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Research article

Reliability and validity of knee valgus angle calculation at single-leg drop landing by posture estimation using machine learning

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ABSTRACT

Background: The consensus on anterior cruciate ligament (ACL) injury prevention involves the suppression of dynamic knee valgus (DKV). The gold standard for evaluating the DKV includes three-dimensional motion analysis systems; however, these are expensive and cannot be used to evaluate all athletes. Markerless motion-capture systems and joint angle calculations using posture estimation have been reported. However, there have been no reports on the reliability and validity of DKV calculations using posture estimation.
Research question: This study aimed to clarify the reliability and validity of DKV calculation using posture estimation.
Methods: Fifteen participants performed 10 single-leg jump landings from a height of 20 cm, and the knee joint angle was calculated using joint points measured using machine learning (MediaPipe Pose) and motion-capture systems (VICON MX). Two types of angle calculation methods were used: absolute value and change from the initial ground contact (IC). Intra- and inter-rater reliabilities were examined using intraclass correlation coefficients, and concurrent validity was examined using Pearson's correlation coefficients. To examine intra-examiner reliability, we performed single-leg jump landings at intervals of ≥3 days.
Results: The calculation by MediaPipe Pose was significantly higher than that by the 3-D motion analysis systems ($p < 0.05$, error range 18.83–19.68°), and there was no main effect of knee valgus angle or time on the excursion angle from IC ($p > 0.05$). No significant concurrent validity was found in the absolute value, which was significantly correlated with the change in IC. Although the inter-rater reliability of the absolute value was low, the change in IC showed good reliability and concurrent validity.
Significance: The results of this research suggest that the DKV calculation by pose estimation using machine learning is practical, with normalization by the angle at IC.

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1. Introduction

Research has been performed to detect risk factors associated with sports injuries, such as cartilage injury and secondary anterior cruciate ligament (ACL) injury after ACL reconstruction [1,2]. Moreover, the knee valgus angle that induces stress on the ligaments due to the tibial internal rotation and tibial posterior displacement associated with knee valgus [3,4] should be investigated in a multicenter cohort study. The gold standard method for this evaluation relies on three-dimensional (3-D) motion analysis systems for knee valgus angle calculation. The prediction of ACL injury as well as knee valgus angle and moment are calculated using the marker position coordinates recorded in 3-D [5]. Nonetheless, 3-D motion analysis systems are expensive and cannot be used to evaluate all athletes. In addition, if the position of the fixed marker used to calculate the joint angle differs, the knee joint valgus angle may differ [6]. Therefore, knee valgus angle evaluation by 3-D motion analysis is limited. Furthermore, previous research was conducted with only 56 participants hindering the reliability of the data [7].

In addition to 3-D motion analysis systems, markerless motion-capture systems and joint angle calculations by posture estimation have been conducted owing to the development of artificial intelligence. Microsoft Kinect™ (Microsoft Corporation, Redmond, USA) was used to calculate the estimated joint center in three dimensions from the infrared irradiation distance and video images. The reported knee valgus angle error during sports activities was 4.22° [8]. Although it is cheaper than 3-D motion analysis systems, Microsoft Kinect™ or the next-generation Azure Kinect DK also incurs costs and does not completely overcome the limitations for athletes and users. OpenPose is a pose estimation model with moderate to strong relationships for knee flexion angles between two-dimensional (2-D) pose estimation using video data and the 3-D model (Genetic Hayes marker set). Furthermore, no significant correlations for the knee abduction angle in single-leg squatting were noted [9]. MediaPipe Pose is an open-source tool released by Google in 2019 that uses deep learning to identify faces, bodies, and gestures in images [10]. MediaPipe Pose is a free open-source database that supports many programming languages and enables motion analysis without limiting the target or user. Furthermore, there have been no reports of the knee valgus angle during landing calculated by posture estimation in artificial intelligence.

Considering the limitations of traditional motion analysis methods that target a limited population due to costly equipment, this study explored the potential of machine learning using artificial intelligence through posture estimation (MediaPipe Pose) as an affordable and straightforward alternative for motion analysis during sports activities to prevent injuries.

This study aimed to clarify the reliability and validity of a knee valgus angle estimation method using machine learning (MediaPipe Pose). We hypothesized that the knee valgus angle calculation using MediaPipe Pose has concurrent validity with that of 3-D motion analysis systems; however, there was an absolute error, although the intra-examiner reliability was adequate.

2. Materials and methods

2.1. Participants

This descriptive laboratory study was conducted at a single center. The participants were healthy adult men who became aware of the research through a poster. We recruited participants (i) who could understand the study and provide informed consent in writing, (ii) without a history of orthopedic surgery for lower limb neuromuscular disease, (iii) without pain, (iv) without the limited knee range of motion, and (v) who carried out regular sports activities. A questionnaire was administered to prospective participants to confirm their history of orthopedic surgery related to lower limb neuromuscular diseases and determine the presence or absence of pain. Additionally, joint angles were measured using a goniometer to assess individuals with limited range of motion in the lower limb. The exclusion criteria included individuals with a history of orthopedic surgery or lower limb pain, limited joint range of motion (i.e., less than 135° of flexion or a not fully extended knee), maintaining posture when jumping and landing, missing data, not carrying out regular sporting activities, and carrying out sporting activities at the competition level (e.g., professional sports level). This study was conducted with the approval of our institutional research ethics committee (Takarazuka University of Medical and Health Care) and in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants.

We determined the sample size using IBM Statistical Package for Social Science (SPSS) Statistics 27 (IBM Japan, Japan, power = 0.8, Pearson correlation parameter = 0.7, which indicated a strong positive correlation [11]). The required sample size was calculated as 13; therefore, we recruited 15 participants.

2.2. Measurement

The jump landing was a single-leg jump-landing motion from a 20-cm height. We used a 5-s duration to maintain a successful landing attitude and asked the participants to perform a successful landing 10 times. The participants were instructed to stand on both legs at a 20 cm elevation, assume a single-legged posture with the right knee flexed, and then land on the force plate in a controlled manner without using the upper limb recoil. The landing posture was maintained for 5 s with the participants being verbally guided. Following five practice trials, measurements were taken until 10 successful trials were completed. The average value from these 10 trials was used for all joint angles in this study. A successful jump landing was defined as a controlled landing without upper limb recoil and the ability to sustain the posture for 5 s. For reliability evaluation, the landing motion was performed a second time after >1 week from the first measurement.

The participants wore clothes with high body adhesion, and 39 infrared reflective markers (diameter: 10 mm) were attached to the entire body in accordance with the Plug-in Gait model of the Vicon Motion System. During the jump-landing measurement, data on the marker position and ground reaction force (GRF) were collected using a 3-D motion analysis system (Vicon MX, Vicon Motion Systems, UK) and a force plate (AMTI, USA). The camera frequency for the 3-D motion analysis was 100 Hz, and the GRF was recorded at 1000 Hz for each force plate. The obtained marker position data were subjected to a 6-Hz low-pass filter (Butterworth fourth-order filter).

The landing motion was captured in the frontal plane using a high-speed video camera (Vicon Vue, Vicon Motion Systems, UK) synchronized with a 3-D motion analysis system. The camera was grounded at a position 5 m from the landing point, and the height was set such that the entire body could be photographed before and after the landing. The positions and heights of the cameras were unified for all participants. Video recordings were performed at 100 Hz frames. The positions of the 3-D motion analysis system, force plate, and high-speed video camera are shown in Fig. 1.

2.3. Data analysis

2.3.1. MediaPipe Pose [12]

MediaPipe Pose consists of MediaPipe Hands and MediaPipe Face Mesh detection systems, which extract the body from the image frame as a region of interest (ROI). The landmarks within the extracted ROIs were predicted using the BlazePose Detector. The BlazePose Detector predicts the body center position (origin of the xyz axis in the frame) and the radius of the circle circumscribing the human body, with the center position as the axis, using the BlazeFace model. Human posture is detected from the face detected by the MediaPipe Face Mesh, the center of the human body, and the circle circumscribing the body. It mechanically learns the positional relationship from the center of the detected human body and the posture information in the BlazePose Detector in the next frame of the video and predicts the landmark model.

We used the Python solution API of open resources on the webpage and performed calculations using Google Collaboratory. A video file (avi file) captured by a high-speed camera was divided into frames using Google Collaboratory and MediaPipe Pose was executed using the divided files.

2.3.2. Calculation of the knee valgus angle

The MediaPipe Pose topology uses 33 points on the human body based on previous face and body detection estimations [13–15]. On the basis of the landmark model, the plane coordinates (x, y) of 23 left hips, 25 left knees, and 27 left ankles were recorded in the JSON files. Using Google Collaboratory, the sparse matrix in the calculated JSON files was converted to a dense matrix, a plane vector was created (v1: left knee to left hip, v2: left knee to left ankle), and the knee valgus angle formed by the vector using Google Collaboratory was calculated as the angle. The angle formed by the plane vector was calculated at the smaller side of the circumference, but the knee valgus angle calculated by the MediaPipe Pose did not exceed 180° in all trials. Low-pass filtering (2 Hz) was applied to the calculated knee valgus angle.

For the 3-D motion analysis systems, the VICON NEXUS 2 (Vicon Motion Systems, UK) software was used from the marker position coordinates attached to the body landmarks and the participant's height, leg length, and distance between both anterior superior iliac spines (Fig. 2). The center points of the hip, knee, and ankle joints were calculated [16] in csv file format. Using Google Collaboratory, we extracted the coordinates (x, y) on the frontal plane from the calculated 3-D joint center point position and created vectors in the same way as in the MediaPipe Pose (v1: left knee joint center to left hip joint center, v2: left knee joint center to left ankle joint center). The cosines of the vectors were calculated from the magnitude and position coordinates of each vector, and the knee valgus angle was calculated using an inverse trigonometric function. The report data included the absolute knee valgus angle and knee valgus excursion (excursion angle from the IC), and comparisons were made using each calculated angle.

The analysis interval of the knee valgus angle in the MediaPipe Pose and 3-D motion analysis systems was 100 ms from the initial contact (IC). IC was defined as the time when the GRF force was >10 N, and the calculated joint angles were represented by the

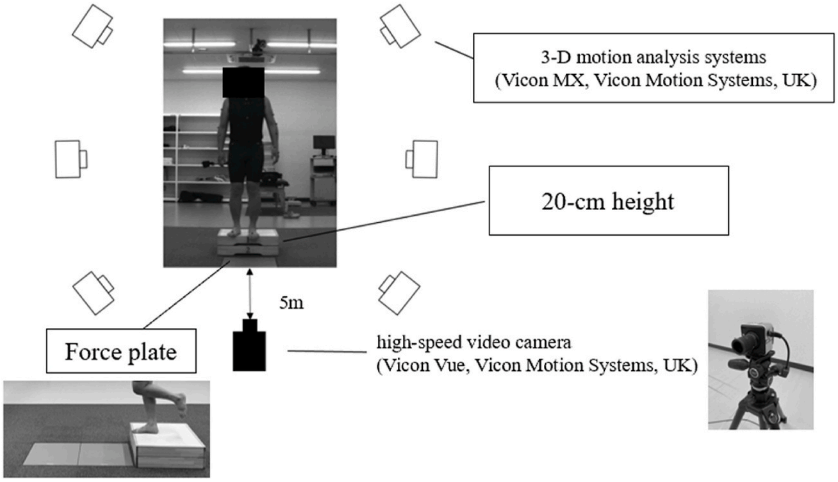

Fig. 1. Measurement environment.

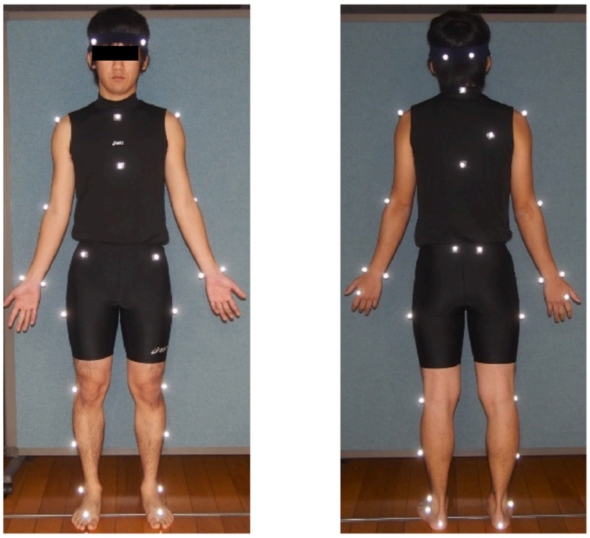
[redacted]

Fig. 2. Marker attachment position.

absolute value and amount of change based on IC (excursion angle from the IC).

2.4. Statistical analysis

IBM SPSS Statistics 27 (IBM Japan, Japan) was used for statistical analysis. The main effects were calculated using repeated two-way analysis of variance (ANOVA) with two factors: the knee valgus angle calculation method (MediaPipe Pose, 3-D motion analysis systems) and time from IC. For concurrent validity, Pearson's correlation coefficient for the knee valgus angle was calculated using each method. Additionally, a Bland–Altman analysis was performed to evaluate the consistency between the MediaPipe Pose and 3-D motion analysis systems. In the Bland–Altman analysis, the upper and lower limits of agreement were set to an angle error of less than 5°, on the basis of that in previous reports [17,18].

To evaluate the reliability of MediaPipe Pose, the intraclass correlation coefficient (ICC) (intra-rater reliability: ICC [3,10]) and the ICC with 3-D motion analysis systems (inter-rater reliability: ICC [3,10]) were calculated. The significance level was <5 %, and ICC values were interpreted as follows: excellent (0.75–1), modest (0.4–0.74), and poor (0–0.39) [19].

3. Results

3.1. Participants

Nineteen participants were excluded because they had experienced an ankle fracture in the past year ($n = 1$) or pain during landing ($n = 1$). In addition, one person who had difficulty maintaining posture when jumping and landing was excluded, and a total of 15 individuals were included (mean ± standard deviation, age; 19.9 ± 1.0 years, height; 173.4 ± 7.2 cm, body mass; 65.4 ± 10.4 kg).

3.2. Knee valgus angle comparison between MediaPipe Pose and 3-D motion analysis systems

Two-way ANOVA showed a main effect of the knee valgus angle calculation method, and the calculation using MediaPipe Pose was significantly higher than that using the 3-D motion analysis system ($p < 0.05$, Fig. 3A). The error ranged from 18.83° to 19.68°. There was no significant effect of time on IC ($p > 0.05$, Fig. 3A). In the Bland–Altman analysis, the angular error was >5° in knee valgus angles during 100 ms from IC, and differences in knee valgus angles between MediaPipe Pose and 3-D motion analysis systems included more negative values than the bias value (bias = −19.28, 95 % limits of agreement: 25.66 to −12.91, Fig. 4A). No significant concurrent validity was found between the MediaPipe Pose and 3-D motion analysis systems for absolute values without 90 ms ($r = 0.590$, $p = 0.021$; Table 1).

There was no main effect of the knee valgus angle or time on the excursion angle from IC ($p > 0.05$, Fig. 3B). In the Bland–Altman analysis, the angular error was <5° in knee valgus angles during the 100 ms from IC (bias = 0.181, 95 % limits of agreement: 3.165 to 3.526, Fig. 4B). Concurrent validity was significantly correlated with the knee valgus angle between the MediaPipe Pose and 3-D motion analysis systems in the excursion angle from the IC ($r = 0.554$ to 0.604, $p < 0.05$, Table 1).

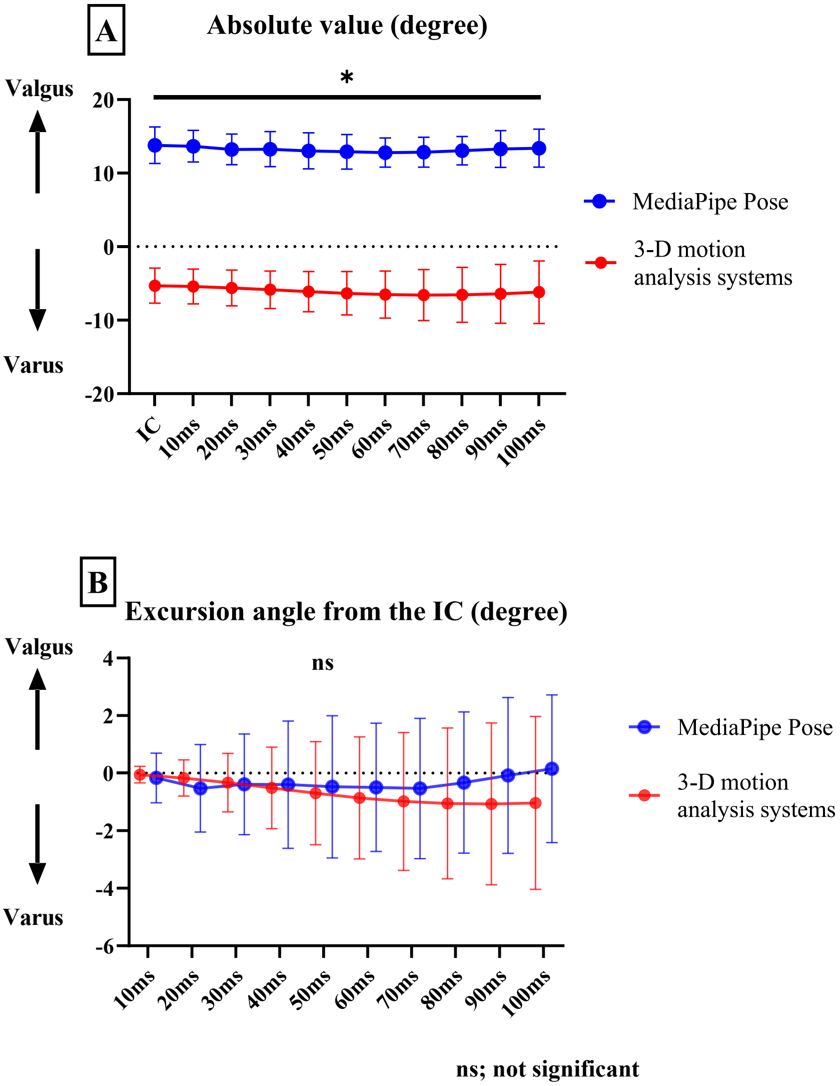

Fig. 3. Knee valgus angle 100 ms from initial contact (IC).

3.3. *Reliability of MediaPipe Pose*

The intra-rater reliability ICC [3,10] in absolute value was 0.7 or higher, indicating that it was the most modest (Table 2). The absolute inter-rater reliability ICC [3,10] was poor during IC to 70 ms after landing (Table 3). The inter-rater reliability of the excursion angle from IC and intra-rater reliability ICC [3,10] from 10 ms to 70 ms after landing was >0.4 (Table 2), which was modest or better. Regarding inter-rater reliability ICC [3,10], there were modest or excellent levels at all time courses (Table 3).

4. Discussion

In this study, the concurrent validity with 3-D motion analysis systems was confirmed, and inter- and intra-rater reliabilities showed adequate results. To our best knowledge, this study is the first to measure the knee valgus angle, which is a risk factor for ACL injury, and to examine its reliability and validity using posture estimation by artificial intelligence.

In a previous study that estimated the sagittal plane angle during jump landing using DeepLabCut for animal behavior analysis, the error in the knee joint flexion angle using the marker-based method was 2.68° [20]. Regarding the markerless system, the error of the knee valgus-varus angle for single-hop landing was 4.69° using Microsoft Kinect™ [8]. The absolute value of the knee valgus angle in this study had a significant main effect between the MediaPipe Pose and the 3-D motion analysis systems, and it was higher than that of the 3-D motion analysis systems. This suggests that the absolute accuracy of the calculated knee valgus angle using MediaPipe Pose was low. Therefore, we calculated the knee valgus angle, excluding the z-component (depth), for which reliability has not been established in the MediaPipe Pose. In addition, the joint center used to calculate the plane angle in the Plug-in Gait model was extracted from the x-

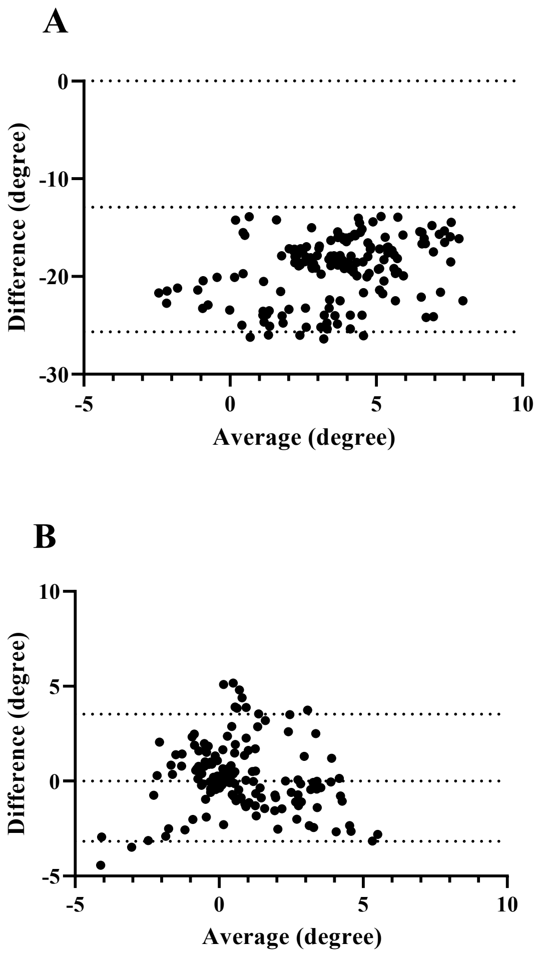

Fig. 4. The Bland–Altman plots demonstrating agreement between methods.

Table 1
Concurrent validity of MediaPipe Pose.

	IC	10 ms	20 ms	30 ms	40 ms	50 ms	60 ms	70 ms	80 ms	90 ms	100 ms
Absolute value											
Pearson's r	0.016	0.017	0.008	0.138	0.181	0.145	0.214	0.368	0.494	**0.590**	0.475
P value	0.954	0.951	0.976	0.623	0.517	0.606	0.443	0.178	0.061	**0.021**	0.074
Change from the IC											
Pearson's r	–	**0.554**	**0.604**	**0.697**	**0.757**	**0.673**	**0.670**	**0.664**	**0.673**	**0.714**	**0.629**
P value		**0.032**	**0.017**	**0.004**	**0.001**	**0.006**	**0.006**	**0.007**	**0.006**	**0.003**	**0.012**

ms; milliseconds.

and y-components of the 3-D data. A previous study reported that the knee joint center calculated using the 3D maker-based method had a mean difference of approximately 30 mm from that calculated using posture estimation models (OpenPose, AlphaPose, DeepLabCut) [21]. The z-component in MediaPipe Pose is currently under development [22], and it may be possible to calculate the 3-D joint angle using the z-component in the future. Therefore, further research may reveal additional applications of MediaPipe Pose.

The validity and consistency of the change in the knee valgus angle from IC were good. These ICCs show good validity, similar to previous research [17,18], and the angle calculation using MediaPipe Pose is comparable to the conventional calculation method. However, good validity was found only for the amount of change; therefore, normalization by participant alignment and by sex may be necessary when applying this method in clinical practice. Regarding the knee joint valgus angle during jump landing, sex, static knee valgus angle, and femorotibial angle on radiography are predictive factors [23–25], and accuracy of the MediaPipe Pose requires further verification by changing the target. There was a fixed error in the absolute angle between the MediaPipe Pose and the 3-D motion analysis systems. The calculation of the joint center in Vicon uses the position coordinates of the marker attached to the body and the height of the participant. MediaPipe Pose does not consider the participants' basic information, including height, and

Table 2
Intrarater reliability of MediaPipe Pose.

	Absolute value		Excursion angle from IC	
	ICC [3,10]	95 % CI	ICC [3,10]	95 % CI
IC	**0.86**	0.59–0.95	–	
10 ms	**0.85**	0.58–0.95	**0.60**	−0.16–0.86
20 ms	**0.86**	0.58–0.95	**0.66**	0.00–0.88
30 ms	**0.87**	0.63–0.96	**0.66**	0.01–0.88
40 ms	**0.87**	0.63–0.96	**0.57**	−0.24–0.85
50 ms	**0.89**	0.7–0.96	**0.63**	−0.08–0.87
60 ms	**0.84**	0.54–0.95	**0.70**	0.13–0.90
70 ms	**0.80**	0.43–0.93	**0.47**	−0.54–0.82
80 ms	**0.70**	0.13–0.90	0.25	−1.18–0.74
90 ms	**0.70**	0.12–0.90	0.28	−1.09–0.76
100 ms	**0.69**	0.09–0.89	0.14	−1.50–0.71

ICC, intraclass correlation coefficient; CI, confidence interval; ms, milliseconds; Bold indicates significant difference ($p < 0.05$).

Table 3
Interrater reliability between MediaPipe Pose and three-dimensional motion analysis systems.

	Absolute value		Excursion angle from IC	
	ICC [3,10]	95 % CI	ICC [3,10]	95 % CI
IC	0.03	−1.88–0.68	–	
10 ms	0.03	−1.88–0.68	**0.50**	−0.49–0.83
20 ms	0.02	−1.93–0.67	**0.60**	−0.19–0.87
30 ms	0.24	−1.26–0.75	**0.75**	0.27–0.92
40 ms	0.31	−1.07–0.77	**0.82**	0.45–0.94
50 ms	0.25	−1.24–0.75	**0.78**	0.35–0.93
60 ms	0.32	−1.02–0.77	**0.80**	0.41–0.93
70 ms	**0.49**	−0.53–0.83	**0.80**	0.40–0.93
80 ms	**0.58**	−0.26–0.86	**0.80**	0.42–0.93
90 ms	**0.69**	0.09–0.90	**0.83**	0.50–0.94
100 ms	**0.59**	−0.21–0.86	**0.77**	0.30–0.92

ICC, intraclass correlation coefficient; CI, confidence interval; ms, milliseconds; Bold indicates significant difference ($p < 0.05$).

estimates the center using only video data. Therefore, the angle was calculated without considering the alignment of the individual, and the knee joint valgus angle may have been excessive.

Regarding the change in IC, errors from each individual's alignment can be reduced by using the IC as a reference point. In the Bland–Altman analysis, the angular error was >5° in the knee valgus angles during the 100 ms from the IC. In a previous study, the average mean difference was 3.2°, and the limits of agreement were 15.6°–21.9° for knee abduction angle in single-leg squatting [9]. Our results are similar to those of previous reports before normalization using the IC angle. Thus, MediaPipe Pose can use an angle that has undergone some correction (landing angle and basic information of the participant) owing to its joint center estimation.

The interrater reliability of MediaPipe Pose was modest, with an ICC of 0.4 or more for both the absolute value and change from the IC. In the markerless analysis, the reliability of the knee-ankle separation ratio in Microsoft Kinect™ and Vicon motion systems is good with ICC = 0.84 to 0.95 [26]. This indicates that it has a higher ICC than the change from the IC in this study. Nonetheless, this is the frontal angle in the 3-D position coordinates using the Microsoft Kinect™ depth sensor, which is different from the 2D position coordinate estimation in MediaPipe Pose. In addition, the depth sensor used in Microsoft Kinect™ is inexpensive and easy to use; however, it cannot be compared with MediaPipe Pose, which is completely free and uses general video data. OpenPose, a posture-estimation model, has good reliability in the angle in the sagittal plane during walking and squat movements [27,28] and is a useful posture-estimation model, although it is expensive for commercial purposes. Examining the appropriate cost and benefit of gait and motion analysis for therapeutic decision-making is necessary [29]. There are many advantages of using MediaPipe Pose to screen the knee valgus angle in multicenter large-scale studies of ACL injuries. Therefore, this study, which examined reliability and validity, has high clinical significance.

This study has some limitations. It was limited to male college students and did not consider women and adolescents with different physical parameters. The frequency of the high-speed camera was 100 Hz. Therefore, angle calculation errors owing to the frequency cannot be ruled out. Because the calculated data were 2-D, the effects of tibial rotation and other joints that greatly contribute to ACL injuries [3,4] could not be excluded. The landing error scoring system, which is used for ACL injury prediction, evaluates the trunk flexion angle and symmetry [30]. Moreover, calculating these angles from the landmarks estimated by the MediaPipe Pose is necessary. This study calculated the sample size on the basis of that in previous studies; however, the sample size was insufficient for clinical applications. Therefore, this study's findings pertain exclusively to the reliability and validity of the MediaPipe Pose and 3-D motion analysis systems and do not establish clinical validity or reliability. While test-retest reliability was assessed, a study involving 12 participants with ACL-reconstructed knees conducted two measurements [31]. Conversely, markerless motion-capture systems require a larger sample size for accuracy verification, up to a 95 % confidence interval [32]. Nonetheless, this study serves as a preliminary exploration of MediaPipe Pose usage and contributes to athlete development in clinical practice.

5. Conclusions

We found that calculating the joint angles using a pose estimation model (MediaPipe Pose) clarified its reliability and validity of the method. Because the concurrent validity of determining the absolute knee valgus angle is low, it is recommended that data calculated from MediaPipe Pose be measured as a change from a certain time point. In the future, we recommend that the resulting angles be interpreted with caution when compared with those of other studies. Although there are issues of low concurrent validity and consistency, this method is simple and can be applied to any athlete. Therefore, it will help create a comprehensive evaluation of ACL injury prevention programs.

Ethical statement

This study was approved by the ethics committee of the author's affiliated institution (Takarazuka University of Medical and Health Care), and the protocols conformed to the guidelines of the Declaration of Helsinki (reference number; 2204221).

Data availability statement

The raw data were generated at Takarazuka University of Medical and Health. Derived data supporting the findings of this study are available from the corresponding author (M.A.) on request.

CRediT authorship contribution statement

Makoto Asaeda: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. **Tomoya Onishi:** Data curation, Methodology, Project administration, Software, Writing – review & editing, Conceptualization, Formal analysis, Supervision, Visualization. **Hideyuki Ito:** Data curation, Investigation, Methodology, Writing – review & editing. **So Miyahara:** Data curation, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **Yukio Mikami:** Conceptualization, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e36338.

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