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Authors

Shogo Sasaki, PhD
Faculty of Health Sciences, Tokyo Ariake University of Medical and Health Sciences
Address: 2-9-1 Ariake, Koto-ku, Tokyo, Japan,
Phone number: +81-3-6703-7000 Fax: +81-3-6703-7100
E-mail: sasaki@tau.ac.jp

Hideyuki Koga, MD, PhD
Department of Joint Surgery and Sports Medicine, Tokyo Medical and Dental University
Address: 1-5-45 Yushima, Bunkyo-ku, Tokyo, Japan
Phone number: +81-3-5803-4020 Fax: +81-3-5803-0401
E-mail: koga.orj@tmd.ac.jp

Tron Krosshaug, PhD
Oslo Sports Trauma Research Center, Norwegian School of Sport Sciences
Address: PB 4014 Ullevål Stadion 0806, Oslo, Norway
Phone number: +47-23-26-23-67 Fax: +47-23-26-23-07
E-mail: tron.krosshaug@nih.no

Satoshi Kaneko, PhD
Graduate School of Sport Sciences, Waseda University
Address: 2-579-15 Mikajima, Tokorozaswa-city, Saitama, Japan,
Phone number: +81-42-947-6879 Fax: +81-42-947-6879
E-mail: kaneko.3104@gmail.com

Toru Fukubayashi, MD, PhD
Faculty of Sport Sciences, Waseda University
Address: 2-579-15 Mikajima, Tokorozaswa-city, Saitama, Japan,
Phone number: +81-42-947-6879 Fax: +81-42-947-6879
E-mail: fukubayashi@waseda.jp

Title

Kinematic analysis of pressing situations in female collegiate football games: New insight into ACL injury causation

Running head

Kinematics of pressing manoeuvres in football

Abstract

The most common events during which anterior cruciate ligament (ACL) injuries occur in football are pressing situations. This study aimed to describe the knee and hip joint kinematics during pressing situations in football games in order to identify kinematic patterns in actions with a high risk for ACL injuries. We filmed 5 female collegiate football matches and identified 66 pressing situations. Five situations with a large distance between the trunk and foot placements in the sagittal plane were analysed using a model-based image-matching technique. The mean knee flexion angle at initial contact (IC) was 13° (range, 8°–28°), and increased by 11° (95% confidence interval [CI], 3°–14°) at 40 ms after IC. As for knee adduction and rotation angles, the knee positions were close to neutral at IC, and only minor knee angular changes occurred later in the sequences. The mean hip flexion was 25° (range, 8°–43°) at IC, and increased by 22° (95% CI, 11°–32°) after 100 ms. The hip was also externally rotated by 7° (range, −19° to 3°) at IC, and gradually rotated internally, reaching 10° of internal rotation (range, −5° to 27°) at 100 ms after IC. This study suggests that the observed knee valgus, internal hip and knee rotation, and static hip flexion previously reported in non-contact ACL injury events are unique to injury situations. In contrast, neither rapid knee valgus nor increased internal rotation was seen in non-injury pressing manoeuvres.

Key words

knee, hip, motion analysis, match situation, high-risk manoeuvre, defender, deceleration

Understanding how sports injuries occur is necessary for developing effective preventative measures. Analysing the biomechanical characteristics of injury-causing situations can provide vital information about how injuries occur. The most accurate and comprehensive description of such situations to date was reported by Koga et al.[1], who utilized a model-based image-matching (MBIM) technique to analyse 10 high-quality video sequences of anterior cruciate ligament (ACL) injuries. In their study, sudden changes in knee flexion, valgus, and internal rotation were seen within the first 40 ms after initial contact (IC).[1] Furthermore, studies based on 3-dimensional (3D) video analyses have reported similar findings in football,[2] basketball and handball,[3] and alpine skiing.[4] However, these studies have not included controls (i.e., players who performed high-risk manoeuvres without injury).

Moreover, Waldén et al.[5] reported that 85% of ACL injuries in football result from non-contact or indirect contact mechanisms, and 77% occur during defence. The most common event leading to non-contact ACL injuries in male professional football players was “pressing” situations, in which the defending player is running at a high speed toward the opponent in possession of the ball.[5,6] In a pressing situation, the defending player will typically decelerate and make an unanticipated cutting manoeuvre in order to reach the ball. Another study using a similar visual analysis for both sexes also reported that most ACL injuries occur in defensive players.[7] Both studies attempted to quantify joint kinematics during defensive plays in football by using visual inspection;[5,7] however, the authors acknowledged that their approach has limited accuracy. Interestingly, in most situations in which detailed knee movements could be estimated, knee valgus was observed. However, it is unknown whether these patterns are direct causes of injury or simply typical characteristics of high-risk pressing situations.

The purpose of this study was, therefore, to describe the knee and hip joint kinematics during pressing situations in football, in order to identify kinematic patterns in high-risk actions for ACL injuries and to compare these patterns with previously reported characteristics of injury-causing situations.[1,8,9]

Materials and Methods

We recorded 5 women’s football matches in Division 1 of Kanto Ladies Football League by using 3 to 5 digital video cameras (HDR-CX590V; Sony, Tokyo, Japan) with a resolution of 1080p and a frame rate of 60 Hz. The cameras were placed around the football field (approximately 3–10 m from the sideline/end-line) at the players’ level (height, 1.3 m) to capture their movements from various angles. The locations of cameras were set at the extensions of the halfway line, penalty box line, and end line.

Selection of representative situations

From the 5 games, we identified 66 events with movements that could be classified as “pressing” situations (Fig. 1). Of the 66 situations, 33 were determined via visual inspection to fulfil the following criteria: 1) good quality images with the camera angle approximating the sagittal view of the athlete, 2) good visibility of the foot making contact with the ground, and 3) an unobscured view of the athletes.

Next, we conducted a simple video analysis of the landing posture at IC by using the sagittal view footage based on the work of Sheehan et al.[10] The authors showed that the distance between the projection of the centre of mass (COM) on the ground and the base of support (BOS) normalized by the femur length (COM_BOS) was greater in athletes with ACL injuries than in controls. They also found that almost all ACL injuries occurred when the trunk was placed more posteriorly and COM_BOS was >1.2. A greater COM_BOS is also associated with a higher running velocity, which corresponds well with that observed in the injury situations reported by Waldén et al.[5] In this pilot study, the intra-class correlation coefficients (ICCs) were calculated to assess the reliability of the measurements for each video frame sequence. The ICC (1,1) and ICC (2,1) values were 0.950 (95% confidence interval [CI], 0.898–0.976) and 0.887 (95% CI, 0.738–0.947), respectively. The COM_BOS in 33 pressing situations was 1.2 ± 0.4 (average ± standard deviation), and 18 events reached a COM_BOS of >1.2. On the basis of these findings, we selected five situations involving 4 collegiate players (age, 20.3 ± 0.5 years; body height, 1.59 ± 0.04 m; body mass, 50.6 ± 2.6 kg) in which the COM_BOS was >1.2 (COM_BOS 1.74, 1.66, 1.53, 1.50, and 1.34, respectively) for subsequent 3D analysis (Fig. 2). These situations were finally selected because 1) the subjects were clearly captured from 4 camera angles and 2) anthropometric measurements could be obtained for the 3D motion reconstruction. Two situations (cases 2 and 3 in Fig. 2) were recorded from the same player. The subjects had no history of serious injury or surgery in the lower extremities. All subjects received clear and complete information about the study, and provided informed consent before the start of the analysis. The ethics committee of our university approved this study (approval number 109).

Video editing

To retain the best possible video quality, the video sequences were converted to the uncompressed TIFF (Tagged Image File Format) format by using Adobe After Effects (CS5; Adobe Systems Inc., San Jose, CA, USA). To synchronize different camera views of the same sequences, manual synchronization was performed using key events in each camera view (e.g., foot strike and ball touching).

MBIM motion analysis

To reconstruct the 3D kinematics of the players, we used a photogrammetric MBIM technique. The MBIM technique can reliably produce estimates of joint kinematics, COM, velocity, and acceleration when 2 or more camera views are available.[11] Details about how the MBIM motion analysis applies to football players have been reported previously.[2,12] Matching was performed using 3D animation software packages (Poser 4 and Poser Pro Pack; Smith Micro Software Inc., Aliso Viejo, CA, USA). The players' surroundings were constructed in the virtual environment according to the actual dimensions of the football field. The models of the fields were then manually matched to the background for each frame in every camera view. A skeleton model from Zygote Media Group Inc. (Provo, UT, USA) was used to track the players' movements. Anthropometric measurements were obtained from all players, and the segment dimensions of the skeleton model were set according to the provided measurements. The skeleton matching started with the pelvis as the parent segment. Next, the distal segments were matched frame by frame until, ultimately, the foot and head segments were matched. One researcher performed all 3D matching tasks. To minimize bias resulting from single-operator judgment, another expert reviewed the matching results and suggested adjustments to ensure the best possible fit. The matching was then adjusted accordingly until a consensus was reached. An example of a matched video is shown in Fig. 3. The knee and hip joint angles were converted into the joint coordinate system created by Grood and Suntay.[13] We used Woltring's generalized cross-validation spline package[14] with a 7-Hz cut-off to estimate velocity and acceleration for the COM translation. The calculations were performed using customized MATLAB® scripts (MathWorks, Natick, MA, USA).

Statistical analysis

We used the Friedman test to determine the changes in knee and hip joint angles between three different time points: IC, 40 ms after IC, and 100 ms after IC. We chose 40 ms because ACL injuries are likely to occur in this period.[1] However, we decided to extend the analysis to cover most of the deceleration phase of the pressing manoeuvres, to see if the results were also consistent. All statistical procedures were performed using IBM SPSS statistics (version 22.0 for Windows), and the statistical significance of all tests was set at $p < .05$. The results are shown as the mean, with 95% CI or range, as noted.

Results

The mean knee flexion angle at IC was 13° (range, 8°–28°), and increased by 11° (95% CI, 3°–14°, $p = .342$) after 40 ms. At 100 ms after IC, the knee flexion angle increased by 45° (95% CI, 32°–58°, $p = .005$). These findings are shown in Fig. 4 and Table 1. As for knee adduction and rotation angles, the knee positions were close to neutral at IC, and practically no angular changes at all occurred later.

The mean hip flexion was 25° (range, 8°–43°) at IC, and increased by 8° (95% CI, 2°–13°, $p = .342$) after 40 ms, and by 22° (95% CI, 11°–32°, $p = .005$) after 100 ms (Fig. 5 and Table 2). The hip was also externally rotated by 7° (range, −19° to 3°) at IC and gradually rotated inward, reaching 10° of internal rotation (range, −5° to 27°) after 100 ms. The hip abduction angle was 30° (range, 23°–38°) at IC and remained fairly constant during the next 100 ms.

Discussion

This is the first study to analyse the knee and hip joint kinematics of defensive action during pressing situations seen in actual football games, by using a 3D analysis technique. The 5 situations of high-risk defensive action during pressing situations showed consistent kinematic patterns. However, the observed kinematic patterns were substantially different from those previously reported for ACL injuries.[1,8,9] In contrast with situations that resulted in injury, there were no rapid knee valgus or internal rotation increases in the observed defensive action during pressing. The hip also displayed a smooth transition into flexion and slight internal rotation after IC, which contrasted with previously reported hip kinematics in injury situations.[8,9]

Knee joint kinematics

The mean knee flexion angle at IC observed in our five situations is comparable with those observed in injury situations, indicating that athletes are likely to land with a relatively straight knee during pressing situations, regardless of whether ACL injury occurs. Waldén et al.[5] reported that male football players sustaining ACL injuries during pressing actions have a low degree of knee flexion (maximum 20°) at IC. The results of a study on ACL injury situations,[1] which used the more precise MBIM technique, match the findings of this study. In their study, which included 10 female handball/basketball players, Koga et al.[1] reported that the knee flexion angles at IC ranged from 11° to 30°. In addition, laboratory-based studies during rapid changes of direction[15] or sidestep cutting manoeuvres[16,17] in female athletes demonstrated shallow knee flexion angles (<30° on average) at IC. The knee flexion angle during the single-leg stop movement, which is similar to pressing situations, was also <20° at IC.[18]

Furthermore, in the analysed non-injury situations, a significant increase by 45° in knee flexion angle at IC and 100 ms later indicated a smooth and controlled knee flexion after landing. Normal cutting manoeuvres, observed using marker-based motion analysis, also show smooth flexion motion of the knee,[11,19] which appears to be similar to our 5 cases. In contrast, a different kinematic pattern has been demonstrated in cutting manoeuvres that result in ACL injuries;[1] there is more rapid and significant displacement by 24° of knee flexion during the first 40 ms after IC in ACL injury cases.

The most prominent differences in knee kinematics between injury and non-injury situations were observed in the frontal and transverse planes. Koga et al.[1] observed a consistent pattern of sudden valgus development and internal rotation in their 10 injury cases, whereas we found no such motion characteristics in our 5 cases. Knee valgus is also frequently identified in injury-causing pressing situations in football,[5] as well as in numerous other video analysis studies.[1,8,20,21,22] The fact that no valgus movement was estimated using the MBIM method in the present cases, in contrast to previously reported ACL injury cases, indicates that frontal knee motion is linked to the injury mechanism.

Hip joint kinematics

The mean hip joint flexion angle at IC (25°) in our 5 cases was substantially lower than that reported by Koga et al.[8,9] for their 10 injury cases, but comparable to the average flexion angles reported by Waldén et al.[5] Differences in the play situations may be a reason for this discrepancy. While in our cases and in those of Waldén et al.,[5] the athletes were football players performing defensive play in pressing situations, the handball and basketball players studied by Koga et al.[8,9] performed offensive manoeuvres. During defensive actions, the trunk will normally have a more upright or leaning-back posture when compared with offensive actions as the athlete is breaking.

In contrast to situations that resulted in injury, in which the hip remained at virtually the same flexion angle of 50° on average during the 100 ms after IC,[8,9] we observed a steady increase in hip flexion after IC (increased by 8° until 40 ms later and by 22° until 100 ms later, respectively). This hip flexion contributes to energy absorption, thereby decreasing the load on the knee.[23] Excessive axial compressive force on the tibio-femoral joint has been linked to the ACL injury mechanism in cadaver studies.[24] In a laboratory-based study, male players demonstrated greater hip flexion displacement and less vertical ground reaction force during single-leg landings than did female players, which possibly contributes to the higher injury risk of female athletes.[25] Female football players also exhibited greater sagittal-plane hip-energy absorption in unanticipated conditions than in anticipated cutting tasks.[17] Hashemi et al.[26] have suggested that a mismatch between hip extension and knee flexion could be a mechanism that causes ACL loading and rupture. In a cadaver study, the same authors demonstrated that restricted flexion of the hip during simulated landings can cause ACL injury.[27]

In the 5 defensive actions during pressing analysed in the present study, the hip was externally rotated by 7° on average at IC and gradually moved internally by 10° on average at 100 ms after IC. In contrast, the hip internal rotation measured in ACL injury situations remained constant at 30° during the 40 ms after IC, which suggests that further movement towards internal rotation is difficult.[8] Several recent studies have reported that limited hip internal rotation range of motion is associated with an increased risk of ACL injury in football players and other athletes.[28,29,30] During sidestep cutting manoeuvres, knee abduction moments increased with hip internal rotation at IC.[31] These findings indicate that hip alignment in the transverse planes at IC may provide an opportunity to change knee kinetics.

Methodological considerations

The current study is important for several reasons. Field-based evaluation of sports performance is necessary because movements that occur in a laboratory environment are likely to be different from movements in real game situations.[12,16,31] Typically, athletes will use greater effort in a real game than during training, even if they are encouraged to perform at competition level. It has been previously shown that the incidence of ACL injury during football games is considerably (10–28 times) higher than during training sessions.[32,33] Moreover, movements that are considered high risk for athletes are typically avoided in laboratory settings for ethical reasons.[11] However, it is perhaps even more important to use the same methods when comparing injury to non-injury situations. Marker-based motion analysis has poor validity because of soft tissue artefacts, and may produce unrealistic kinematics[11,34,35] for the secondary planes of motion.[36,37] Using the same methodology will reduce systematic errors. Moreover, the MBIM method will likely be less influenced by soft tissue artefacts, and may therefore produce more realistic valgus angles. In a cadaver study, the MBIM technique achieved excellent accuracy and correlation compared with the bone-pin marker-based motion analysis.[38]

Some limitations must be considered when interpreting the findings of this study. First, the kinematic estimates from MBIM motion analysis are based on ordinary video cameras and can therefore not be expected to be perfect.[11] In addition, there is a risk of bias resulting from the fact that the analysts were aware that the analysed situations involved only non-injured players. Nevertheless, the MBIM technique has been demonstrated to be far more accurate than simple visual inspection.[11,39] The quality of the videos used for analysis was also generally good, which allowed for more accurate matching. In addition, the hip and knee kinematic time history data from MBIM motion analysis proved to be very similar to that from marker-based motion analysis.[11] Furthermore, the patterns of joint kinematics proved to be highly consistent, in particular during the period between IC and 40 ms after IC. Therefore, the observed differences between our results and those of injury situations that were analysed using roughly the same methodology are likely valid.

Second, this study was limited to only 5 high-risk cases. In addition, 2 of the 5 situations involved the same player. However, the kinematics from the 2 situations revealed that the hip and knee flexion, hence the movement, was substantially different, thus justifying including both situations. Nevertheless, 5 situations is clearly a limited sample. However, these situations were selected carefully based on stringent criteria, and can thus represent high-risk situations from actual football games. Meanwhile, it should be kept in mind that the COM_BOS criteria by Sheehan et al.[10] was originally based on injury situations involving run-stop or jump activities from various sport events. Those situations may be different from the present cases. Nevertheless, approximately half (18 of 33) of the situations in the current study had a COM_BOS of >1.2, suggesting that these situations had clear similarities. Importantly, however, these 5 situations showed consistent results and were substantially different from the kinematics previously reported in injury situations.

Third, the recorded video sequences had a relatively low frame rate (60 Hz). Although this frame rate impedes accurate estimation, for example, of changes in angular velocities and the timing of IC, it does not affect the measured joint angles. This limitation is also present in most other video analyses in the literature.[10,12,20,21]

Fourth, we focused the knee and hip joint kinematics in the present research; however, ankle and trunk motion or coordination may also affect ACL loading. An extended analysis including such variables could potentially provide further insight into injury causation. Interestingly, although not formally tested, the kinematics of the current study (Figs. 4 and 5) seem to be different from those of Koga et al.[1,8,9] also before landing (greater knee flexion angles before IC and more eternally rotated hip at IC). Recent studies[31,40] suggest that the landing technique and joint alignment at IC can affect the ground reaction force and knee abduction moment during the deceleration phase.

Finally, although pressing has been identified to be the largest category of injury-causing situations among professional male athletes, this may not be the case in female collegiate football players. However, a recent study by Kaneko et al.[41] reported that non-professional female football players also sustained non-contact ACL injury during pressing.

Perspectives

From the present study, it was apparent that neither rapid knee valgus nor increased internal rotation was seen in high-risk pressing cases, which is in contrast to previously reported ACL injury situations. In addition, the hip displayed a smooth transition into flexion and slight internal rotation after IC. Therefore, this study suggests that the observed knee valgus, internal hip and knee rotation, and static hip flexion previously seen in ACL injury events are unique to such situations. This strengthens the current view that knee alignment in the frontal and transverse planes as well as hip motion may be essential for preventing non-contact ACL injuries. Hence, players, coaches, and clinicians should focus on reducing the internal hip rotation and knee valgus, as well as having adequate hip flexion movement during game play. Current injury prevention programs focusing on such movement patterns have been shown to reduce ACL injury rates by approximately 60%.[42,43,44] Future studies should investigate how to reduce the effective time used in such programs while still maintaining their preventive effect, in order to increase uptake and compliance.

Conflict of interest

The authors declare that they have no conflicts of interest.

Contributors

SS designed the study plan, collected and analysed the data, and completed the final manuscript.

HK and TK helped in analysing the data and in preparing the manuscript. SK helped in collecting and analysing the data. TF conducted the study.

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Table 1. Knee kinematics during high-risk pressing actions at initial ground contact (IC), and at 40 ms and 100 ms after IC.

Variable	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**mean (95%CI[a])**
Knee flexion at IC, deg	8	10	12	9	28	13 (6–21)
Knee flexion at 40ms, deg	13	21	25	23	38	24 (16–32)
Knee flexion at 100ms, deg	59	49	70	63	51	58 (51–66)
Knee adduction[b] at IC, deg	0	2	3	2	1	2(1–3)
Knee adduction [b] at 40ms, deg	-2	2	0	3	0	1 (-1–2)
Knee adduction [b] at 100ms, deg	0	1	1	2	-1	1 (-1–2)
Knee internal rotation [c] at IC, deg	3	-1	0	-4	2	0 (-2–2)
Knee internal rotation [c] at 40ms, deg	2	-2	0	-2	3	0 (-2–2)
Knee internal rotation [c] at 100ms, deg	0	-2	0	2	1	0 (-1–1)

[a] 95% confidence interval

[b] Adduction/abduction of tibia relative to the femur. Negative values represent abduction from neutral, positive adduction.

[c] Rotation of tibia relative to the femur. Negative values represent external rotation from neutral, positive internal rotation.

Note: Case 2 and 3 are contributed from the same player.

Table 2. Hip kinematics during high-risk pressing action at initial ground contact (IC), and at 40 ms and 100 ms after IC

Variable	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**mean (95%CI[a])**
Hip flexion at IC, deg	30	13	43	8	29	25 (12–37)
Hip flexion at 40ms, deg	34	16	48	26	38	32 (22–43)
Hip flexion at 100ms, deg	58	25	57	51	44	47 (35–58)
Hip adduction [b] at IC, deg	-31	-26	-38	-33	-23	-30 (-25–-36)
Hip adduction [b] at 40ms, deg	-28	-24	-36	-34	-27	-30 (-25–-34)
Hip adduction [b] at 100ms, deg	-31	-21	-38	-24	-27	-31 (-24–-38)
Hip internal rotation [c] at IC, deg	-8	-9	-3	-19	3	-7 (-14–0)
Hip internal rotation [c] at 40ms, deg	-2	-5	-4	7	9	1 (-4–7)
Hip internal rotation [c] at 100ms, deg	18	1	-5	27	11	10 (-1–22)

[a] 95% confidence interval

[b] Adduction/abduction of femur relative to pelvis. Negative values represent abduction from neutral, positive adduction.

[c] Rotation of femur relative to pelvis. Negative values represent external rotation from neutral, positive internal rotation.

Note: Case 2 and 3 are contributed from the same player.

100 ms before IC　33 ms before IC　IC　33 ms after IC　100 ms after IC

Fig. 1. An example of frame sequences depicting a high-risk pressing action from 100 ms before initial foot contact (IC) to 100 ms after IC.

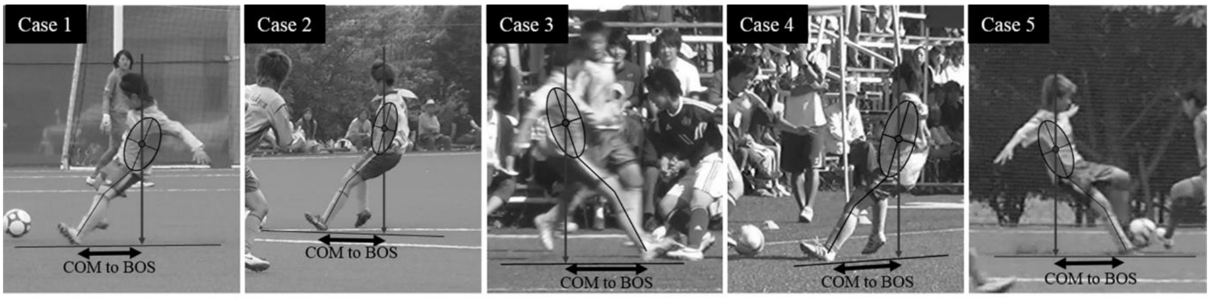

Fig. 2. Preliminary two-dimensional video analysis to screen high-risk pressing actions. The distance from the center of mass (COM, approximately located at the center of the trunk) to the base of support (BOS, the point bisecting the line of contact between the shoe and the floor) at the point of initial contact was measured, and 5 cases in which the COM to BOS distance was greater than 1.2 pix/pix were selected for further three-dimensional motion analysis as high-risk pressing events.

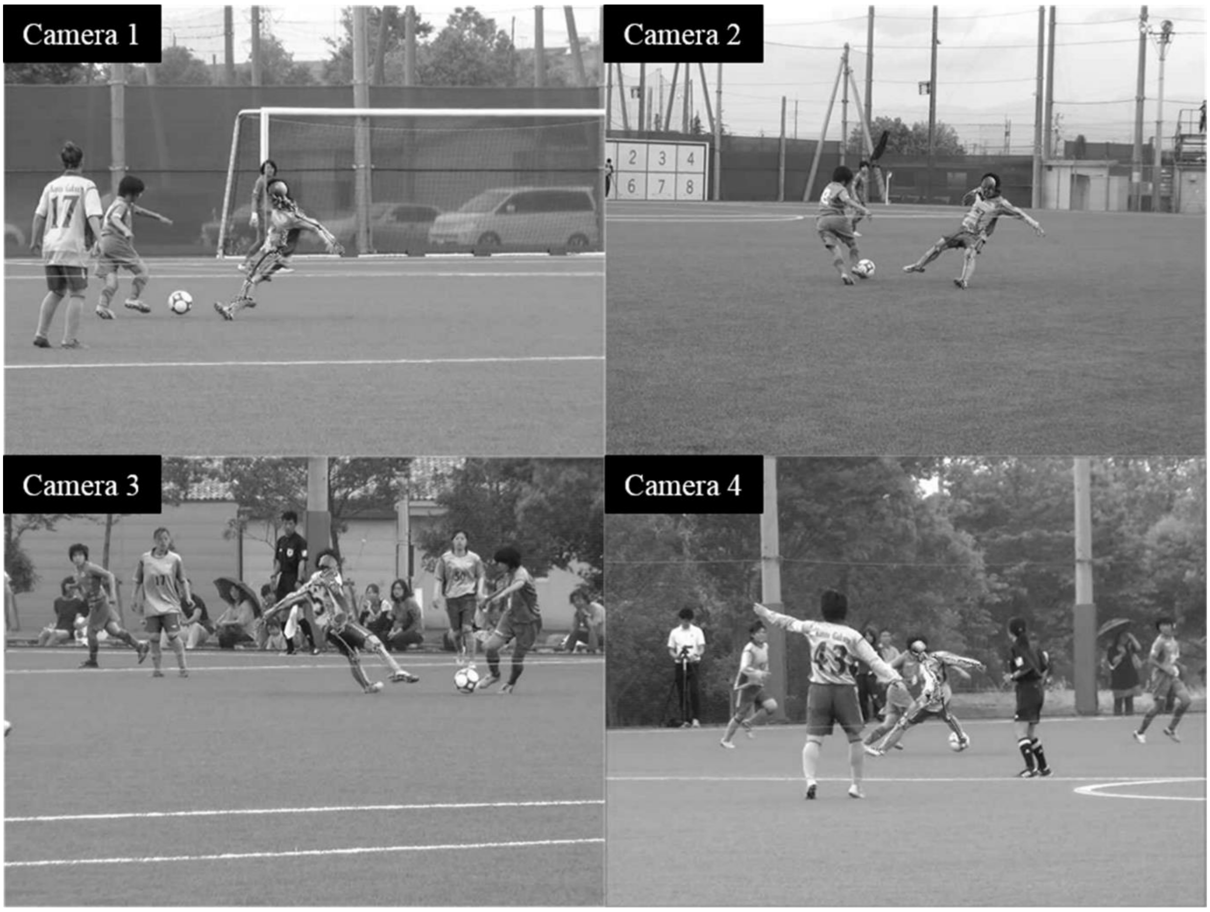

Fig. 3. An example of a video matched in Poser. The sequence of initial foot contact has been synchronized from 4 different camera views. The customized skeleton and football court models were matched with the videos' background images using Poser®.

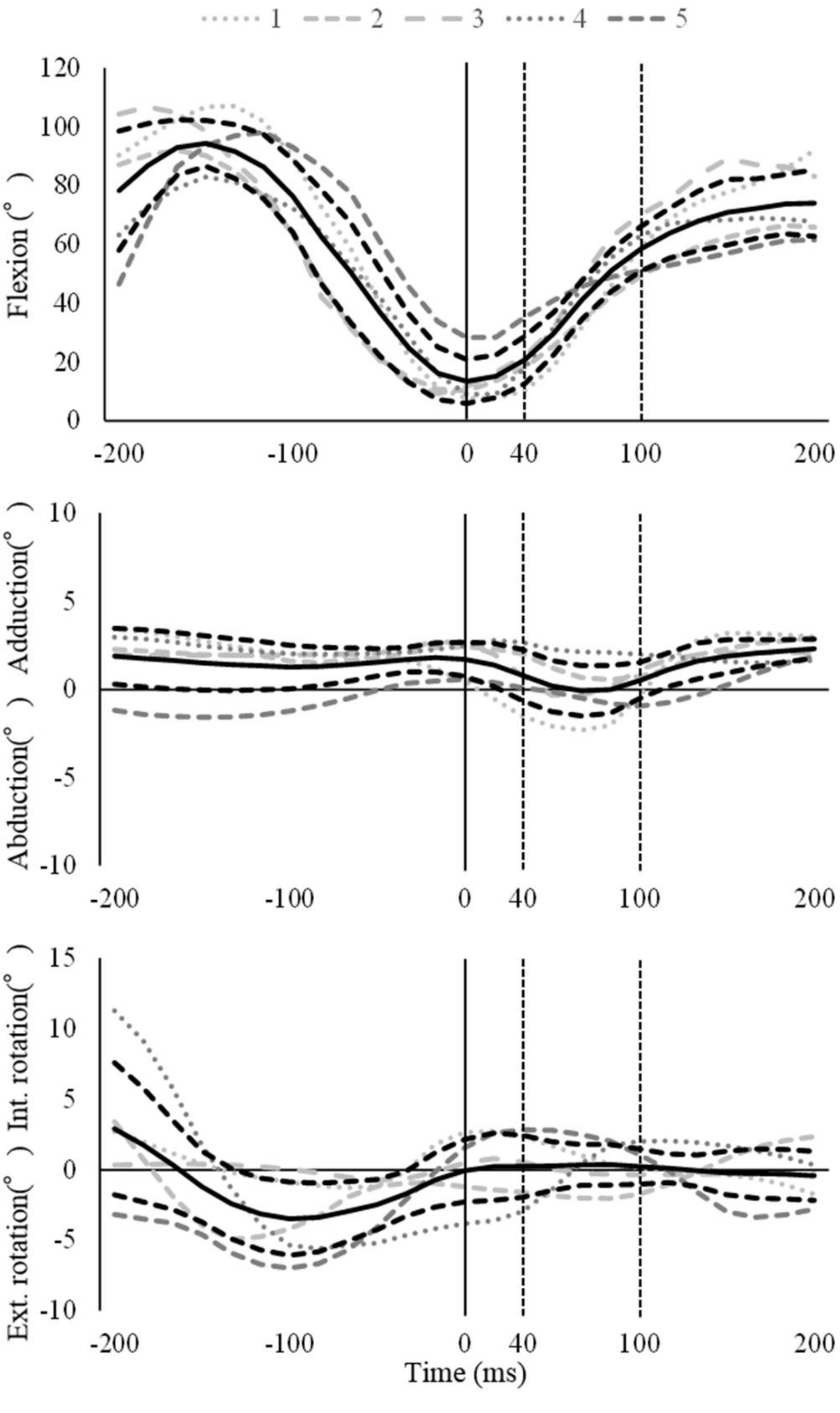

Fig. 4. Time sequences of knee flexion, abduction/adduction, and rotation angles for each of the 5 cases, as well as the mean (thick black line), with 95% confidence intervals (CI; thick dotted lines). Time 0 indicates initial contact (IC) and the dotted vertical lines indicate the time points 40 ms and 100 ms after IC, respectively. “Ext. rotation” indicates external rotation and “Int. rotation” indicates internal rotation.

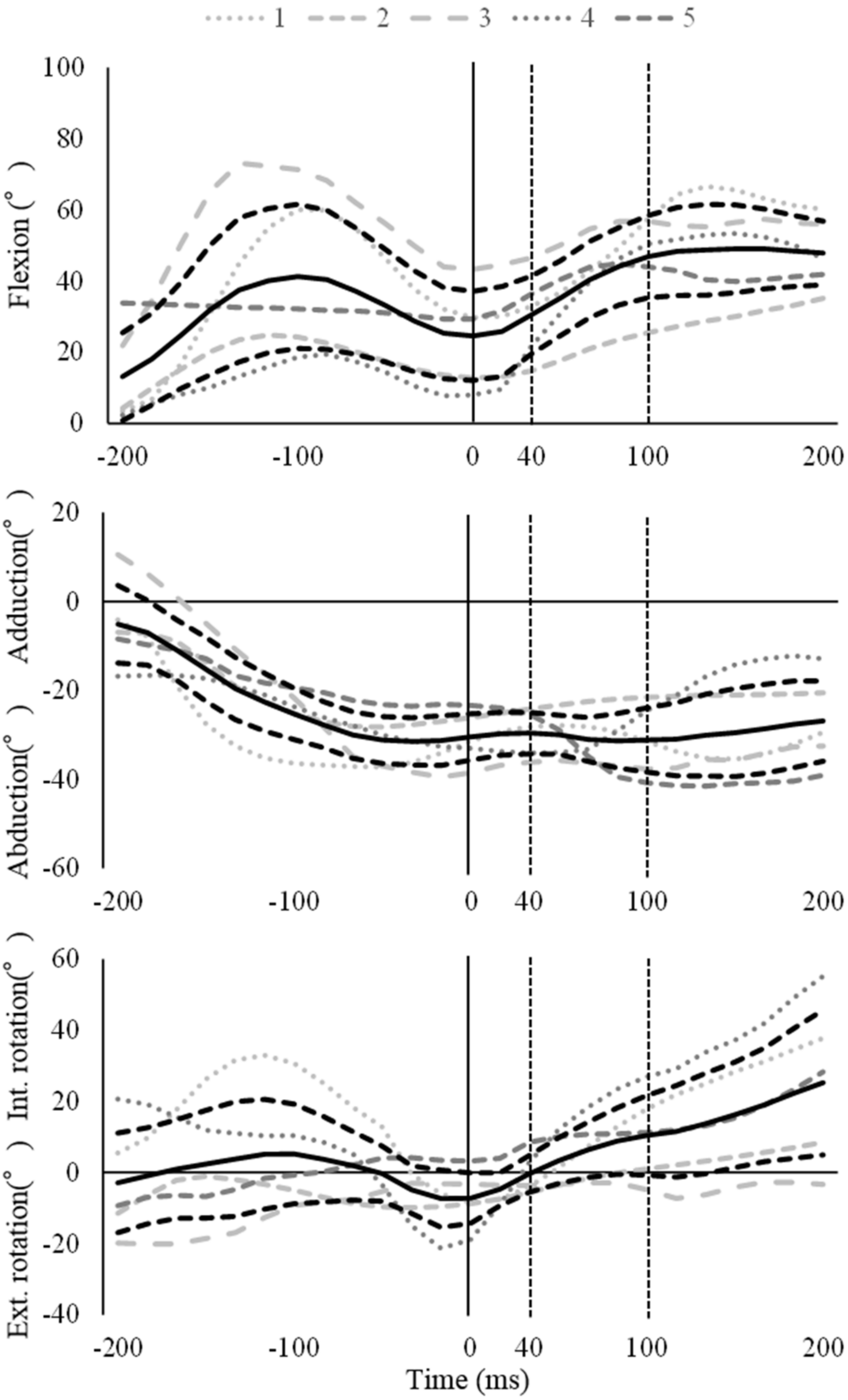

Fig. 5. Time sequences of hip flexion, abduction/adduction, and rotation angles for each of the 5 cases, as well as the mean (thick black line) with 95% confidence intervals (CI; thick dotted lines). Time 0 indicates initial contact (IC) and the dotted vertical lines indicate the time points 40 ms and 100 ms after IC, respectively.