Scand J Med Sci Sports
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DOI: 10.1111/j.1600-0838.2006.00558.x

SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences

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Accepted for publication 15 March 2006

Background: **Methods for analyzing the mechanisms of injuries in sports from video sequences of injury situations are so far limited to a simple visual inspection, which has shown poor accuracy.** ***Purpose:*** **To investigate whether a new model-based image-matching technique could successfully be applied to estimate kinematic characteristics of three typical anterior cruciate ligament (ACL) injury situations.** ***Methods:*** **A four-camera basketballvideo, a three-camera European team handball video and a single-camera downhill skiing video were imported into the program Poser® 4, where a skeleton model and a model of the surroundings were matched to the background image frame by frame. When the match was considered satisfactory, joint angles as well as velocity and acceleration of the center of mass were calculated using Matlab®.** ***Results:*** **In the basketball and handball matchings, the skeleton and surrounding models were successfully matched to the background through all frames in all camera angles. Detailed time courses for joint kinematics and ground reaction force were obtained, while less information could be acquired from the single-view skiing accident.** ***Conclusion:*** **The model-based image matching technique can be used to extract kinematic characteristics from videotapes of actual ACL injuries, and may provide valuable information on the mechanisms for ACL injuries in sports.**

Recent studies from team sports like soccer and European team handball have demonstrated that non-contact anterior cruciate ligament (ACL) injuries can be prevented through training programs focusing on knee control, balance, technique and strength (Caraffa et al., 1996; Mandelbaum et al., 2005; Olsen et al., 2005). However, the mechanisms of injury are poorly understood, and controversy exists on the loading patterns involved (DeMorat et al., 2004; McLean et al., 2005), which limits our ability to develop improved and targeted prevention programs (Krosshaug et al., 2005). A complete description of the mechanisms for a particular injury type in a given sport needs to account for the events leading to the injury situation (e.g., playing situation, player and opponent behavior), as well as include a precise description of whole body and jointbiomechanics at the time of injury (Bahr & Krosshaug, 2005).

Data and insight into injury mechanisms can be obtained through different approaches, including surveys of injured athletes, laboratory motion analysis, cadaver studies or mathematical simulations (Krosshaug et al., 2005). However, with the exception of rare accidents during biomechanical research experiments, the only approach that has the potential to record the kinematics of a real injury situation is analysis of injury videos. In addition to the direct information gained, e.g., knee flexion angles, video analysis is essential to verify whether simulations, whether they are mathematical simulations, cadaver simulations or *in vivo* simulations, actually correspond to what is seen in real injury situations. Despite the potential significance of obtaining precise motion estimates from actual ACL injury situations, research is so far limited, possibly owing to a lack of precise methods for video analysis. To date, studies have been based on simple visual inspection to extract information on joint kinematics (Ettlinger et al., 1995; Boden et al., 2000; Ebstrup & Bojsen-Moller, 2000; Teitz, 2001; Olsen et al., 2004). In a recent study, Krosshaug et al. (2006) found that the reliability of visual estimates was poor, even among experienced researchers. Knee flexion was underestimated by 19° on average, and the variability between analysts was considerable. These poor results may partly be attributed to the difficulty in interpreting segment attitudes and assessing joint angles in three planes. Furthermore, the simple visual inspection approach cannot produce continuous estimates of joint angles and positions, which are necessary for a detailed biomechanical analysis of the injury mechanisms, i.e., joint angle time histories, velocities and accelerations.

Our group has therefore developed a model-based image-matching technique to describe joint motion from uncalibrated video recordings (Krosshaug & Bahr, 2005). This method was found to produce much better estimates of kinematics compared with the simple visual inspection, regardless of the numbers of camera views available. However, the method has so far only been applied to non-injury situations in a laboratory environment. The purpose of this paper was therefore to investigate whether this technique could successfully be applied to estimate kinematic characteristics of three typical ACL injury situations from basketball, downhill skiing and European team handball.

Material and methods

Three ACL injury situations from basketball, downhill skiing and European team handball, recorded with uncalibrated cameras, were chosen for analysis. The videos were transformed from their original format into uncompressed AVI sequences before further processing to avoid loss of quality. Then, the sequences were deinterlaced using the Adobe Photoshop (version 4.0, Adobe Systems Inc., San Jose, California, USA) de-interlacing filter in Adobe AfterEffects (version 5.0, Adobe Systems Inc.).

To reconstruct the three-dimensional kinematics of the injured athletes, we utilized a new photogrammetric model-based image-matching technique (Krosshaug & Bahr, 2005). The matchings were performed using the commercially available program Poser® 4 and the Poser® Pro Pack (Curious Labs Inc., Santa Cruz, California, USA). First, models of the surroundings were manually matched to the background for each frame in every camera view, using a key frame and spline interpolation technique, by adjusting the camera calibration parameters (position, orientation and focal length). The surroundings were modeled using points, straight lines and curved lines (e.g. basketball court; see Fig. 1). We utilized a skeleton model from Zygote Media Group Inc. (Provo, Utah, USA) for the athlete matching. This model consisted of 21 rigid segments with a hierarchical structure, using the pelvis as the parent segment. The pelvis motion was described by three rotational and three translational degrees of freedom. The motion of the remaining segments was then described with three rotational degrees of freedom relative to their parent, e.g., the shank relative to the thigh. In the matchings, we allowed for 57 degrees of freedom. The matching procedure has been described in detail by Krosshaug and Bahr (2005).

We used Woltring's Generalized Cross Validation Spline package (Woltring, 1986) with a 7 Hz cutoff to obtain velocity and acceleration estimates for the center of mass translation. Normalized ground reaction forces were calculated based on estimated accelerations of the center of mass. The knee and hip joint angles were converted into the joint coordinate system convention of Grood and Suntay (1983).

Basketball injury

The basketball video showed a situation where a male player developed an ACL injury to the right knee in a one-leg landing, filmed with four cameras (Fig. 1). The videotape used for the analyses was supplied by the National Basketball Association (NBA) in DigiBeta NTSC format. The quality was generally very good, although fast-moving body parts were somewhat blurry. The sequence that was matched lasted for approximately 0.8 s. The relative surface area of the athlete to the total video frame size was 18.8% (camera 1), 4.7% (camera 2), 3.8% (camera 3) and 1.2% (camera 4). The relative angle between cameras 1 and 2 was 113°, between cameras 1 and 3 153°, between cameras 1 and 4 100°, between

Fig. 1. Matching of the four-camera basketball injury situation 50 ms after initial ground contact. The four panels show the customized skeleton model and the basketball court model superimposed on and matched with the background video image from cameras 1–4. One Poser phantom camera (camera 1) can be seen as a wireframe model in the bottom left panel as an exact fit.

cameras 2 and 3 47°, between cameras 2 and 4 16°, between cameras 3 and 4 57°.

By examining the synchronization of the video sequences based on ball catching and foot strike, we found that two of the camera views were shifted in time by approximately 1/120 s compared with the two other camera views. We therefore interpolated the pictures between frames in order to achieve a full set of images at each time step, resulting in an effective frame rate of 120 Hz for all four camera views using the software Morpheus (version 1.85, Morpheus Software, LLC, Santa Barbara, CA, USA). Approximately 15–20 corresponding points were identified on two consecutive frames in order to generate an interpolated frame. These points were chosen either on the injured subject or on landmarks/lines used for camera calibration, in order to optimize the interpolation and avoid blurriness at these sites.

Although other players were visible, they did not occlude the view of the injured player to any significant extent. However, his right foot was outside the field of view in camera 1. The dimensions of the basketball court, as well as the basket and backboard, were modeled based on NBA standards. No anthropometrical measurements were available, except for the subject's height and body mass. The segment dimensions were therefore iteratively adjusted during the matching process until finally, a fixed set of scaling parameters was determined. The center of mass for the segments was then determined by the method of de Leva (1996). Because the shank axial rotation was difficult to assess precisely, we distributed the rotation evenly between the ankle and knee joint, using foot orientation as guidance.

Team handball injury

The team handball video showed an ACL injury to the right knee in a female player during a one-leg cutting movement from right to left, filmed with three cameras (Fig. 2). The videotape was supplied by the Norwegian Broadcasting Corporation in BetaSP PAL format, and the quality was generally very good. Nevertheless, fast-moving body parts were somewhat blurry, and it was therefore difficult to assess thigh rotation precisely. Other players partly occluded the injured player in one camera view, but this mainly occurred after the injury presumably had occurred.

The effective frame rate after deinterlacing was 50 Hz, and the total duration of the matching sequence was 1 s. Cameras 1 and 2 (zoom camera) were in a similar location filming from an oblique frontal view with a relative angle of only 5°. The relative surface resolution of the injured athlete was 1.2% of the total frame size for camera 2 and 5.6% for camera 3. For camera 3, filming from the rear above the resolution of the athlete was approximately 1.4%, and the relative angles to cameras 1 and 2 were 45° and 50°, respectively.

Measurements of the line markings on the handball court and goal posts were used for calibration when modeling the surroundings. Anthropometrical measurements were obtained from the athlete, and body segment parameters were calculated, using a modified version (Krosshaug & Bahr, 2005) of Yeadon's inertia model (Yeadon, 1990). In addition to the modifications described in Krosshaug and Bahr (2005), the chest was separated into one extra solid to fit the female anatomy better. The skeleton model segment dimensions were set based on these measurements. Again, the axial rotation was evenly distributed between the ankle and knee joint.

Downhill skiing injury

The alpine skiing video showed a downhill skier developing an ACL injury to the left knee filmed from one camera view only (Fig. 3). The videotape was supplied by the Norwegian Broadcasting Corporation in BetaSP PAL format, with a frame rate of 50 Hz after deinterlacing. The quality was relatively poor because of low contrast and the snow thrown by the athlete and his skis. The relative resolution of the athlete was 2.9% of the total image size. The skis were assumed rigidly connected to the feet. The ski suit had markings that were used to assess body configuration. However, as can be seen in Fig. 3, it was difficult to assess thigh rotation. Only a few surrounding landmarks were visible, and as the coordinates for these

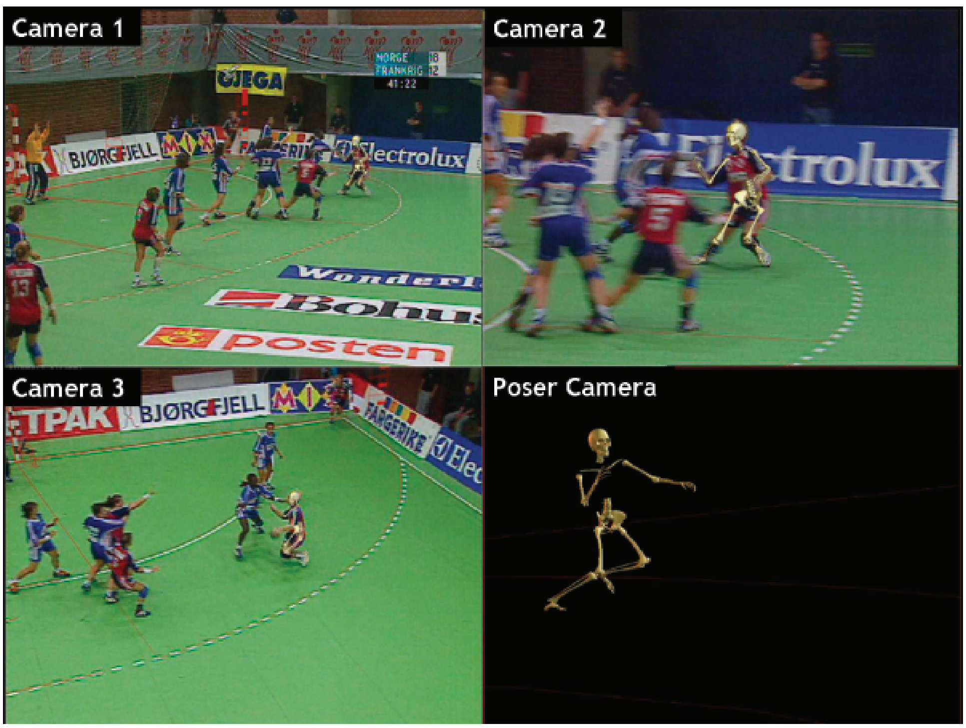

Fig. 2. Matching of the three-camera team handball injury situation 140 ms after initial ground contact. Three panels show the customized skeleton model and the handball court model superimposed on and matched with the background video image from cameras 1–3. The bottom right panel shows the skeleton model from an alternative view created in Poser.

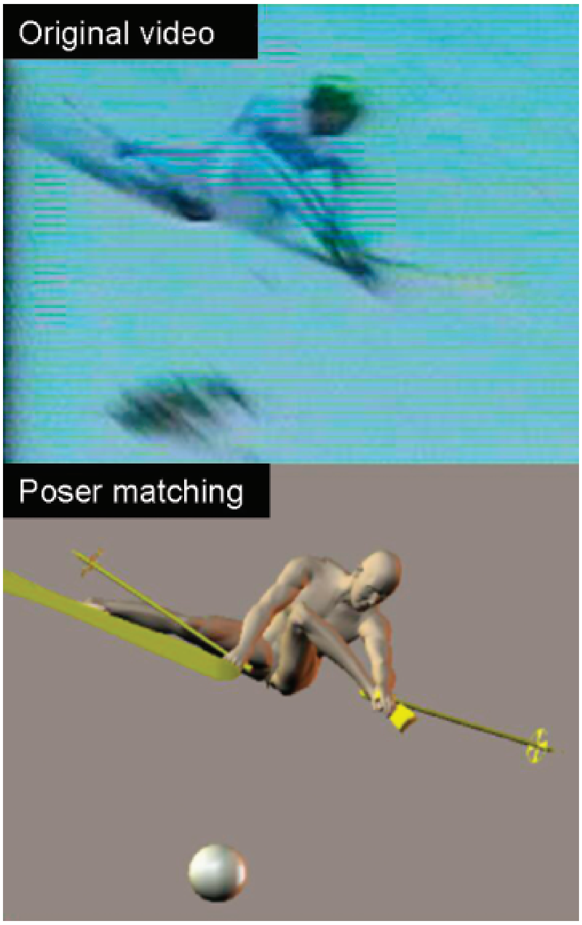

Fig. 3. Matching of the single-camera alpine skiing injury situation 400 ms into the matched picture sequence. The left panel shows the skier in the original video sequence. The right panel shows the resulting matching visualized with a nude model.

landmarks were not known, it was not possible to determine position and velocity reliably. Anthropometrical measurements were obtained from the injured athlete, and body segment parameters were calculated, using a modified version (Krosshaug & Bahr, 2005) of Yeadon's inertia model (Yeadon, 1990), and the skeleton model segment dimensions were set accordingly.

Results

Basketball injury

The injury occurred when the player landed on his right leg after he had caught the ball in the air while driving for the basket. The period before the initial ground contact was a flight phase, although the forefoot touched the ground slightly during the first few frames of the matching. As can be seen in an example in Fig. 1, we were able to match successfully both the basketball court model and the skeleton model to the background image sequence. The visual match was excellent in all camera views for all frames, i.e. all joints, as well as the feet, hands and head were relatively stable relative to the athlete boundaries. However, the upper extremities appeared slightly less accurate. A good match was also seen in between the positioning of the Poser cameras and two actual cameras that were seen in the images (see Fig. 1, lower left panel – at this point, the other camera is no longer visible).

The horizontal approach speed was estimated to be 5.6 m/s (Fig. 4), and the cutting angle was 10°. The normalized ground reaction force estimates remained close to zero during the airborne period for the vertical and mediolateral directions, but the anteroposterior force estimate fluctuated somewhat more (± 1 bw). At initial contact, the hip flexion angle was estimated to be approximately 23° and knee flexion angle 13°. After approximately 30 ms, the vertical force reached its peak at close to four times the body weight. At this point, the hip and knee flexion angles had increased to 38° and 35°, respectively, and the valgus angle had increased rapidly to 14°. The knee rotation was less than 5°. The maximal anteroposterior force was seen somewhat later: at approximately 60 ms. The body position of the athlete at initial ground contact, and at 30 and 60 ms after initial contact, is shown in Fig. 5.

Team handball injury

The injury occurred when the player performed a side-step cutting maneuver from right to left on an artificial floor. As can be seen in Fig. 2, we were able to match successfully the handball court model and the skeleton model to the background image sequence. The visual match appeared excellent in all frames. As for the previous case, all joints, as well as the feet, hands and head were relatively stable relative to the athlete boundaries. However, the match was slightly better for the lower than the upper extremities.

The horizontal speed at initial ground contact was estimated to be 3.6 m/s (Fig. 6), and the cutting angle was approximately 67°. At initial ground contact, the hip was flexed 19°, abducted 26° and externally rotated 16°. The knee was flexed 11°, while rotation and varus–valgus position was neutral. When the vertical force reached its peak at 2.8 times the body weight 40 ms after initial contact, the hip joint flexion angle was nearly constant, whereas the knee flexion had increased to 31°. At the same time, a peak valgus angle of 15° was seen. The maximal anteroposterior force was seen somewhat later: at 100 ms. The body position of the athlete at initial ground contact, and at 40 and 100 ms after initial contact is shown in Fig. 7.

During the period before initial ground contact, the athlete was not completely airborne, as there was slight contact with the contralateral foot initially. However, loading during this phase seemed to be

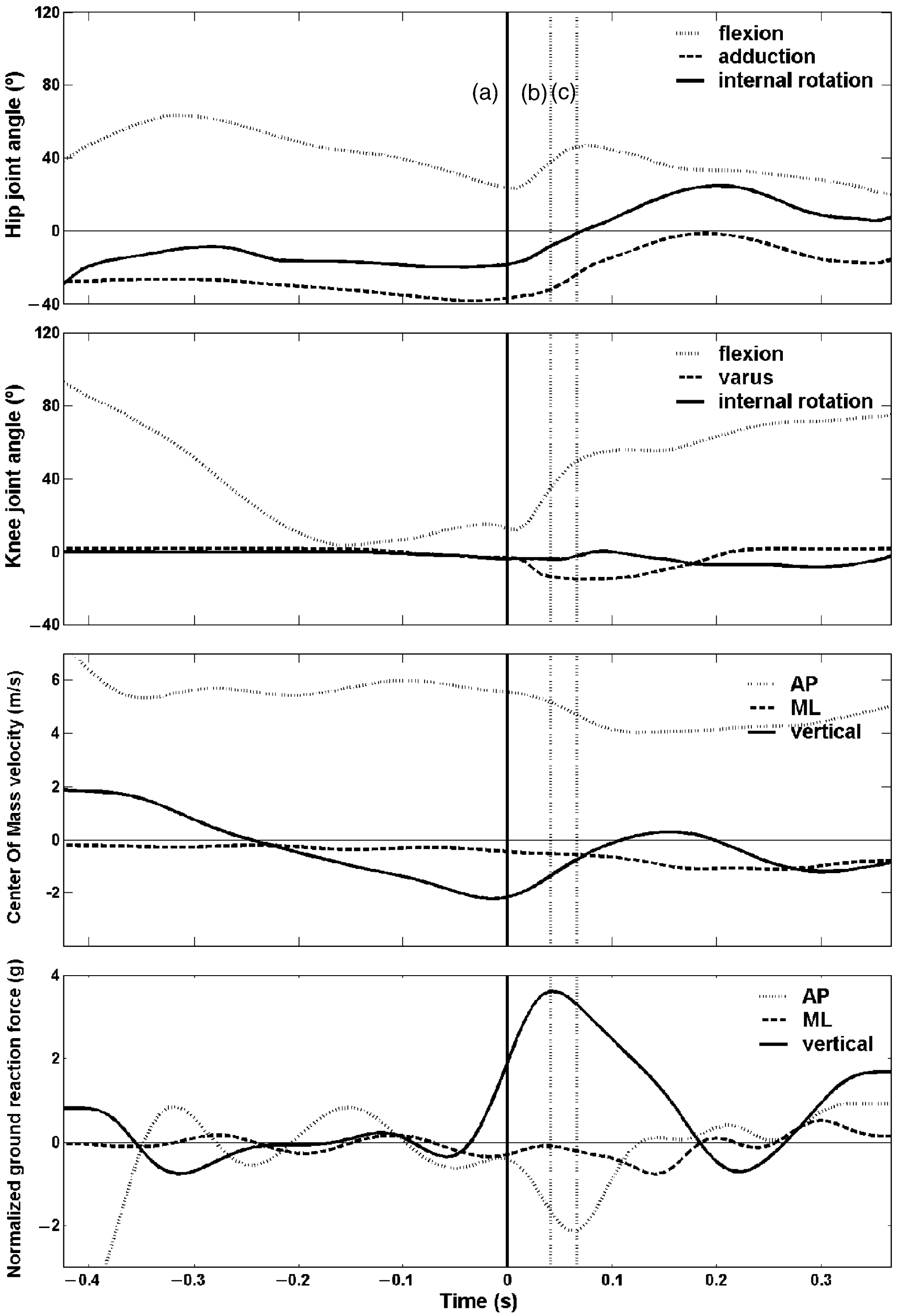

Fig. 4. Time sequence of hip joint angle (°), knee joint angle (°), center of mass velocity (m/s) and normalized ground reaction force (g) of the injured right leg for the basketball injury situation. The solid vertical line (a) indicates initial ground contact. The two dotted vertical lines indicate the time points 30 ms (b) and 60 ms (c) after initial contact, respectively, corresponding to the peak vertical and horizontal force.

minimal, and this assumption is supported by the force estimates.

Downhill skiing injury

We matched 550 ms of the video sequence, and Fig. 8 shows the body position of the athlete 200, 340 and 440 ms into the sequence. The skier lost his grip on his right side, outer ski while preparing for a left turn, causing him to go into a wide sprawling position before the edge of the left ski caught. The left knee was then severely twisted, resulting in an ACL tear. Finally, the skier was forcefully thrown into the air. The visual match appeared good, but due to the relatively poor video quality, and the fact that only one camera view was available, it was somewhat difficult to assess whether the matching was performed correctly at all frames (e.g., the right foot in Fig. 3). However, video sequences generated from different viewpoints using different frame rates (i.e., video speed) indicated that the match was satisfactory. The lack of known landmarks in the background prevented the use of any surrounding model.

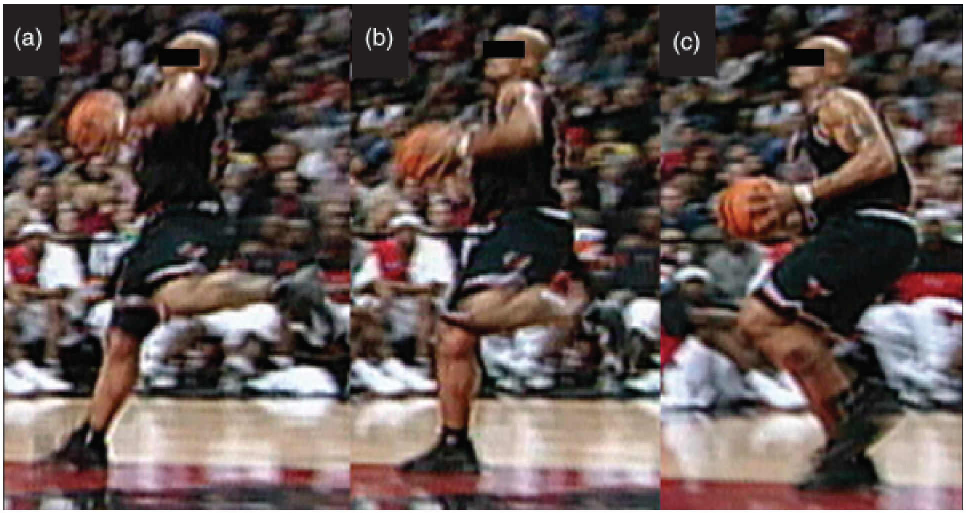

Fig. 5. Frame sequence of basketball injury (enlargement of camera 1 view) showing the athlete at initial ground contact (a), at 33 ms (b) and (c) 100 ms, respectively.

While the right ski was slipping, left hip flexion and internal rotation increased gradually, peaking around 400 ms at about 140° and 50°, respectively (Fig. 9). The knee internal rotation peaked at 40° after 340 ms. At this point, the knee flexion angle was 65° and the valgus angle was 15°. The valgus angle then increased to 30° after 440 ms.

Discussion

Although the model-based image-matching technique is subjective, in the sense that it is dependent on the operator's ability to perform the model matching consistently, this method has shown to be much more accurate than the simple visual inspection approach (Krosshaug et al., 2006). The advantages over simple visual inspection of injury videos (Ettlinger et al., 1995; Boden et al., 2000; Ebstrup & Bojsen-Moller, 2000; Teitz, 2001; Olsen et al., 2004) are obvious. First, through computer models, the operator is able to visualize in three dimensions the segment poses that appear to be the best match. Second, the joint angles are calculated automatically. Third, the matching technique can provide continuous descriptions of angular and translational displacements and their derivatives. This greatly expands the possibilities for biomechanical assessments, e.g. determining the time of injury or how different motion patterns may contribute to increased knee loading.

The method is also versatile, because it can be used in many different situations, regardless of the motion performed, the camera angle, the number of camera views or whether the camera is stationary or in motion. However, if no known landmarks are present in the background picture, it is not possible to estimate the body velocity and acceleration. Nevertheless, joint kinematics can still be calculated.

Assessment of the matchings

For obvious ethical reasons, laboratory measurements of injury situations cannot be performed. Comparing motion estimates with lab trials may even have limited value, as injury situations most likely differ from non-injury situations. Therefore, although it is not possible to evaluate the quality of the current matchings by comparing with a gold standard, we wanted to investigate whether this technique could successfully be applied to estimate kinematic characteristics of the three ACL injury situations presented here. In fact, the quality of the matchings can still be assessed using the visual goodness of fit for the surroundings and skeleton models to the actual video footage as guidelines, as well as the timing of airborne motion. However, even if the skeleton joints may match the underlying picture and the match appears excellent, there is no guarantee that the axial rotations of the segments are correct. As our ability to determine axial rotation depends on how well we can see, e.g., surface shape and landmarks, it is also necessary to consider the quality of the input. Poor picture quality, partial occlusion, low sampling rate, lack of known landmarks in the video image or having only one camera may lead to suboptimal matchings. The more usable information available, the easier it will be to discover errors in the motion patterns. However, more information also means that producing a consistent continuous motion throughout the sequence is made even more challenging.

Of the three injury situations studied, the basketball video sequences represent the best input that can be expected from real injury situations, with one front, two side and one rear view and excellent picture quality. Cameras 3 and 4 provided overviews with numerous landmarks that were distributed over

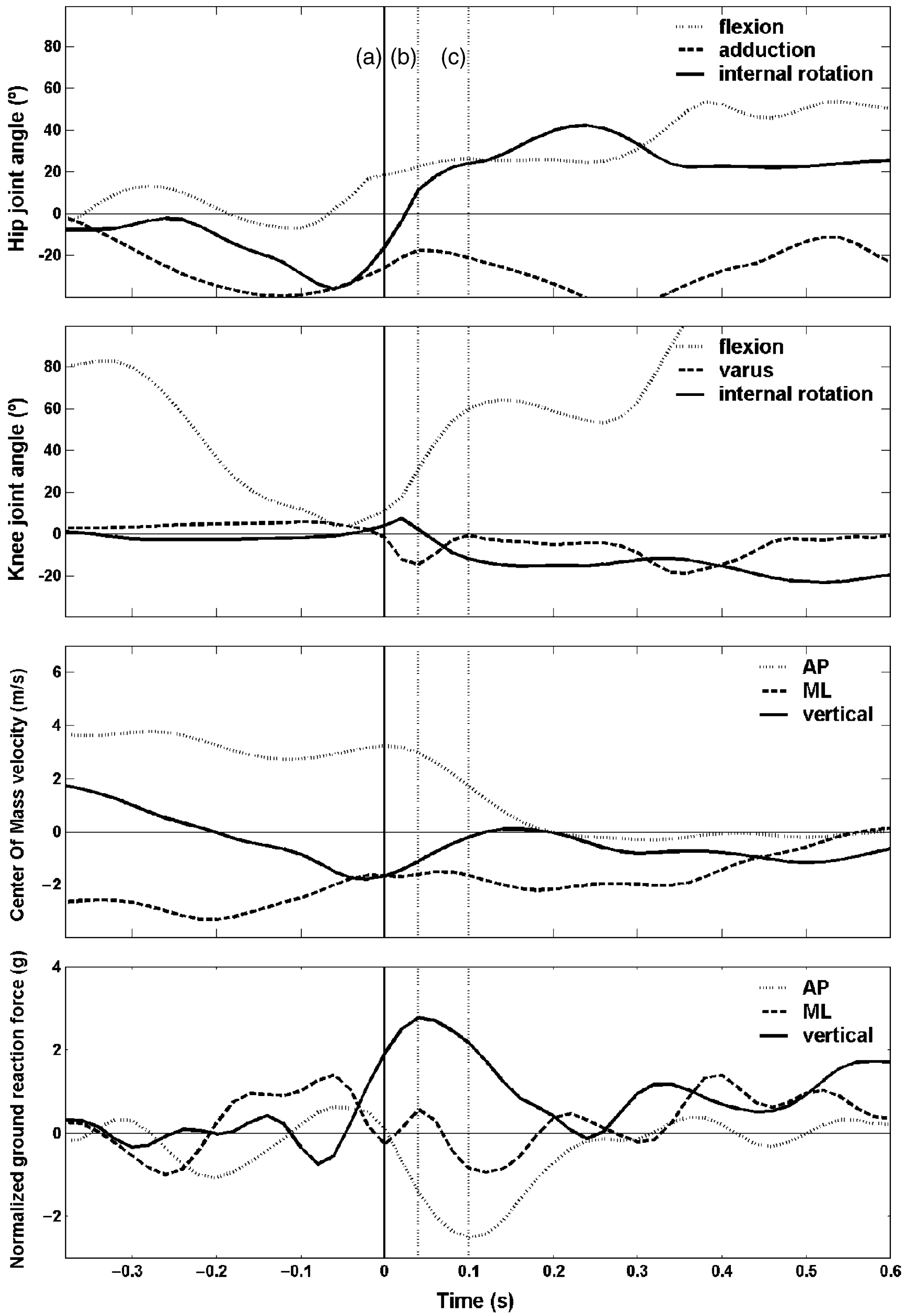

Fig. 6. Time sequence of hip joint angle (°), knee joint angle (°), center of mass velocity (m/s) and normalized ground reaction force (g) of the injured right leg for the team handball injury situation. The solid vertical line (a) indicates initial ground contact. The two dotted vertical lines indicate the time points 40 ms (b) and 100 ms (c) after initial contact, respectively, corresponding to the peak vertical and horizontal force.

large parts of the video image for exact camera calibration (Fig. 1), enabling us to position the athlete correctly in space. The close-up views from cameras 1 and 2, with a higher relative resolution of the athlete, could then be used to fine tune the positioning of the athlete from one frame to the next. After several iterations of manual fitting, the model of the basketball court matched very well in all of the camera views throughout the sequence. The fact that the virtual Poser camera can be seen directly over the actual camera (see Fig. 1, bottom left panel) confirms that the camera seen in the image (camera 1), as well as the camera through which we see the actual image (camera 3) are calibrated accurately.

Although no cameras could be seen in the three-camera team handball matching, the nearly parallel overview and close-up views made it possible to fine tune the body position throughout the sequence. However, having no front or rear camera view may introduce a suboptimal estimate for the medio-lateral positioning of the athlete. In contrast, we could not estimate the center of mass velocity and acceleration

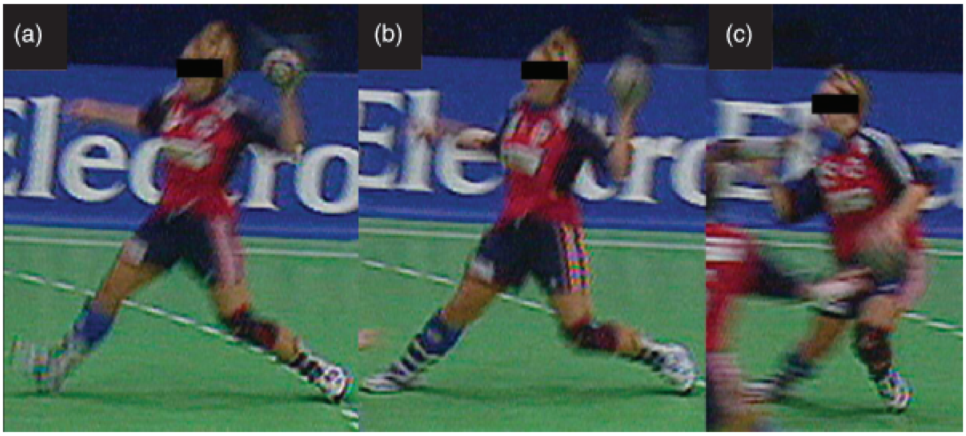

Fig. 7. Frame sequence of team handball injury (enlargement of camera 2 view) showing the athlete at initial ground contact (a), at 40 ms (b) and at 100 ms (c), respectively.

in the alpine skiing video because there were no known landmarks in the video sequence.

The matching of the skeleton to the video image of the athlete appeared to be excellent for the basketball and handball situations, achieving a good fit with the skeleton model joints in all frames. Even so, it is likely that axial rotations of the thigh and shank were less accurate than hip and knee flexion and abduction angles, as matching rotational orientation is more difficult because of the shape of the segments, lack of visible landmarks and also skin motion that occurs relative to the underlying bones. The athlete's clothing also limits our ability to assess pelvis and thigh orientation precisely. As shown in our laboratory study (Krosshaug & Bahr, 2005), estimating pelvic rotation is also difficult although having multiple cameras filming both in the floor plane and from above is helpful, as was the case for the basketball and the handball situations. In contrast, determining joint motion that does not occur in the camera plane is more difficult (e.g., spine flexion and knee flexion in Fig. 8(c)). Although the model-based image technique cannot provide perfect estimates in all situations, sensitivity testing showed that the valgus estimates during the first 30 ms of the basketball matching and 40 ms of the team handball matching were relatively robust (data not shown), as varying femoral rotation did not substantially affect the estimated valgus angle at low knee flexion angles.

For the skiing video, snow spray and relatively poorer video quality made it more difficult to interpret the segment poses for individual frames (Fig. 8). But after several iterations assessing the skier in different views, a satisfactory result was achieved, which was consistent throughout the matching. One advantage when matching skiing injuries is that shank rotation can probably be matched quite accurately based on ski-boot orientation. However, assessing thigh axial rotation was quite difficult and valgus angle estimates must be interpreted with caution, as they are highly dependent on thigh rotation in this flexed position. Owing to the possible errors in such low-quality, single-camera situations, the accuracy needed for the specific research question should therefore be carefully assessed before being considered for analysis.

Foot orientation guided the shank rotation matching in the basketball and handball videos as well. However, although shank rotation estimates were shown to be excellent in the validation study (Krosshaug & Bahr, 2005), we cannot be certain that this was the case here as well. First, we did not have a clear view of the foot attitude in any of the situations. Second, the assumption that the rotation is evenly distributed between the knee and ankle joint has not been validated, and should be tested in laboratory studies. Third, this relationship will probably be altered in case of an ACL injury.

We have previously shown that estimates for velocity and acceleration can be achieved with reasonable accuracy in the vertical direction (for camera views parallel to the floor plane), provided that at least two perpendicular camera views are available (Krosshaug & Bahr, 2005). Based on this, it may be assumed that the acceleration estimates for the four-camera basketball matching are at least as accurate as the laboratory results. Another indication that the estimates are reasonably good is that the calculated ground reaction forces are close to zero in all directions before initial ground contact.

Nevertheless, the relatively low frame rate in standard TV recordings makes it difficult to capture force peaks (Krosshaug & Bahr, 2005). We therefore wanted to study whether the interpolation technique utilizing the out-of-phase video sequences would produce a more detailed acceleration curve. However, the shapes of the vertical and horizontal acceleration curves of the 120 Hz basketball matching were very similar to the 50 Hz handball matching. Furthermore, the initial force transient (Bobbert et al., 1992; McLean et al., 2003; Krosshaug & Bahr, 2005), normally seen in a heel-landing impacts was not observed in either case. Another indication of the limited temporal resolution is the fact that the

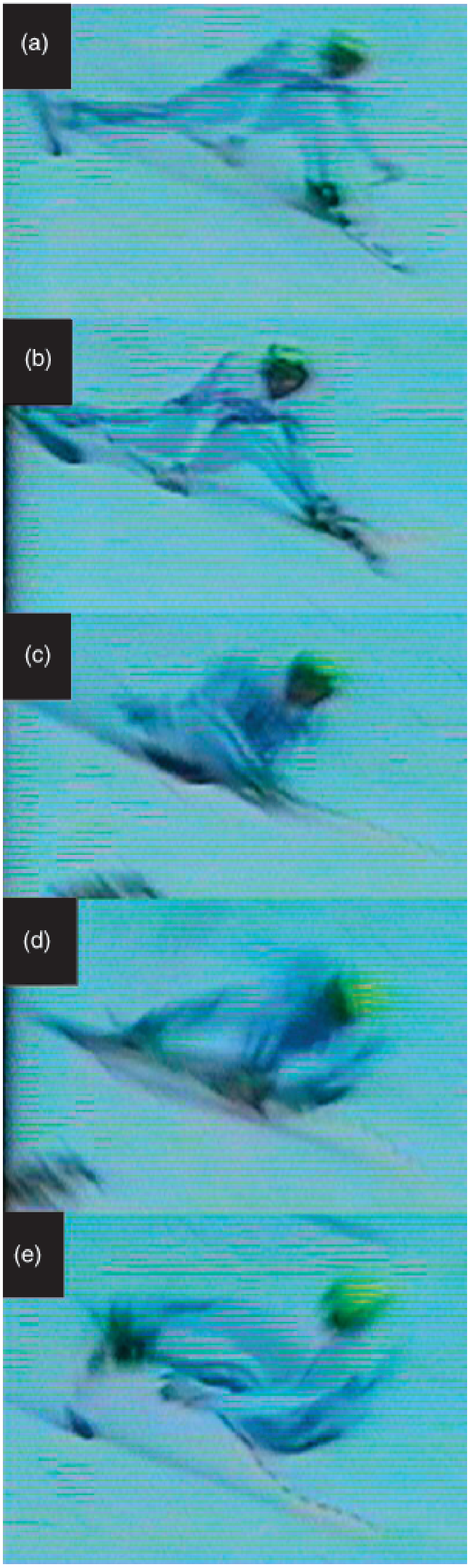

Fig. 8. Frame sequence of alpine skiing injury showing the athlete 200 ms (a), 340 ms (b), 440 ms (c), 500 ms (d) and 580 ms (e) into the matched frame sequence, respectively.

vertical force increases above zero about 30–50 ms before the actual initial contact in both situations. Thus, it seems as though the advantage gained by using the frame interpolation technique used for the basketball video is limited.

It should be noted that the method is time consuming. Matching a 1-s video sequence can be expected to take an experienced operator approximately 1–2 months. Although a considerable research effort has been put into automating tracking and reconstruction of human motion from video sequences, the challenges in handling single and multiple uncalibrated camera recordings without restrictions on camera motion, human motion, clothing, light setting, etc., still prevent a general solution to the problem (Moeslund & Granum, 2001; Moeslund, 2003). Furthermore, reaching adequate accuracy for biomechanical purposes, or simply estimating axial rotations of the segments seems to be difficult using automated (Cheung et al., 2005; Sminchisescu & Triggs, 2005) or even semi-automated systems (Zheng et al., 2000; Barron & Kakadiaris, 2005). Thus, our model-based image-matching technique at present provides a suitable framework for utilizing the available information optimally in injury situations, where controlled experimental techniques cannot be used. In the future, automatic camera calibration techniques will be considered that can potentially reduce the matching time by some amount, but owing to the iterative nature of the skeleton model matching, processing time is nevertheless expected to be considerable.

Injury mechanism considerations

For this study, we chose to analyze ACL injury videos from sports where such injuries are frequent, and we aimed to represent the range of video quality that can be expected from injuries occurring during TV broadcasts. Although previous studies reported in the literature using simple visual inspection of injury videotapes hypothesize that non-contact ACL injuries in team/ball sports occur at a flexion angle of less than 30° (Boden et al., 2000; Kirkendall & Garrett, 2000; Teitz, 2001; Olsen et al., 2004), this methodology has been shown to have poor precision and accuracy (Krosshaug et al., 2006). A key limitation of the visual inspection method is that it is not possible to determine the exact timing of the rupture (Boden et al., 2000; Olsen et al., 2004). One potential advantage of the current model-based image-matching technique is that it may be possible to estimate the timing of the injury with greater precision using different criteria, i.e. by determining when the joint configuration becomes abnormal, by observing sudden changes in the joint angular motion and by assessing the ground reaction forces. When examin-

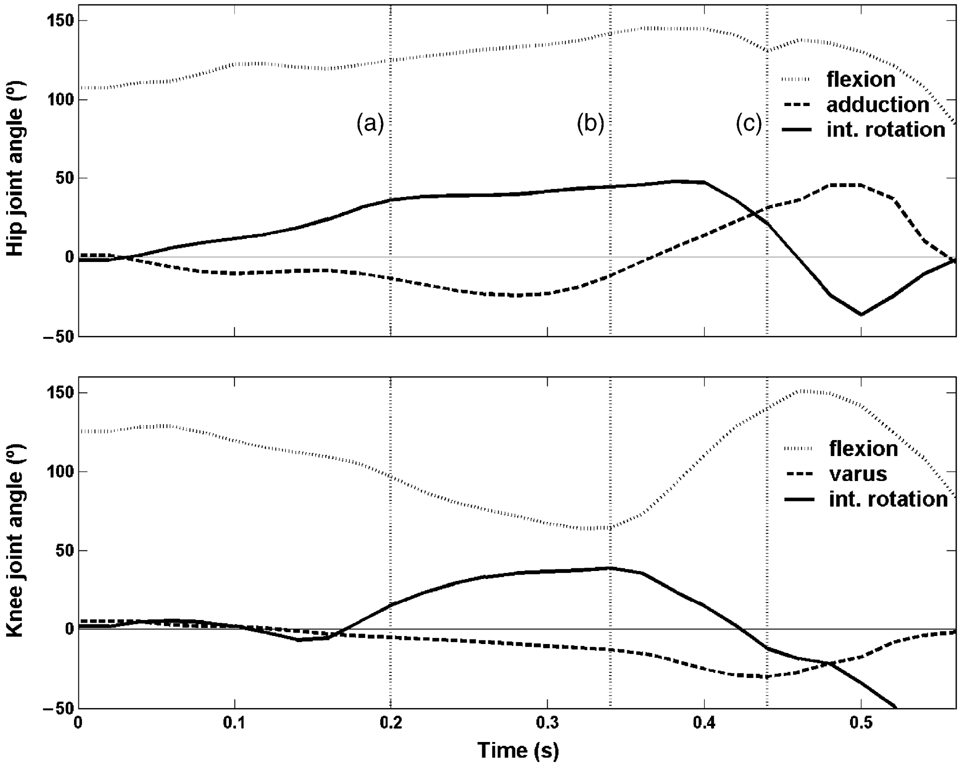

Fig. 9. Hip and knee joint angle history (°) for the injured left leg for the alpine skiing injury situation. The three dotted vertical lines (a), (b) and (c) indicate the time points 200, 340 and 440 ms into the matched frame sequence, respectively.

ing the time course for knee joint angles in the basketball and team handball cases, the valgus angle increased abruptly, increasing from 4° to 15° within 30 ms and from 3° to 16° within 40 ms, respectively. These time periods also correspond to the maximal vertical forces, but according to our previous validation study (Krosshaug & Bahr, 2005), the true maximal force peak will most likely lie some time before the estimated maximum. However, at this point it is not known how the ground reaction forces correspond to ACL loading, although the *in vivo* case study of Cerulli et al. (2003) indicates some degree of ACL force increase at the vertical ground reaction force peak. Nevertheless, these results indicate that valgus loading on a relatively straight leg (from about 15° to 40°) may be a key causative factor.

This interpretation supports previous theories from video studies, and also agrees with recent findings by Hewett et al. (2005), who showed that female athletes who tended to land with increased dynamic valgus and high abduction loads are at increased risk of ACL injuries. However, analyses of a larger sample of cases and comparisons of injury vs non-injury situations are necessary to evaluate whether this is indeed a general trend or merely a result of estimate errors or a non-typical situation. Unfortunately, the limits of joint motions during combined and dynamic loading, beyond which ACL injury occurs, are not known precisely. Also, knee laxity may vary considerably between subjects (Rozzi et al., 1999; Medrano & Smith, 2003). In addition, it is well known that even small joint translations, which are not possible to determine from video sequences, may substantially influence ACL loading (Markolf et al., 1995; DeMorat et al., 2004). Therefore, even if a precise time course of joint angles can be obtained, we need to combine research approaches, e.g. video analysis, clinical findings and simulation studies, to provide better evidence (Krosshaug et al., 2005).

The alpine skiing injury situation does not correspond to any of the injury mechanisms previously described in recreational alpine skiing, like e.g. the phantom foot mechanism, the boot-induced anterior drawer mechanism or the valgus-external rotation mechanism (Natri et al., 1999) Although several characteristics matched the phantom foot mechanism, e.g. catching the ski edge followed by internal rotation of the shank, others were distinctly different, e.g. weight and arms forward. Although the “wide snow plow” mechanism seen here is one that has not been described in the literature, similar motion patterns are seen in other videos that we have collected from elite super-G and downhill skiing. A key feature seems to be the twisting of the shank due to the ski catching the inner edge. However, if the kinematics leading up to the injury can be quantified, this information can potentially be utilized to prevent injuries, e.g., by technique changes, equipment changes or designing more “intelligent” binding release criteria and systems (Bahr & Krosshaug, 2005). Preventive measures have previously been applied with promising results in recreational skiing, as was demonstrated in the study of Ettlinger et al. (1995) using injury awareness training. However, if we are to prevent ACL injuries at the elite level, a systematic approach to collect and analyze more injury videos is needed.

Perspectives

Data and insight into injury mechanisms can be obtained through different approaches, including surveys of injured athletes, laboratory motion analysis, cadaver studies or mathematical simulations (Krosshaug et al., 2005). However, with the exception of rare accidents during biomechanical research experiments, the only approach that has the potential to record the kinematics of a real injury situation is analysis of injury videos. Previous video analysis studies, studying e.g., non-contact ACL injury mechanisms (Ettlinger et al., 1995; Boden et al., 2000; Ebstrup & Bojsen-Moller, 2000; Teitz, 2001; Olsen et al., 2004), have merely used a simple visual inspection approach. However, a recent study showed that the reliability of such visual estimates was poor, even among experienced researchers.

In the present study, frame-by-frame three-dimensional reconstructions of three ACL injury video sequences could be produced successfully, using a new model-based image-matching technique. This method has previously been validated with much better results as compared with the simple visual inspection approach. From the high-quality handball and basketball videos, which included multiple views, a detailed time course for joint kinematics and ground reaction force was obtained, while less information could be provided from the single-view skiing accident. As long as the quality of the video input is good, the method may give valuable information on the mechanisms for ACL injuries in sports.

Key words: injury biomechanics, joint motion, image processing, human body model, photogrammetry.

Acknowledgements

The Oslo Sports Trauma Research Center has been established at the Norwegian University of Sport & Physical Education through generous grants from the Norwegian Eastern Health Corporate, the Royal Norwegian Ministry of Culture, the Norwegian Olympic Committee & Confederation of Sport, Norsk Tipping AS and Pfizer AS.

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