead squat (ICC, 0.66-0.89) and knee valgus during the

TABLE 4
Inter- and Intrarater Reliability for Knee, Ankle, and Jump Height Kinematic Variables[a]

	Interrater		Intrarater	
Variable	ICC (95% CI)	RSE	ICC (95% CI)	RSE
Maximum knee flexion, overhead squat	0.99 (0.98 to 1)	1.12°	0.95 (0.87 to 0.98)	2.82°
Maximum knee flexion, unilateral squat	0.99 (0.98 to 1)	1.18°	0.81 (0.46 to 0.93)	5.65°
Maximum knee flexion, lateral lunge	0.99 (0.98 to 1)	1.17°	0.86 (0.61 to 0.95)	5.15°
Maximum knee valgus angle, overhead squat	0.79 (0.56 to 0.91)	0.12°	0.37 (−0.05 to 0.68)	0.37°
Maximum knee valgus angle, unilateral squat	0.82 (0.62 to 0.92)	0.27°	0.85 (0.68 to 0.94)	0.22°
Maximum knee valgus angle, lateral lunge	0.59 (0.24 to 0.81)	1.21°	0.43 (0.02 to 0.72)	1.10°
Maximum ankle flexion, overhead squat	0.90 (0.78 to 0.96)	1.69°	0.81 (0.59 to 0.92)	2.32°
Maximum ankle flexion, unilateral squat	0.88 (0.72 to 0.95)	2.08°	0.70 (0.41 to 0.87)	3.59°
Maximum ankle flexion, lateral lunge	0.93 (0.84 to 0.97)	2.19°	0.68 (0.36 to 0.86)	4.29°
Jump height, vertical jump[b]	1 (0.99 to 1)	0.75 cm	0.97 (0.91 to 0.99)	2.06 cm
Jump height, unilateral vertical jump[b]	1 (0.99 to 1)	0.49 cm	0.96 (0.90 to 0.98)	1.92 cm
Mean unilateral hop height, 5 hops	0.99 (0.98 to 1)	0.64 cm	0.91 (0.80 to 0.96)	2.15 cm

[a]ICC, intraclass correlation coefficient; RSE, residual standard error.
[b]Of 84 times each variable was measured, vertical jump height, left unilateral vertical jump height, and right unilateral vertical jump height were missing data 12, 21, and 30 times, respectively.

overhead squat (ICC, 0.55-0.94), the unilateral squat (ICC, 0.60-0.82), and the lateral lunge (ICC, 0.59-0.89), where the lowest values were interpreted as moderate. However, the absolute interrater reliability for hip flexion during the overhead squat (RSE, 3.782-7.657) makes this less concerning for practitioners, as normative values for flexion range of motion are likely >100°.[24] Knee valgus RSE values were also favorable, with the largest RSE with respect to interrater reliability being 1.205°. In other words, the ICCs for hip flexion or knee valgus were not as strong as other variables; nonetheless, the absolute agreement between devices makes integration into athlete monitoring processes reasonable.

The ICCs for intrarater reliability of the markerless motion capture system again ranged from moderate to excellent for all movements and corresponding variables. Most variables presented moderate intrarater reliability. However, the ICCs for knee valgus during the overhead squat, unilateral squat, and lateral lunge indicated mostly poor intrarater reliability—although values ranged widely, even exceeding 0.75 (ie, good reliability) during the overhead squat and unilateral squat. Generally, intrarater reliability was lower than interrater reliability for the same measurement of consideration, although this could be partly attributed to the familiarization or warm-up effect between the first and second sets. Supporting this potential explanation, the intrarater absolute agreement of shoulder internal rotation was much larger (RSE, 11.345°-13.685°) relative to interrater values (RSE, 1.595°-2.056°). Furthermore, the respective intrarater ICC values were similar, comparing the 2 markerless motion capture systems across most variables. Therefore, practitioners using a markerless motion capture system should be familiar with absolute reliability measures (eg, RSE) for each variable to better discern whether changes after an intervention can be truly attributed to the support provided or normal measurement variability.[15]

The data should be considered within the context of the joint or nature of the movement. For example, knee valgus angles during movement tasks will be influenced by the anatomical properties of the athlete (eg, femur length), making normative values more difficult to establish.[16] Therefore, practitioners intervening in hopes of reducing knee valgus should pursue directionality (ie, reduction in knee valgus) and change relative to the athlete's baseline in lieu of settling into a normative range. With such a conservative RSE (0.225°-1.706°), practitioners could reasonably apply the present study's markerless motion capture system within that scope. Despite moderate-to-good intrarater agreement, ankle dorsiflexion demonstrated an RSE of as high as 4.288°. Hence, determining the meaningfulness of change after an intervention in a clinical or sports performance setting will be more difficult considering the similarity between the observed RSE and the minimum detectable change at the ankle joint.[15,19]

Both inter- and intrarater reliability were excellent for bilateral and unilateral vertical jumps. Furthermore, the RSE ranged from 0.336 cm to 2.064 cm, consistent with other common means of approximating center of mass displacement during jumping tasks using flight time[17] and the impulse-momentum relationship.[14] Therefore, the markerless motion capture system is a satisfactory tool for assessing jumping abilities. Notably, the percentage of the number of jump movement repetitions missed by the system during the present study was 14% to 36% across the bilateral vertical jump and right and left unilateral vertical jumps. Although the absences did not follow a recognizable pattern, they could be explained by performing 3 jumps in succession without adequate time between repetitions, as the processing algorithm expects a trial with a single jump. Alongside the excellent relative and strong absolute agreement of jump height, it is highly likely that more time between repetitions would reduce or resolve the issue of missed repetitions observed in the present investigation. Alternatively, the markerless motion capture algorithm may be challenged during rapid movements. For example, the missed repetitions observed may have resulted from identifying when participants were disengaged with the floor between takeoff and landing, not permitting approximation of flight times (and, therefore, jump height). This comment is speculative, as we are not privy to the proprietary features or methods of calculating jump height. Nonetheless, practitioners are encouraged to collect multiple trials of each jump type with adequate rest between repetitions to account for the missing values observed in the present study. Because of the nature of the data, the potential influence of missing repetitions on the measurement of jump height during 5 sequential unilateral hops is unknown. Unlike all other variables that used peak values, data were reported as a mean across a maximum of 5 trials, with no indication of the number of repetitions used (eg, only 3 repetitions were used in presented means because of missed repetitions).

CONCLUSION

Markerless motion capture allows sport practitioners to describe movement in terms of kinematics, which is useful in screening or technical development. The results of the present study indicate that markerless motion capture is reliable when comparing the results of multiple systems or multiple collection periods. However, practitioners should consider both relative and absolute agreement, as that is critical in applying the information provided by markerless systems. Ultimately, markerless motion capture will progress to capturing the sports movements themselves. It appears to provide a suitable alternative to subjectively scored screening protocols—an advantage brought about by the granularity afforded in a markerless motion capture system. Reliably describing joint position during a movement screen allows for a more objective evaluation of the direction and subsequent success of interventions. This may not only have athlete health benefits but also position coaches to guide technical development with greater precision. Undoubtedly, markerless motion capture will continue to scale its presence in sports. Future research should explore the potential improvements in the reliability and accuracy of these systems, especially when capturing movements with high segment or system velocities.

ACKNOWLEDGMENTS

The authors thank DARI Motion for providing access to the 2 systems used in this study.

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APPENDIX

TABLE A1
Inter- and Intrarater Reliability for Shoulder Kinematic Variables[a]

	Interrater 1		Interrater 2		Intrarater 1		Intrarater 2	
Variable	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE
Max external rotation								
Left	0.96 (0.91-0.99)	1.98°	0.95 (0.88-0.98)	2.64°	0.87 (0.71-0.95)	3.96°	0.88 (0.71-0.95)	3.55°
Right	0.98 (0.96-0.99)	1.62°	0.98 (0.94-0.99)	1.66°	0.89 (0.75-0.96)	4.39°	0.92 (0.76-0.97)	3.63°
Max internal rotation								
Left	0.99 (0.98-1)	2.06°	0.99 (0.98-1)	1.91°	0.73 (0.46-0.88)	11.35°	0.70 (0.40-0.87)	12.68°
Right	0.99 (0.98-1)	1.60°	1 (0.99-1)	1.37°	0.59 (0.23-0.81)	13.69°	0.53 (0.15-0.77)	14.50°
Max flexion								
Left	0.94 (0.61-0.98)	2.34°	0.94 (0.74-0.98)	2.89°	0.87 (0.70-0.94)	4.88°	0.90 (0.77-0.96)	4.59°
Right	0.94 (0.80-0.98)	2.70°	0.97 (0.89-0.99)	2.03°	0.83 (0.64-0.93)	5.42°	0.81 (0.59-0.92)	5.85°

[a]ICC, intraclass correlation coefficient; max, maximum; RSE, residual standard error.

TABLE A2
Inter- and Intrarater Reliability for Thorax Kinematic Variable[a]

	Interrater 1		Interrater 2		Intrarater 1		Intrarater 2	
Variable	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE
Max rotation								
Left	0.95 (0.81-0.98)	1.88°	0.96 (0.85-0.98)	1.35°	0.82 (0.62-0.92)	3.67°	0.71 (0.42-0.87)	4.31°
Right	0.93 (0.76-0.98)	1.72°	0.92 (0.68-0.97)	1.79°	0.78 (0.54-0.90)	3.86°	0.78 (0.54-0.90)	3.47°

[a]ICC, intraclass correlation coefficient; max, maximum; RSE, residual standard error.

TABLE A3
Inter- and Intrarater Reliability for Hip Kinematic Variables[a]

	Interrater 1		Interrater 2		Intrarater 1		Intrarater 2	
Variable	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE
Max flexion, overhead squat								
Left	0.74 (0.42 to 0.89)	6.34°	0.83 (0.18 to 0.95)	3.78°	0.81 (0.60 to 0.92)	5.49°	0.79 (0.53 to 0.91)	5.88°
Right	0.66 (0.34 to 0.85)	7.66°	0.89 (0.75 to 0.95)	4.21°	0.78 (0.54 to 0.90)	5.90°	0.83 (0.61 to 0.93)	5.31°
Max flexion, unilateral squat								
Left	0.97 (0.93 to 0.99)	2.81°	0.96 (0.74 to 0.99)	2.86°	0.87 (0.71 to 0.95)	6.36°	0.85 (0.64 to 0.94)	7.13°
Right	0.96 (0.91 to 0.98)	3.49°	0.91 (0.80 to 0.96)	4.80°	0.76 (0.51 to 0.90)	8.23°	0.78 (0.53 to 0.90)	8.36°
Max flexion, lateral lunge								
Left	0.96 (0.88 to 0.98)	3.65°	0.95 (0.76 to 0.98)	3.57°	0.89 (0.74 to 0.95)	6.50°	0.80 (0.57 to 0.92)	8.24°
Right	0.92 (0.82 to 0.97)	4.60°	0.94 (0.86 to 0.97)	4.73°	0.55 (0.18 to 0.79)	11.21°	0.71 (0.42 to 0.87)	9.42°
Max abduction, overhead squat								
Left	0.74 (−0.02 to 0.92)	1.60°	0.85 (0.11 to 0.96)	1.44°	0.72 (0.43 to 0.87)	2.78°	0.78 (0.54 to 0.90)	2.52°
Right	0.82 (0.04 to 0.95)	1.15°	0.87 (0.05 to 0.97)	1.25°	0.80 (0.56 to 0.91)	2.04°	0.75 (0.47 to 0.89)	2.55°

[a]ICC, intraclass correlation coefficient; max, maximum; RSE, residual standard error.

TABLE A4
Inter- and Intrarater Reliability for Knee Kinematic Variables[a]

	Interrater 1		Interrater 2		Intrarater 1		Intrarater 2	
Variable	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE
Max flexion, overhead squat								
Left	0.99 (0.97-1)	1°	0.99 (0.96-1)	1.20°	0.91 (0.80-0.96)	3.68°	0.92 (0.82-0.97)	3.36°
Right	0.99 (0.99-1)	0.88°	0.99 (0.98-1)	1.12°	0.95 (0.87-0.98)	2.82°	0.94 (0.86-0.97)	2.96°
Max flexion, unilateral squat								
Left	1 (0.97-1)	0.82°	0.99 (0.97-1)	1.28°	0.73 (0.42-0.88)	7.10°	0.71 (0.42-0.87)	7.22°
Right	1 (0.99-1)	0.88°	0.99 (0.98-1)	1.18°	0.81 (0.46-0.93)	5.65°	0.80 (0.43-0.92)	5.66°
Max flexion, lateral lunge								
Left	0.99 (0.96-1)	0.89°	0.99 (0.91-1)	0.87°	0.92 (0.77-0.97)	4.30°	0.91 (0.75-0.97)	4.39°
Right	0.99 (0.99-1)	1.11°	0.99 (0.98-1)	1.17°	0.86 (0.61-0.95)	5.15°	0.89 (0.67-0.96)	4.42°
Max valgus angle, overhead squat								
Left	0.94 (0.85-0.97)	0.38°	0.55 (0.18-0.79)	1.02°	0.85 (0.66-0.93)	0.68°	0.55 (0.17-0.79)	0.85°
Right	0.69 (0.38-0.86)	0.33°	0.79 (0.56-0.91)	0.12°	0.37 (0-0.68)	0.37°	0.32 (0-0.64)	0.38°
Max valgus angle, unilateral squat								
Left	0.60 (0.25-0.81)	0.15°	0.60 (0.25-0.82)	0.58°	0.21 (0-0.58)	0.46°	0.12 (0-0.51)	0.73°
Right	0.63 (0.28-0.83)	0.31°	0.82 (0.62-0.92)	0.27°	0.85 (0.68-0.94)	0.23°	0.51 (0.13-0.76)	0.42°
Max valgus angle, lateral lunge								
Left	0.84 (0.65-0.93)	0.66°	0.86 (0.69-0.94)	1.01°	0.49 (0.09-0.75)	1.71°	0.29 (0-0.63)	1.72°
Right	0.89 (0.75-0.95)	0.46°	0.59 (0.24-0.81)	1.21°	0.43 (0.02-0.72)	1.10°	0.39 (0-0.69)	1.32°

[a]ICC, intraclass correlation coefficient; max, maximum; RSE, residual standard error.

TABLE A5
Inter- and Intrarater Reliability Results for Ankle Kinematic Variables[a]

	Interrater 1		Interrater 2		Intrarater 1		Intrarater 2	
Variable	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE
Max flexion, overhead squat								
Left	0.90 (0.15-0.98)	1.23°	0.95 (0.88-0.98)	1.55°	0.89 (0.75-0.96)	2.00°	0.89 (0.75-0.95)	2.19°
Right	0.86 (0.69-0.94)	1.89°	0.90 (0.78-0.96)	1.69°	0.81 (0.59-0.92)	2.32°	0.76 (0.50-0.89)	2.50°
Max flexion, unilateral squat								
Left	0.92 (0.81-0.97)	1.90°	0.93 (0.83-0.97)	1.58°	0.80 (0.58-0.91)	2.85°	0.85 (0.66-0.93)	2.55°
Right	0.89 (0.74-0.95)	2.20°	0.88 (0.72-0.95)	2.08°	0.70 (0.41-0.87)	3.59°	0.78 (0.54-0.90)	2.83°
Max flexion, lateral lunge								
Left	0.94 (0.86-0.97)	2.06°	0.97 (0.92-0.99)	1.38°	0.78 (0.50-0.91)	3.28°	0.65 (0.32-0.84)	4.44°
Right	0.93 (0.83-0.97)	1.94°	0.93 (0.84-0.97)	2.19°	0.68 (0.36-0.86)	4.29°	0.76 (0.40-0.90)	3.27°

[a]ICC, intraclass correlation coefficient; max, maximum; RSE, residual standard error.

TABLE A6
Inter- and Intrarater Reliability Results for Jump Height Kinematic Variables[a]

	Interrater 1		Interrater 2		Intrarater 1		Intrarater 2	
Variable	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE	ICC (95% CI)	RSE
Vertical jump[b]	1 (1-1.00)	0.44 cm	1 (0.99-1)	0.75 cm	0.97 (0.91-0.99)	2.06 cm	0.96 (0.91-0.99)	2.36 cm
Unilateral vertical jump height								
Left[b]	1 (0.99-1)	0.55 cm	0.99 (0.99-1)	0.58 cm	0.99 (0.98-1)	0.71 cm	0.98 (0.90-1)	0.87 cm
Right[b]	1 (1-1)	0.34 cm	1 (0.99-1)	0.49 cm	0.96 (0.90-0.98)	1.92 cm	0.96 (0.91-0.99)	1.64 cm
Mean unilateral hop height								
Left	0.97 (0.93-0.99)	1.26 cm	0.99 (0.98-1)	0.62 cm	0.85 (0.67-0.94)	2.89 cm	0.85 (0.64-0.94)	2.82 cm
Right	1.00 (0.99-1.00)	0.42 cm	0.99 (0.98-1)	0.64 cm	0.91 (0.80-0.96)	2.15 cm	0.90 (0.78-0.96)	2.32 cm

[a]ICC, intraclass correlation coefficient; RSE, residual standard error.
[b]Of 84 times each variable was measured, vertical jump height, left unilateral vertical jump height, and right unilateral vertical jump height were missing data 12, 21, and 30 times, respectively.