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Sports Court-Based Camera Calibration Technique for Three-Dimensional Reconstruction of Knee Joint Kinematics

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Abstract

Videos of sports injuries provide beneficial insight for understanding their mechanisms. Recently, video analysis of actual injuries is particularly focused upon by researchers studying the anterior cruciate ligament (ACL). It is expected that establishing a technology capable of quantifying 3D knee kinematics using accidentally filmed videos of injuries could further our understanding of the ACL injury mechanism. The purpose of this study was to validate a camera calibration technique using sports court geometries to establish a methodology to extract 3D knee joint kinematics from uncalibrated video sequences. Four cameras were calibrated using line intersections and the vertical goal mouth of a handball court. A 1.6-m scaling pole, goniometer-embedded link model, and jump-landing motions were filmed, and those 3D kinematics were reconstructed via the direct linear transformation method. The reconstructed values were compared with direct measurements and marker-based motion capture data to assess the accuracy of the reconstruction. Inter- and intra-operator differences were quantified to evaluate the objectivity and reliability of the technique. The length errors ranged from 0.65 to 1.7 cm and angular errors were 1.67°–3.90°. Knee flexion/extension was most accurately reconstructed (errors: 2.71°–4.25°), and the knee adduction/abduction showed moderate accuracy (errors: 3.13°–5.35°). The axial rotation showed large errors of 5.02°–6.53°. Although some limitations exist, the error ranges were small relative to those of previously reported knee displacements during actual ACL injury. Therefore, this technique can be used to quantify knee kinematics from uncalibrated video sequences with reasonable precision.

Key words: direct linear transformation method, three dimensional knee kinematics, anterior cruciate ligament injury, camera calibration

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Ⅰ. Introduction

Several approaches have been employed to investigate the biomechanical factors underlying sports injuries such as motion analysis of maneuvers mimicking injurious situations[1–3], cadaver experiments[4, 5], and computer simulations[6, 7]. Video analysis of actual injury situations has recently been recognized as an effective methodology to quantify an injured athlete's motion, because it is free from ethical issues or restrictions of direct measurements during real sports events.

Technical aspects of video analysis for sports injuries have been developed and utilized, especially in studies aimed at identifying the mechanisms of noncontact anterior cruciate ligament (ACL) injuries[8–11]. In the early stages of the development of video analysis, Olsen[11] evaluated the injured knee joint configuration based on experts' subjective judgment. This study outlined the mechanism of ACL injury, and the results were considered somewhat objective; however, they were not sufficient [12]. Hewett et al.[8] processed still images of ACL injuries and suggested that the combination of the lateral trunk and knee abduction motion contributes to increasing ACL injury risk, particularly in females. Krosshaug and Bahr[12] developed a video processing technique for quantifying the time history of 3D knee joint kinematics from multiple video data. Based on this technique, Koga et al.[13] reported that a complicated 3D mechanism (i.e., combination of tibial internal rotation and abduction relative to the femur) occurs during ACL injury.

To reconstruct 3D knee kinematics from multiple video data, known geometric information must be simultaneously filmed in the background of the video. Sports court lines are strong candidates for such calibration references, because most of video sequences capture the court lines along with the injured athletes. Moreover, the geometry of sports courts is easily referenced in rulebooks. The idea of court-based camera calibration is itself not novel[14], and widespread applications have been developed using the court-based camera calibration technique such as real-time overlaying of the graphics for a soccer pitch[15], detecting the specific location of a football pitch[16], and obtaining 2D[16, 17] and 3D[18, 19] trajectories of players and balls on a court. However, to the best of our knowledge, no studies have validated the use of a sports court as a camera calibration object for reconstructing detailed knee joint kinematics. Krosshaug et al.[20] used court geometry to reconstruct 3D knee kinematics in their application study. However, because their technique was not validated using a real sports court[12], the potential of the court-based reconstruction of 3D knee kinematics remains unknown.

Therefore, in this study, we aimed to assess the precision of reconstruction of human knee kinematics using the court-based camera calibration technique to establish a methodology for investigating the mechanism of ACL injury. A team handball court was used because ACL injuries are common among handball players[21]. Moreover, because there are sufficient planar reference points around the area where injuries are most likely to occur (i.e., the area between the goal and free throw area lines), successful reconstruction of 3D knee kinematics is expected. In this study, the following points were specifically investigated.

1) To validate the accuracy of the court-based camera calibration, 3D motions of known artificial objects (a scaling pole and a link joint model) were computationally digitized, and the errors were evaluated by comparison with direct measurements. This procedure allowed us to validate the reconstruction accuracy by eliminating the human error arising from manual digitization. One concern for the handball court was that the only available vertical reference points were the mouths of the goals, which were fixed at the both ends of the court. We also investigated whether the small number and the uneven distribution of the vertical reference points would cause differences in the reconstruction accuracy between different areas.

2) To quantify the errors in reconstructed knee kinematics, the manually digitized kinematic data were compared with data obtained using the marker-based optical motion capture system.

Ⅱ. Materials and Methods

A. Experimental setting and data recording

An officially certified handball court was used. Before the experiment, court geometry accuracy was verified using a laser distance meter (Leica DISTO D8, Leica Geosystems, Heerbrugg, Switzerland), and we confirmed that the largest deviation from the rulebook was <1 mm in length and <0° in angle. Thus, we considered our court to be applicable as a calibration object. The origin of the court coordinate system was defined at the right-side corner (Figure 1). The three orthogonal axes were defined as follows: the x-axis pointed to the left, the y-axis pointed backward, and the z-axis pointed upward. The planar reference points were defined as follows: two corners (1, 2): the midpoint of the goalkeeper's line (3), the midpoint of the 7-m throw line (4), and evenly spaced segments of the free throw area line (5–67). The vertical reference points (G1–G34) were defined as the boundaries between the red and white strips painted on the goal mouth. Camera Nos. 1 and 2 (SONY HDR-XR560, Resolution: 1920 × 1080, Sampling rate: 30 Hz, Noninterlaced; Sony Corp., Tokyo, Japan) were located on the extension of the center line and 2 m outside of the side line. Distance from the goal mouth was 23.3 m. This camera position was usually used to film the handball games because the both courtside can be filmed evenly. Video recordings of the sports injuries are generally accidental events, thus we consider it is important to use usually used camera positions to evaluate the court-based camera calibration technique. Camera Nos. 3 and 4 were located at 10 m from the end line and 2 m outside of the side line. This camera position was also well accepted to film the games because the conflict between offense and defense is performed around the free throw area line. All cameras were firmly fixed 5 m above from the court level so as to cover the two court corners, goal mouth, and all segments of the free throw area line. This

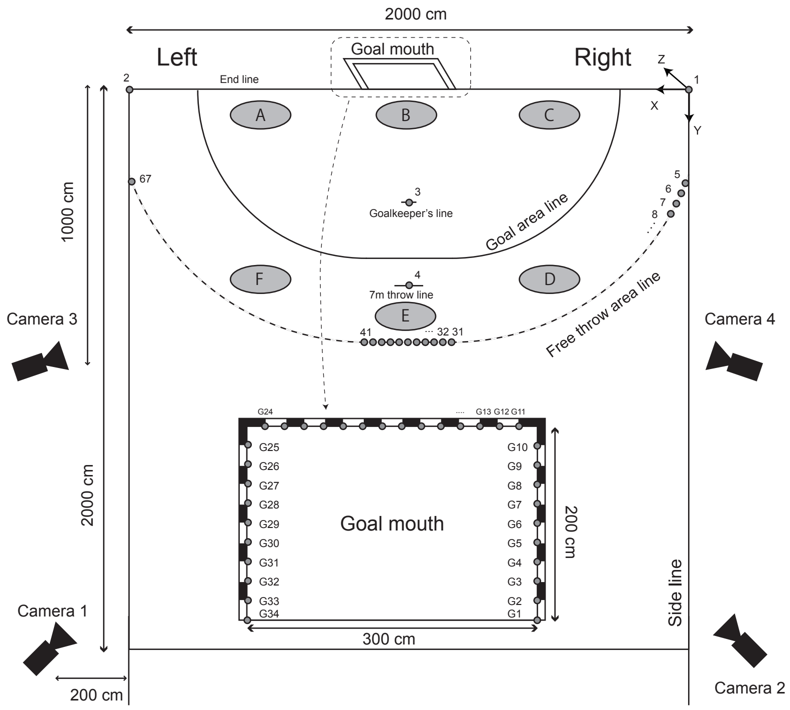


Figure 1 The experimental settings and reference points on the handball court.

The origin of the court coordinate system was defined as the right-side corner. Two corners (1, 2), the middle of the goalkeeper's line (3), the middle of the 7-m throw line (4), and every dot on the free throw area line (5-67) were designated as planar reference points. The color boundaries of the goal mouth were designated as vertical reference points. Trials for the scaling pole and link model were conducted at locations A-F (gray shaded circles).

camera height corresponds to the camera viewing from the spectator seat.

B. Trial

1. Length trial with a scaling pole

A scaling pole (Figure 2A) comprising two black markers 20 cm in diameter was filmed while an operator moved it along the x-axis of the court coordinate system (from left to right) at approximately 1 m/s. The inter-marker distance was 1.6 m. Ten trials per 6 different locations (locations A–C were near and D–F were far from the vertical reference points) were performed to investigate whether uneven distribution of the vertical reference points influences the accuracy of the reconstruction (Figure 1).

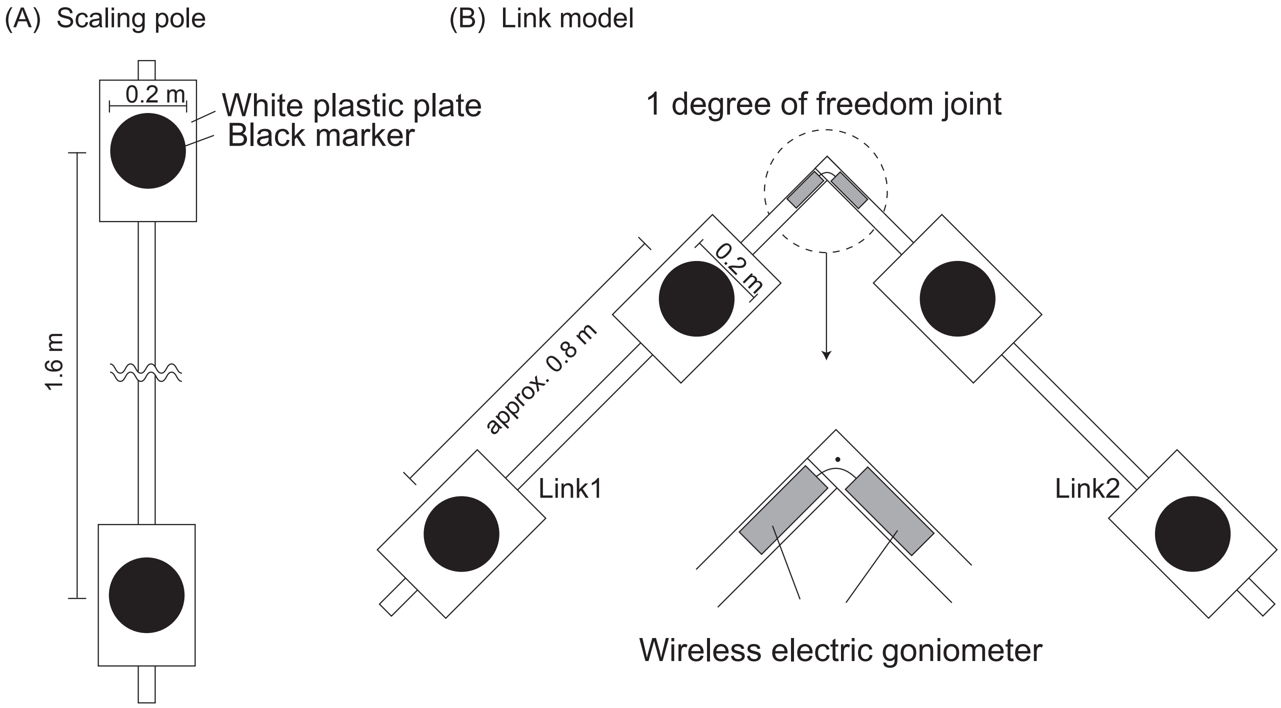


Figure 2 The artificial objects used for length and angle trials

(A) The scaling pole had two black markers of 20-cm diameter. The inter-marker distance was 1.6 m. (B) A goniometer-embedded link model. Each link had two markers.

2. Angle trial with a link joint model

The reconstruction accuracy in the angle was assessed using a custom-made, two-link joint model (Figure 2B). Two markers were attached to each link to specify the joint altitude in the camera images. The operator rotated the joint at approximately 60°/s and filmed the joint at locations A–F. Note that as the orientation of the joint model was always along the x-axis of the court coordinate system, the joint altitude with respect to the optical axis of each camera varied depending on the location (A–F). In particular, at D and F, the joint rotation direction became nearly parallel to the optical axes of cameras 1 and 3, respectively, and the accuracies were expected to decrease. A wireless electric goniometer (ZB-154H, NIHON KODEN, Tokyo, Japan) embedded at the joint was used to measure the true angle at 1-kHz sampling frequency. The cameras were synchronized by capturing the light-emitting diode (LED) light onset. The goniometer data were measured together with the analog signal from the LED light to synchronize the video data.

3. Knee joint kinematics trial

A healthy, right-handed female handball player participated in the experiment. Written consent was obtained from the participant before the trial, which was approved by the local ethics board. The reflective markers were attached at the following landmarks: tip of the big toes, medial and lateral malleolus, tibial tuberosity, medial and lateral femoral epicondyles, frontal aspect of the thigh, great trochanter, and the anterior and posterior superior iliac spine. After capturing the static calibration trials, the subject performed ten jump shots at location E and was filmed by four cameras. In addition, the trajectories of the reflective markers were captured using an optical motion capture system (Opti Track, 6×S250e cameras, resolution: 832 × 832, sampling rate: 30 Hz; NaturalPoint, Inc., OR, USA) for comparison with the court-based camera calibration.

C. Data processing

To determine the objectivity and reliability of our technique, two operators (OpA and OpB) processed all datasets twice for length, angle, and knee kinematics trials. OpA was a senior biomechanics researcher who was familiar with the manual digitization of human motion. OpB was a graduate student who was less experienced in digitizing human motion.

Lens distortions were corrected by a previously described method 15. The image coordinates of the reference points were obtained using the custom-made LabVIEW script within the Vision Development Toolbox (National Instruments Corporation, TX, USA). First, the movie data were converted from the RGB to binary images with the function (Threshold2), and the position of the pixels with high contrast (e.g., white court lines on a dark background or black markers attached to the artificial objects] were identified. The court lines were then detected by the Hough transform, and the image coordinates of the court corners were obtained by computing the line intersections. The positions of the planar reference points were obtained by computing the center of mass of the pixel groups of each segment of the free throw area line. The image coordinates of the vertical reference points were obtained by identifying the boundaries of the striped pattern on the goal mouth. As observed from this image processing procedure, all image coordinates of the reference points were obtained computationally. To obtain the direct linear transformation (DLT) parameters for each camera, the DLT method was applied to the image coordinate set and the corresponding known 3D coordinates. These DLT parameters achieved small mean standard deviations (SDs) of 0.57 (0.55) cm, 1.13 (1.07) cm, and 0.27 (0.33) cm for the x-, y- and z-directions, respectively, between the positions of the reconstructed reference points and the known 3D coordinates.

The image coordinates of the markers attached to the artificial objects were also digitized computationally, and 3D positions were computed with the DLT reconstruction. The positional data were smoothed with the second-order, low-pass, zero-lag digital Butterworth filter with 6-Hz cut-off frequency. Subsequently, the inter-marker distance and the angle between the links were calculated.

To calculate the knee joint kinematics, the following anatomical landmarks were manually digitized: left and right sides of the great trochanter; the center of the hip, knee, and ankle joints; and the distal tip of the big toes. To determine the shank and thigh segment orientation, the lateral femoral epicondyles and lateral malleoli were also digitized. Subsequently, the DLT reconstruction was applied to obtain the 3D coordinates of the landmarks.

Based on the marker-based motion data, the positions of the centers of the joints were also calculated. The center of the hip was estimated according to the method of Bell et al.[22]. The center of the knee joint was defined as the mid-point of the medial and lateral femoral epicondyles and 2.5 cm distal of the lateral femoral epicondyle[23]. The center of the ankle was defined as the mid-point of the medial and lateral malleoli and 1 cm distal of the lateral malleolus[23]. The 3D positions of the joint centers were smoothed with a second-order, low-pass, zero-lag digital Butterworth filter with 12- and 10-Hz cut-off frequencies for the vertical and horizontal components, respectively.

Based on the 3D positions of the joint centers, three-link kinematic models of lower limbs were defined for each camera calibration technique. The segment coordinate system for the thigh and shank was defined as follows: the z-axis represents the longitudinal axis pointing upward, the y-axis represents the axis pointing laterally and perpendicular to the z-axis, and the x-axis was a cross-product between the y- and z-axes pointing forward. To describe the 3D knee joint kinematics, the joint coordinate system 24 was applied. The time window of interest began 1 s before and ended 1 s after the first foot impact during single leg landing from the handball player's jump shot.

D. Error evaluation and statistical analysis

To evaluate the effect and interaction of the unevenly distributed vertical reference points and the objectivity (inter-operator difference) and reliability (intra-operator difference) of the technique, mixed design analysis of variance (ANOVA) with two within-subject factors (location (A–F) and processing session (first and second processing)) and one between-subject factor (operators (OpA and OpB)) was conducted using the data obtained from the length and angle tests. The dependent variables were the root mean square (RMS) errors in length and angle between the court-based technique and direct measurements. If any factors were found to have a noticeable effect, a post-hoc Tukey Honestly Significant Difference test was employed to determine statistical significance. The significance level was set at $P < 0.05$. For knee joint kinematics, the errors were presented as RMS errors and maximum differences between the court- and marker-based methods throughout the trial.

Ⅲ. Results

A. Errors in length and angle tests

The ANOVA test revealed no significant interactions among the three factors (operators, locations, and processing sessions) for both length and angle tests. For the length test, only the locations had a significant effect ($F = 46.6$, $P < 0.01$). The post-hoc test showed that locations A–C, which were near the vertical reference points, showed significantly smaller errors than locations D–F (Table 1). These results indicate that the distance from the vertical reference points negatively influences the length errors. The smallest mean length error (i.e., smallest SD) of 0.65 (0.3) cm was found at location B, which was the location nearest to the vertical reference points. The largest mean error (i.e., largest SD) of 1.7 (0.33) cm, was found at location E.

For the angle test, although slight overestimations were observed around 100°–140°, overall agreement between the reconstructed and measured angles was obtained for each location (Figure 3). Similarly, in the length test, only the location had a significant effect on the errors between the calculated and measured angles ($F = 49.2$, $P <$

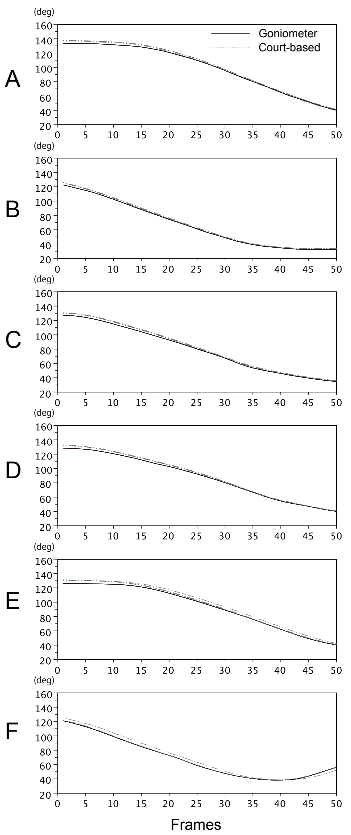
Table 1 Errors in length and angle trials [mean (SD)]

		Location					
		A	B	C	D	E	F
Length (cm)	Operator A	0.80 (0.23)	0.65 (0.30)	0.80 (0.27)	1.25 (0.21)^{A,B,C}	1.56 (0.29)^{A,B,C}	1.66 (0.43)^{A,B,C}
	Operator B	0.85 (0.25)	0.78 (0.26)	0.92 (0.27)	1.17 (0.23)^{A,B,C}	1.70 (0.33)^{A,B,C}	1.33 (0.48)^{A,B,C}
Angle (deg)	Operator A	2.22 (1.21)	1.67 (1.51)	2.49 (2.02)	3.67 (2.55)^{A,B,C,E}	1.92 (1.66)	3.76 (2.16)^{A,B,C,E}
	Operator B	1.92 (1.06)	1.91 (1.26)	2.52 (2.10)	3.70 (2.48)^{A,B,C,E}	1.68 (1.29)	3.90 (2.26)^{A,B,C,E}

Note: Super script denotes the location where the significant difference was found within the operator.
Since the main effect of processing session was not found, the values were averaged for each processing session.

Table 2　Errors in the reconstructed knee joint kinematics [mean (SD)]

		Flexion/Extension (deg)	Adduction/Abduction (deg)	Internal/External rotation (deg)
Operator A	First processing	3.09 (1.89)	3.13 (3.12)	6.15 (4.71)
	Second processing	2.71 (2.75)	3.45 (2.45)	6.53 (5.04)
Operator B	First processing	3.04 (2.54)	3.80 (3.57)	6.31 (4.46)
	Second processing	4.25 (2.42)	5.35 (3.08)	5.02 (3.60)



Figuer 3　The angle data comparison between the reconstructed from videos and measured with goniometer at each location

The solid line represents the goniometer data, and the gray dashed lines show the data from reconstructed the video image. Although some overestimations were observed around 100°–140°, the overall time patterns of the reconstructed angle data agreed well with the measured data.

0.01). The post-hoc test showed a slightly different result from the length test in that the errors at locations D (3.67°–3.70°) and F (3.76°–3.90°) were significantly greater than those at the other locations (Table 1), and the errors at location E (1.68°–1.92°) were not significantly different from those at locations A–C.

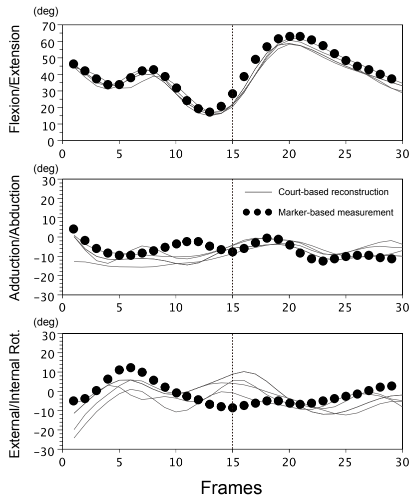


Figure 4　The knee kinematics comparison between the reconstructed with court-based technique and measured with the marker-based motion capture system

The dotted line represents the motion capture data, and the thin solid lines show the reconstructed data. The dashed vertical line at the 15th frame indicates the timing of the foot-floor contact. The knee flexion/extension was most accurately reconstructed. The reconstructed adduction/abduction data showed a slight deviation from the 9th to 15th frames, but agreed well with the measured data after foot contact. The external/internal rotation was the most inaccurate among these three angles.

B.　Errors in knee joint kinematics

The general time patterns of the knee joint angles reconstructed using the court-based technique broadly matched those obtained with the marker-based technique (Figure 4). The flexion/extension (flex/ex) angle was most precisely reconstructed with a mean (SD) error ranging from 2.71° (2.75°) to 4.25° (2.42°) (Table 2). The adduction/abduction (add/abd) was moderately accurate with a mean (SD) error ranging from 3.13° (3.12°) to 5.35° (3.08°) (Table 2). Reconstruction of the internal/external (int/ext) rotation was the most inaccurate with a mean (SD) error ranging from 5.02° (3.60°) to 6.53° (5.04°) (Table 2). Overall, the averaged differences between the results obtained using the court-based technique and the marker-based measurements were 3.27° for knee flex/ex, 3.93° for knee add/abd, and 6.00° for int/ext knee rotation (Table 2).

Ⅳ. Discussion

This study assessed the accuracy of court-based camera calibration technique for reconstructing human knee kinematics. Generally, reconstructed knee kinematics are influenced by two different errors, i.e., camera calibration errors and noise arising from the manual digitizing of body landmarks. We reasoned that these two errors should be evaluated separately. Thus, we first assessed the camera calibration accuracy alone using artificial objects, and then evaluated reconstructed knee kinematics that include potential error derived from human error.

A. Accuracy of the court-based camera calibration technique

Regarding our first objective, the errors for length with the court-based technique were <2 cm. This distance was only 0.1% of the handball court width (20 m). Furthermore, the maximum angle errors were <5°. Without using artificial reference objects, this precision level was achieved using the court geometric information alone. We reasoned that acquisition of precise image coordinates for reference points is quite important for accurate 3D reconstruction. To satisfy this issue, a custom-made LabVIEW script was developed to detect the positions of the reference points computationally. The small deviations between the reconstructed 3D reference point positions and the corresponding 3D coordinates demonstrated that the computational digitization worked well for acquiring precise reference point positions. The high color contrast between the court lines and floor was convenient for the automatic detection of reference points 14. Furthermore, the ANOVA test showed that no significant differences existed between operators and processing sessions in the length and angle tests. Hence, the accuracy of the court-based camera calibration technique was acceptable once the image coordinates for both the reference points and the objects were precisely determined. However, it is still difficult to conclude that the court-based calibration is sufficiently accurate for any type of motion analysis, because the requirements for precision vary for different research objectives. For example, studies requiring extremely high precision may not be possible because the accuracy level of the court-based technique is constrained by the video resolution. Notably, computational image processing is strongly recommended not only to increase calibration accuracy but also to maintain intra- and inter-operator consistency.

B. Influence of unevenly distributed vertical reference points

The limited number of the vertical reference points and poor camera orientations were found to be limitations in this technique. The errors in length measured at locations D–F were greater than those at locations A–C (Table 1), which clearly illustrates that length errors increase with increasing distance from the vertical reference points. In addition to the length errors, the angular errors also were increased at locations D and F. These increased errors were attributed to the poor relationship between the orientation of the link model and the cameras' optical axes such that the direction of joint rotation became nearly parallel to the optical axes of cameras 1 and 3 at locations D and F, and those camera views may not recognize the joint motion properly. This problem was expected because most studies have reported poor precision in reconstructing movement along the optical axis 12. Therefore, the reconstructed data near location E, which is the most active area during handball games, inevitably include errors derived from the limited number of vertical reference points.

Camera distance from the markers could be a potential source of the errors, however, few vertical reference points relatively much affected the reconstruction accuracy rather than the camera distance. If the close camera positioning could cancel the errors arising from the few vertical reference points, the length errors from the location D–F, the areas close to the cameras, were much smaller than those of the location A–C. It is thus not expected to decrease the errors by controlling the camera positions. To obtain the precise positional data far from the vertical reference points, another vertical information such as advertisement on the wall is a practical solution rather than the camera positioning.

C. Accuracy of knee joint kinematics and the corresponding objectivity and reliability

In addition to errors arising from the limited number of vertical reference points, numerical noise arising from the manual digitizing was expected to increase error in the reconstructed knee kinematics. To achieve the second research objective, we must address whether the errors in the reconstructed knee joint angles permit sufficient description of the knee joint motion usually observed in real injury situations. Krosshaug and Bahr 12 developed a video analysis technique named the model-based image matching (MBIM) technique. Their validation study showed that the potential errors of the MBIM technique were<7.5° for knee flex/ex, 4.9° for knee add/abd, and 9.1° for knee int/ext rotation using three camera views and not using any sports court reference points. Using this technique, Krosshaug et al. 20 analyzed video sequences of a female handball player's ACL injury at the right-back position (approximately location D in the present study) and reported that 15° peak knee abduction was observed 40 ms after the initial foot-floor contact. Koga et al. 13 also used the MBIM technique to investigate ACL injuries of female handball players and reported that 7°–15° knee abductions and 5°–21° peak external tibial rotations occurred at the knee at the time of injury. These studies successfully described the abnormally displaced knee kinematics because the potential errors of the MBIM technique were sufficiently small with respect to the joint angular displacement observed during ACL injuries. Compared to the precision of these previous techniques, the precision level determined for our court-based technique is sufficient for quantifying potentially abnormal joint kinematics during ACL injuries. Although the issue of too few vertical reference points was obvious, the precision of the court-based technique is still adequate for investigating the mechanism of ACL injuries.

In this study, the marker-based technique is used as a reference to evaluate the reconstruction accuracy in knee kinematics of the court-based technique. It is known that the marker-based technique also has potential limitation to detect precise knee kinematics. For example, the positional data from markers potentially contain oscillatory noises from skin artifacts. In addition, the markers on the skin do not always correspond to the bony movement. However, we must address what is the source of the angle difference between marker-based technique and court-based technique observed in this study. In flex/ex, both techniques showed similar trends through the landing trial. However, there were temporary inverse trends between techniques around 11 frames for add/abd and around 15 frames for ext/int. Obviously, these difference occurred because each technique used different position data to calculate joint angles, and it is not due to inaccuracy of the court-based technique itself. As mentioned in method section, the marker-based technique can computationally determined the center of hip joint by calculating from the position of the ASIS and great trochanter markers. On the other hand, the court-based technique needed to manually digitize the center of the hip joint from the 2D video data based on the anatomical knowledge. This technical difference produced differences in original positional coordinates and resulted in the errors of calculated knee joint angles. Figure 4 showed that the four angle data from the court-based technique showed similar trends, indicating that the positional coordinate from four individual digitizing processes had less deviation. This suggests that once the precise positional data were obtained, the precise angle reconstruction will be achieved by the court-based technique. Our length and angle trials also support the reconstruction accuracy of the court-based technique itself. Therefore the technical concern of the court-based technique is how to obtain precise positional data of the given body landmarks with manual digitizing.

While both operators showed small errors in reconstructing knee joint angles, OpB, who was the less experienced operator, scored a large error in the knee add/abd angle during her second data processing session (5.35°, Table 2). This human error could be another drawback of this technique when manual digitization is employed, the results may vary depending on operator's skill. For an individual with less knowledge of human anatomy, detecting the exact positions of joint centers with sufficient consistency is difficult. OpB proved the difficulty of the video processing in that detection of the hip joint center was especially difficult, potentially leading to the increased error in the knee add/abd angle during her second processing session. To eliminate such human error, a computational tracking algorithm could be introduced; however, describing the knee configuration in detail remains difficult. This may be due to the computational algorithm working under ideal conditions such as no occlusion of the targeted body parts, but the qualities of sports videos are not always favorable for such computer algorithms. In some cases, the orientation of an occluded limb or the positions of body landmarks of clothed players will need to be determined during the actual video editing procedure 8. In such cases, we believe that manual manipulation by experienced operators is the most robust and objective approach to ensure reconstructed motion quality. Although not included in this study, feedback-based data improvement [12] and the use of a kinematic constraint based on subjects' anthropometrics[25] can minimize human error and contribute to improved reconstruction accuracy.

In conclusion, the present study validated the accuracy of a court-based camera calibration technique aimed at reconstructing knee joint kinematics in the absence of a calibration object. Although increased errors were observed in areas far from the vertical reference points, the overall accuracy of the 3D reconstructions was reasonable. The reconstruction errors for the knee joint kinematics achieved by this technique were less than those of the previously reported video analysis technique, and the court-based camera calibration technique was found to sufficiently describe the abnormally displaced knee joint kinematics that occurs during ACL injury. At this time, even with the methodological concerns, such as errors arising from manual digitization, the court-based camera calibration technique can be used to quantify injurious knee motions from actual injury videos and provide beneficial insight for understanding the mechanism of ACL injury.

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