Mok, K.-M., Fong, D. T.-P., Krosshaug, T., Hung, A. S. L., Yung, P. S.-H., Chan, K.-M. (2011). An ankle joint model-based image-matching motion analysis technique. *Gait & Posture, 34*, 71-75.

ABSTRACT

This study presented a model-based image-matching (MBIM) motion analysis technique for ankle joint kinematic measurement. Five cadaveric below-hip specimens were manipulated through a full range of ankle joint motions in bare-foot and shoed conditions. The ankle motions were analyzed by bone-pin marker-based motion analysis and MBIM motion analysis techniques respectively. The root mean square errors of all angles of motion were less than 3 degrees. The average Intraclass Correlation Coefficients (ICCs) for the intra-rater reliability were greater than 0.928 and the average ICCs for the inter-rater reliability were greater than 0.948 for all ranges of motion. Excellent validity, intra-rater reliability and inter-rater reliability were achieved for the MBIM technique in both bare-foot and shoed conditions. The MBIM technique can therefore provide good estimates of ankle joint kinematics.

INTRODUCTION

Ankle ligamentous sprain is one of the most common injuries encountered in sports (Fong et al., 2007; Fong et al., 2009a). A precise description of the injury situation is a key component to understanding the aetiology and injury mechanism (Bahr and Krosshaug, 2005). The injury mechanisms of ankle ligamentous sprain have been described as a combined inversion and internal rotation of the ankle joint (Safran et al., 1991), or plantarflexion with the subtalar joint adducting and inverting (Vitale & Fallat, 1988). Fong et al. (2009b) reported the ankle joint kinematics from a single accidental ankle supination sprain case under skin-marker motion analysis, the finding is that dorsiflexion instead of plantarflexion was found at injury. A study analyzed the ankle supination sprain injuries using video analysis, Andersen et al. (2004) reported two major injury mechanisms as: (1) impact by opponent on the medial aspect of the leg just before or at foot strike, which resulted in a laterally directed force causing the player to land with the ankle in a an excessive inverted position; and (2) forced plantarflexion when the injured player hit the opponent's foot when attempting to shoot or clear the ball. However, those conclusions only revealed the injury mechanism qualitatively. Although determination of the direct cause of the injury, namely the joint loading, may be difficult based on video analysis (Krosshaug and Bahr, 2005), a recent study on the mechanisms of ACL injuries (Koga et al. 2010) have clearly demonstrated that quantification of the observed kinematics can provide important insight into the mechanism of injury.

A direct approach to study such injuries is to analyze video sequences of real ankle sprain injury incidents captured during televised sport events. However, it is not possible to use standard biomechanical method to analyse these video sequences (Krosshaug and Bahr, 2005). Krosshaug and Bahr (2005) introduced a Model-Based Image-Matching (MBIM) technique for reconstructing three-dimensional human motion from uncalibrated video sequences, and successfully employed this technique to analyze anterior cruciate ligament injuries (Krosshaug et al., 2007, Koga et al., 2010).

The developed MBIM technique has been validated, but only validated for the hip and knee joints. In order to utilize the MBIM technique to analyze ankle joint motions, it is necessary to first evaluate its validity and reproducibility. Therefore, the purpose of this study was to validate the MBIM technique for estimating ankle joint kinematics in a cadaveric lower limb specimen using bone-pin marker-based motion analysis as the gold standard.

MATERIALS AND METHODS

Experimental setup

Five cadaveric below-hip specimens (shank length = 32.4±1.9cm, shank circumference = 24.6±1.4cm, foot length = 22.5±0.7cm, foot width = 8.2±0.6cm) were prepared for testing. The shank length was defined as the distance between the lateral femoral epidcondyle and lateral malleolus. Shank circumference was defined as the maximum circumference along the shank. Foot length was defined as the anterior-posterior length measurement from the lateral calcaneus to the tip of the long toe; foot width was defined as the maximal medial-lateral distance measured perpendicular to the long axis of the foot. These anthropometrical measurements were used to customize the skeleton model used in the Model-Based Image-Matching technique. The Achilles tendon and surrounding soft tissues around the ankle joint were dissected to increase joint range of motion, given that basic structure was intact.

Bone-pin marker based video motion analysis

Hofmann II external fixation 5.0mm bone-pins (Stryker, USA) with triads of reflective markers were drilled into the posterolateral side of the calcaneus and into the tibia through the lateral tibial condyle (Reinschmidt et al., 1997a). Figure 1 showed the bone-pin makers on cadavers with two testing conditions, bare-foot and shoed. A hole on the lateral posterior side of the shoe was prepared for the penetration of bone-pins, given that there is no interference between the bone-pins and shoes. Four video cameras (Casio EX-F1, Tokyo, Japan) were used to record the ankle motion at 30Hz with 640x480 resolutions from different views. A static calibration trial in the anatomical position served as the offset position to determine the segment embedded axes of the shank and foot segment. The foot coordinate system was aligned with the Laboratory Coordinate System (LCS) (Reinschmidt et al., 1997b). Reflective skin markers were attached to the lateral femoral epicondyle, medial femoral epicondyle, lateral malleolus and medial malleolus to define knee and ankle joint centers (Wu et al., 2002). These markers were removed after the static calibration. The line connecting the knee joint centre and the ankle joint centre was defined as the longitudinal axis of the shank segment (X1). The anterior-posterior axis of the shank segment (X2) was the cross product between X1 and the line joining the lateral femoral epicondyle and medial femoral epicondyle. The medial-lateral axis of the shank segment was the cross product of X1 and X2. Full-range plantarflexion/dorsiflexion, inversion/eversion and relative circular motion between the two shank and foot segments were performed manually on the ankle joint. The video recordings from the four video cameras were analyzed by a video motion analysis system (Ariel Performance Analysis System, USA) which was used to calculate the reflective marker's three-dimensional coordinates. A singular value decomposition method was employed to calculate the transformation from triad reference frame to anatomical shank and foot reference frame (Sodervist and Wedin, 1993). Joint kinematics were resolved by the Joint Coordinate System (JCS) method (Grood and Suntay, 1983).

Model-Based Image-Matching motion analysis

The videos were analyzed using the MBIM technique (Figure 3). 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, for instance, the boundaries of the mechanical jig. We utilized a skeleton model from Zygote Media Group Inc.

(Provo, Utah, USA) for the athlete matching of the leg. The model for lower extremity consisted of 9 rigid segments with a hierarchical structure, using the pelvis as the parent segment. In our study, 5 rigid segments were enough for one side. 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 foot relative to the shank. The matching procedure has been described in detail by Krosshaug and Bahr (2005). Two researchers, A and B, performed the manual skeleton matching process five times on each specimen. Both researchers possessed good human biomechanics knowledge and were trained to implement the MBIM technique by following the same protocol (Figure 2). Because the default ankle joint center of the Zygote skeleton model was not located at the mid-point between the malleoli, the ankle joint centre was adjusted in the Joint Editor Section of the Poser software. The centre of ankle joint were preset as right side [-0.045 0.030 -0.008] and left ankle side [0.045 0.030 -0.008] according to the joint centre definition in ISB recommendation (Wu et al., 2002). After the initial matching was completed, the motions of the skeleton model were reassessed and adjusted frame by frame to ensure a smoothed motion.

Statistical analysis

The differences between bone-pin marker-based motion analysis and MBIM technique were quantified using Root Mean Square (RMS) error. Bivariate Pearson correlations were calculated to compare the similarity of the trends between the two techniques. Intra-rater reliability and inter-rater reliability within the MBIM technique were assessed using Intraclass Correlation Coefficients (ICCs). Since the MBIM technique provide continuous joint angle time histories, ICCs with two-way mixed model average measures were calculated to evaluate reliability (Hopkins, 2000).

Fleiss (1986) suggested that an ICC coefficient of >0.75 was considered as evidence of good agreement. However, in the present study, we defined that an ICC coefficient of >0.90 was required to achieve excellent reliability.

RESULTS

Validity

In both testing conditions, the RMS errors were less than three degrees for all angles of motion (plantar/dorsiflexion, inversion/eversion, internal/external rotation). The measurement difference, standard deviation of difference, 95% limits of agreement and related statistical results were reported in table 1. The Pearson's correlations were higher than 0.946 for all angles of motion and conditions. In general, the MBIM technique achieved excellent accuracy and correlation with the results from the bone-pin marker-based motion analysis.

Intra-rater reliability

Results of ICC coefficients on three angles of motion were shown in table 2. In both bare-foot and shoed conditions, the ICC coefficients for intra-rater reliability demonstrated excellent correlation (ICC coefficient >0.955) for all angles of motion. Intra-rater reliability was considered to have been achieved as all ICC coefficients were greater than 0.950, and the analysis was reproducible from a single researcher.

Inter-rater reliability

Results of ICC coefficients on three angle of motion were shown in table 3. In both testing conditions, the ICC coefficients for inter-rater reliability demonstrated excellent correlation (ICC coefficient >0.952) for angles of motion between two investigators. Inter-rater reliability was considered to have been achieved as all ICC coefficients were greater than 0.90, and the analysis was reproducible for different researchers.

DISCUSSION

Skin-marker based motion analysis is the most common present approach to investigate joint kinematics. Previous studies comparing skin markers compared to bone-pin markers gave RMS error of 4.7° for plantarflexion/dorsiflexion angle, 4.6° for inversion/eversion angle and 3.6° for internal/external rotation angle under slow speed running (Reinschmidt et al., 1997a). For MBIM motion analysis technique, the RMS errors of the three angles of motion were less than 3° for the entire testing motion (Table 2), the expected improvement in accuracy using bone pins was evident, although a direct comparison was not possible since neither in the running or ankle manipulation studies were both recorded concurrently. In our study, bare-foot and shoed conditions were also tested. Basketball shoes was chosen because basketball shoes had high tops which covered the whole ankle joint, and this made the most difficult situation for the skeleton matching process. By visual inspection, there was shear movement between the foot and shoe, the underlying movement of foot segment was hidden. Nevertheless, the accuracy of MBIM technique in shoed conditions is still very good. Regarding the reliability of the MBIM technique, the average ICC coefficients for the intra-rater reliability were greater than 0.928 for all ranges of motion and the average ICC coefficients for the inter-rater reliability were greater than 0.948. These results implied that different trained researchers can produce the same results with excellent reliability.

A detailed protocol for the matching is suggested in this study, which we believe is crucial for the excellent results. During the skeleton matching process, researchers should be carefully in identifying the longitudinal axis orientations of the shank and the foot segments. Inversion/eversion, it was highly dependant on the orientation of the foot segment. The foot segment could be regarded as a rectangular board. The orientation of the plantar foot would be key information to match the foot skeleton on the video images. Using the top view camera and front view camera in Poser, the detailed orientation of the foot segment could be seen and further fine tuning was possible. In the previous validation study of Krosshaug and Bahr (2005) a relatively large discrepancy in internal/external rotation of the knee joint was obtained between the Poser method and the reflective marker based method. This was identified to originate form the thigh segment, likely due to soft tissue artifacts of the thigh relative to the underlying bone (Krosshaug & Bahr, 2005). Similarly, the shank was comparably difficult to be perfectly matched. In the matching of the tibia model on the images, the patellar position and the anterior edge of the shank were the decisive landmarks to define the internal rotation orientation of the shank. Those two anatomical landmarks were chosen because the underlying soft tissue was relatively thin, and they could precisely reflect the rotation orientation of the tibia. Lastly, researchers were suggested to reassess the motion of the skeleton model for the whole video and adjusted frame by frame to ensure a smooth matched motion.

The MBIM motion analysis technique is a novel approach to reconstruct the three-dimensional kinematics from uncalibrated video sequences, however the authors would like to point out several directions for the MBIM technique to be further developed. Firstly, more than four commercial softwares were employed in the whole analysis. It would be more user-friendly and time-effective if an all-in-one software was developed. Secondly, the skeleton matching process was extremely time-consuming to the researcher. The process could be more time-saving if camera position estimation and edge detection technique were implemented (Oe et al., 2005). The camera position estimation technique could help matching the virtual environment in a more precise and faster manner, and the edge detection technique could objectively outline the segment boundary for skeleton matching. However, this kind of development was currently not possible on the MBIM motion analysis technique because of the dependence on commercial softwares. The kinematics can be further analyzed by to figure out the internal stress and liagmentous tension (Chao et al., 2007). MBIM motion analysis technique may potentially be developed into a sophisticated video analysis for research or clinical uses, such as the mechanisms of injuries captured on tape.

CONCLUSION

Excellent validity, intra-rater reliability and inter-rater reliability were achieved for the MBIM technique in both bare-foot and shoed conditions. The MBIM motion analysis technique can therefore provide excellent estimates of ankle joint kinematics.

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REFERENCES

1. Andersen TE, Floerenes TW, Arnason A, Bahr R. Video analysis of the mechanisms for ankle injuries in football. American Journal of Sports Medicine 2004, 32(Suppl): S69-S79.
2. Bahr R, & Krosshaug T. Understanding injury mechanisms: A key component of preventing injuries in sports. British Journal of Sports Medicine 2005, 39(6): 324-329.

3. Chan KM, Fong DTP, Hong Y, Yung PSH, Lui PPY. Orthopaedic sport biomechanics – a new paradigm. Clinical Biomechanics 2008, 23(1 Supp): 21-30.
4. Chao EYS, Armiger RS, Yoshida H, Lim J, Haraguchi N. Virtual interactive musculoskeletal system (VIMS) in orthopaedic research, education and clinical patient care. Journal of Orthopaedic Surgery and Research 2007, 2:2.
5. Fleiss JL (Ed), (1986) The design and analysis of clinical experiments New York, John Wiley & Sons.
6. Fong DTP, Hong Y, Chan LK, Yung PSH, Chan KM. A systematic review on ankle injury and ankle sprain in sports. Sports Medicine 2007; 37(1): 73-94.
7. Fong DTP, Chan YY, Mok KM, Yung PSH, Chan KM. Understanding acute ankle ligamentous sprain injury in sports. Sports Medicine, Arthroscopy, Rehabilitation, Therapy and Technology 2009a; 1: 14.
8. Fong DTP, Hong Y, Shima Y, Krosshuag T, Yung PSH, Chan KM. Biomechanics of supination ankle sprain: a case report of an accidental injury event in the laboratory. American Journal of Sports Medicine 2009b; 37(4): 822-827.
9. Grood E S & Suntay W J. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. Journal of Biomechanical Engineering 1983; 105(2): 136-144.
10. Hopkins WG. Measures of Reliability in Sports Medicine and Science. Sports Medicine 2000; 30(1): 1-15.
11. Krosshaug T & Bahr R. A model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences. Journal of Biomechanics 2005; 38(4): 919-929.
12. Krosshaug T, Slauterbeck JR, Engebretsen L, Bahr, R. Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences. Scandinavian Journal of Medicine and Science in Sports 2007; 17(5): 508-519.
13. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engretsen L, Bahr R, Krosshaug T. Mechanisms for noncontact anterior cruciate ligament injuries. American Journal of Sports Medicine 2010; 35(11):2218-2225.
14. Oe M, Sato T, Yokoya N. Estimating Camera Position and Posture by Using Feature Landmark Database: Lectures Notes in Computer Sciences Heideberg, Springer Berlin 2005: 171-181.

15. Reinschmidt C, van Den Bogert AJ, Murphy N, Lundberg A, Nigg BM. Tibiocalcaneal motion during running, measured with external and bone markers. Clinical Biomechanics 1997a; 12(1): 8-16.
16. Reinschmidt C, van Den Bogert AJ, Nigg BM, Murphy N, Lundberg A. Effect of skin movement on the analysis of skeletal knee joint motion during running. Journal of Biomechanics 1997b; 30(7): 729-732.
17. Safran MR, Benedetti RS, Bartolozzi AR 3rd, Mandelbaum BR.. Lateral ankle sprains: a comprehensive review: part 1: etiology, pathoanatomy, histopathogenesis, and diagnosis. Medicine and Science in Sports and Exercise 1991, 31(7 Supp): 429-437.
18. Soderkvist I & Wedin PA. Determining the movements of the skeleton using well-configured markers. Journal of Biomechanics 1993; 26(12): 1473-1477.

19. Vitale TD, Fallat LM. Lateral ankle sprains: evaluation and treatment. Journal of Foot Surgery 1988, 27(3): 248-258.
20. Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, Whittle M, D'Lima DD, Cristofolini L, Witte H, Schmid O, Stokes I. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--part I: ankle, hip, and spine. Journal of Biomechanics 2002; 35(4): 543-548.
21. Zinder SM, Granata KP, Padua DA, Gansneder BM. Validity and reliability of a new in vivo ankle stiffness measurement device. Journal of Biomechanics 2007; 0(2): 463-467.

FIGURE LEGENDS

Figure 1. Bone-pin makers on cadavers with two testing conditions, bare-foot and shoed

Figure 2. An example of finished skeleton matching using MBIM motion analysis technique, skeleton model on video images

Figure 3. Protocol of the ankle joint model-based image-matching motion analysis technique