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# An ankle joint model-based image-matching motion analysis technique

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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°. 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 angles 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.



## 1. Introduction

Ankle ligamentous sprain is one of the most common injuries encountered in sports [1,2]. A precise description of the injury situation is a key component to understanding the aetiology and injury mechanism [3]. The injury mechanisms of ankle ligamentous sprain have been described as a combined inversion and internal rotation of the ankle joint [4], or plantarflexion with the subtalar joint adducting and inverting [5]. Fong et al. [6] reported the ankle joint kinematics from a single accidental ankle supination sprain case using skin-marker based motion analysis, and they found that dorsiflexion instead of plantarflexion occurred during ankle ligamentous sprain injury. Another study by Andersen et al. [7] analyzed ankle supination sprain injuries using video analysis, and they 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 which causes the player to land with the ankle in a an excessively inverted position; and (2) forced plantarflexion when the injured player hit the opponent's foot while attempting to shoot or clear the ball. However, these conclusions only revealed the injury mechanism qualitatively. Although determination of the direct causes of the injury, such as joint loading, may be difficult based on video analysis [3], a recent study on the mechanisms of ACL injuries [8] have clearly demonstrated that quantification of the observed kinematics can provide important insights for understanding the mechanisms of injury.

A direct approach to study such injuries is by analyzing video sequences of real ankle sprain injury incidents captured during televised sport events. However, it is not possible to use standard biomechanical methods to analyze these video sequences [9]. Krosshaug and Bahr [9] 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 [8,10].

However, the developed MBIM technique has only been validated for the hip and knee joints. In order to apply the MBIM technique on the analysis of 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.

## 2. Materials and methods

### 2.1. Experimental setup

Five cadaveric below-hip specimens (shank length = 32.4 ± 1.9 cm, shank circumference = 24.6 ± 1.4 cm, foot length = 22.5 ± 0.7 cm, foot width = 8.2 ± 0.6 cm)

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cm) 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, and 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. Before testing, the Achilles tendon and surrounding soft tissues around the ankle joint were dissected to increase joint ranges of motion, provided that the basic structures were intact.

### 2.2. Bone-pin marker based video motion analysis

Hofmann II external fixation 5.0 mm 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 [11]. Fig. 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 insertion of bone-pins, given that there is no interference between the bone-pins and the shoe. Four video cameras (Casio EX-F1, Tokyo, Japan) were used to record the ankle motion at 30 Hz with $640 \times 480$ 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) [12]. 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 [13]. 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 [14]. Joint kinematics were resolved by the Joint Coordinate System (JCS) method according to Grood and Suntay [15].

### 2.3. Model-based image-matching motion analysis

The videos were analyzed using the MBIM technique (Fig. 3). The matchings were performed using the commercially available program Poser® 4 and the Poser® Pro Pack (Curious Labs Inc., Santa Cruz, CA, 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 modelled using points and straight lines from the boundaries of the mechanical jig. We utilized a skeleton model from Zygote Media Group Inc. (Provo, Utah, USA) for the skeleton matching of the leg. The model for lower extremity consisted of nine rigid segments with a hierarchical structure, using the pelvis as the parent segment. In our study, five rigid segments were adequate for one side. The pelvis motion was described by three rotational and three translational degrees of freedom. The motions of the remaining segments were then described with three rotational degrees of freedom relative to their parent segment, e.g., the foot relative to the shank. The matching procedure has been described in detail by Krosshaug and Bahr [9]. 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 (Fig. 2). Since the default ankle joint centre 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 in the Poser software. The centre of the ankle joint were preset as [$-0.045$ 0.030 $-0.008$] at the right ankle and [0.045 0.030 $-0.008$] at the left ankle side according to the ISB recommendation [13]. After the initial matching was completed, the motions of the skeleton model were reassessed and adjusted frame by frame to ensure a smooth motion.

### 2.4. 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 provided continuous joint angle time histories, ICCs with two-way mixed model average measures were calculated to evaluate reliability [16]. Fleiss [17] 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.

**Fig. 1.** Bone-pin makers on cadavers with two testing conditions: bare-foot and shoed.

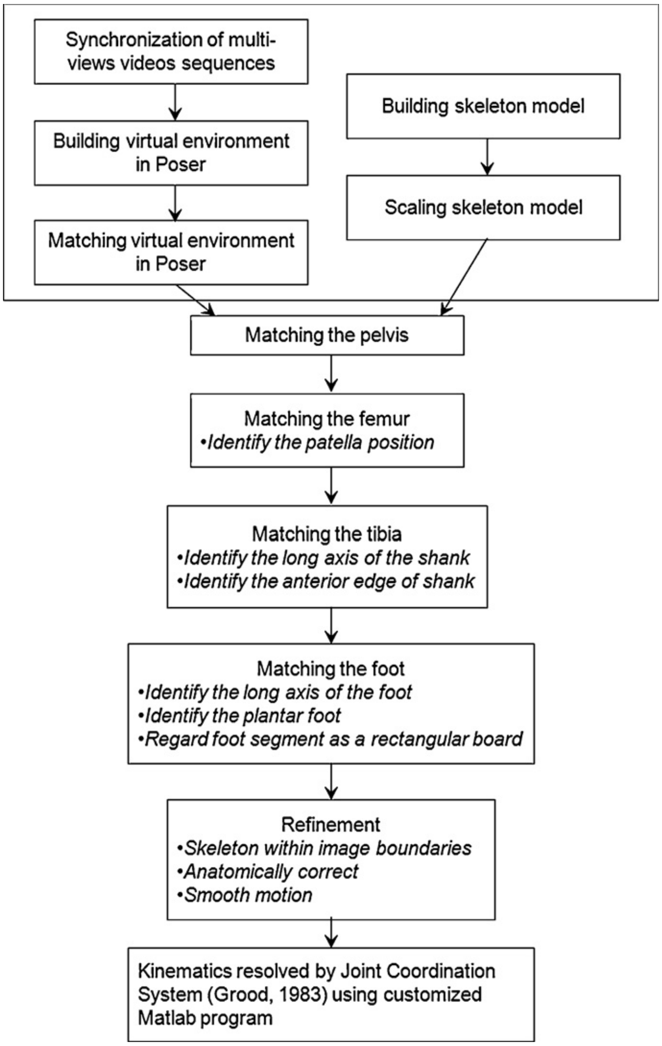


**Fig. 2.** Protocol of the ankle joint model-based image-matching motion analysis technique.

**Table 1**
Accuracy and Correlation for all angles of motion in two testing conditions.

| | Bare-foot | Shoed |
|---|---|---|
| Plantarflexion+/dorsiflexion− | | |
| Root mean square (rms) error | 2.08 | 2.36 |
| Mean difference (*d*) | −0.27 | 0.20 |
| S.D. of difference | 2.05 | 2.47 |
| 95% limits of agreement | −4.29 → 3.75 | −4.64 → 5.04 |
| Pearson's correlation (*R*) | 0.996 | 0.985 |
| *R* square ($R^2$) | 0.991 | 0.971 |
| Average range of motion (°) | −39.7 → 67.9 | −47.6 → 48.4 |
| Inversion+/eversion− | | |
| Root mean square (rms) error | 1.99 | 2.95 |
| Mean difference (*d*) | 0.29 | 0.82 |
| S.D. of difference | 2.09 | 2.97 |
| 95% limits of agreement | −3.81 → 4.39 | −5.00 → 6.64 |
| Pearson's correlation (*R*) | 0.996 | 0.998 |
| *R* square ($R^2$) | 0.992 | 0.996 |
| Average range of motion (°) | −48.7 → 82.3 | −42.5 → 61.7 |
| Internal rotation+/external rotation− | | |
| Root mean square (rms) error | 2.01 | 2.20 |
| Mean difference (*d*) | −0.29 | 0.40 |
| S.D. of difference | 1.75 | 2.87 |
| 95% limits of agreement | −3.72 → 3.14 | −5.23 → 6.03 |
| Pearson's correlation (*R*) | 0.952 | 0.946 |
| *R* square ($R^2$) | 0.907 | 0.894 |
| Average range of motion (°) | −13.7 → 5.9 | −11.4 → 6.7 |

**Table 2**
Intra-rater reliability (intra-class correlation).

| | Plantarflexion/dorsiflexion | | Inversion/eversion | | Internal/external rotation | |
|---|---|---|---|---|---|---|
| Researcher | A | B | A | B | A | B |
| Bare-foot | | | | | | |
| Leg 1 | 0.999 | 0.998 | 0.997 | 0.993 | 0.957 | 0.968 |
| Leg 2 | 0.997 | 0.999 | 0.999 | 0.999 | 0.991 | 0.987 |
| Leg 3 | 0.997 | 0.996 | 0.992 | 0.995 | 0.986 | 0.983 |
| Leg 4 | 0.998 | 0.999 | 0.997 | 0.999 | 0.978 | 0.981 |
| Leg 5 | 0.992 | 0.998 | 0.999 | 0.999 | 0.971 | 0.958 |
| Average | 0.997 | 0.998 | 0.997 | 0.997 | 0.977 | 0.975 |
| Shoe-wearing | | | | | | |
| Leg 1 | 0.997 | 0.999 | 0.994 | 0.997 | 0.928 | 0.945 |
| Leg 2 | 0.990 | 0.997 | 0.997 | 0.987 | 0.940 | 0.987 |
| Leg 3 | 0.994 | 0.994 | 0.998 | 0.998 | 0.980 | 0.974 |
| Leg 4 | 0.996 | 0.994 | 0.996 | 0.997 | 0.976 | 0.980 |
| Leg 5 | 0.995 | 0.995 | 0.995 | 0.997 | 0.953 | 0.950 |
| Average | 0.994 | 0.996 | 0.996 | 0.995 | 0.955 | 0.967 |

## 3. Results

### 3.1. 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 for all conditions. In general, the MBIM technique achieved excellent accuracy and correlation compared with the results from the bone-pin marker-based motion analysis.

### 3.2. 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

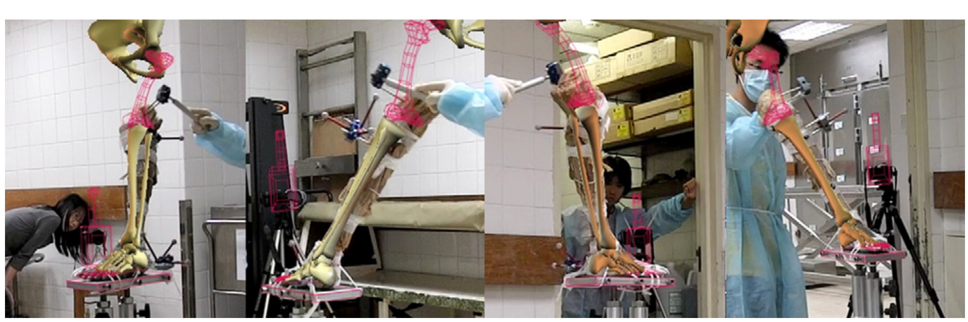

**Fig. 3.** An example of completed skeleton matching using MBIM motion analysis technique, skeleton model on video images.

**Table 3**
Inter-rater reliability (intra-class correlation).

| Condition | Plantarflexion/dorsiflexion | Inversion/eversion | Internal/external rotation |
|---|---|---|---|
| Bare-foot | 0.996 | 0.994 | 0.952 |
| Shoe-wearing | 0.993 | 0.997 | 0.948 |

coefficients for intra-rater reliability demonstrated excellent correlation (ICC coefficient >0.955) for all angles of motion. Intra-rater reliability was considered to be acceptable since all ICC coefficients were greater than 0.950, and therefore the analysis was reproducible by a single researcher.

### 3.3. Inter-rater reliability

Results of ICC coefficients on three angles 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 the two investigators. Inter-rater reliability was considered to be acceptable since all ICC coefficients were greater than 0.90, and therefore the analysis was reproducible by different researchers.

## 4. Discussion

Skin-marker based motion analysis is the presently the most common approach to investigate joint kinematics. Previous studies comparing skin markers 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 [11]. For the MBIM motion analysis technique, the RMS errors of the three angles of motion were less than 3° for all the testing motions (Table 2). In our study, bare-foot and shoed conditions were also tested. Basketball shoes was chosen since they have high tops that cover the whole ankle joint, rendering a difficult situation for the skeleton matching process. Nevertheless, the accuracy of the MBIM technique in shoed conditions is still very high. Regarding the reliability of the MBIM technique, the average ICC coefficients for the intra-rater reliability were greater than 0.928 for all angles 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 procedure is suggested in this study, which is vital in obtaining accurate results. During the skeleton matching process, researchers should be careful in identifying the longitudinal axis orientations of the shank and the foot segments. Inversion and eversion were highly dependant on the orientation of the foot segment. The foot segment may be regarded as a rectangular board. The orientation of the plantar foot would be the 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 by Krosshaug and Bahr [9], a relatively large discrepancy in internal/external rotation of the knee joint was observed between the Poser method and the reflective marker based method. This originated from the thigh segment, likely due to soft tissue artifacts of the thigh relative to the underlying bone [9]. 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 orientation of the internal rotation of the shank. These two anatomical landmarks were chosen because there are less underlying soft tissues, and they could more accurately reflect the rotation of the tibia. Lastly, researchers were suggested to reassess the motion of the skeleton model for the whole video and adjust frame by frame to ensure a smoothly 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 time-consuming for the researchers. The process could be more time-saving if camera position estimation and edge detection techniques were implemented [18]. The camera position estimation technique could help match the virtual environment in a more precise and efficient manner, and the edge detection technique could objectively outline the segment boundary for skeleton matching. However, these kinds of development were currently not possible for the MBIM motion analysis technique due to the use of commercial softwares. The kinematics can be further analyzed to determine the internal stress and liagmentous tension [19]. MBIM motion analysis technique may potentially be developed into a sophisticated video analysis tool for research or clinical uses.

## 5. Conclusion

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


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## Conflict of interest

None declared.

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