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The Use of Model Matching Video Analysis and Computational Simulation to Study the Ankle Sprain Injury Mechanism

Regular Paper

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Abstract Lateral ankle sprains continue to be the most common injury sustained by athletes and create an annual healthcare burden of over $4 billion in the U.S. alone. Foot inversion is suspected in these cases, but the mechanism of injury remains unclear. While kinematics and kinetics data are crucial in understanding the injury mechanisms, ligament behaviour measures - such as ligament strains - are viewed as the potential causal factors of ankle sprains. This review article demonstrates a novel methodology that integrates model matching video analyses with computational simulations in order to investigate injury-producing events for a better understanding of such injury mechanisms. In particular, ankle joint kinematics from actual injury incidents were deduced by model matching video analyses and then input into a generic computational model based on rigid bone surfaces and deformable ligaments of the ankle so as to investigate the ligament strains that accompany these sprain injuries. These techniques may have the potential for guiding ankle sprain prevention strategies and targeted rehabilitation therapies.

Keywords Injury, Lateral ankle sprain, Kinematics, Ligament strain, Methodology.

1. Introduction

Ankle sprains are a common injury in sport[1], and the most common diagnosis is that of the ligamentous sprain in the lateral ankle ligaments[2]. The commonly suggested aetiology is that of incorrect foot positioning at landing plus the delay of the peroneal muscle's reaction; the commonly suggested mechanism is an excessive and explosive inversion - or supination - which is a combination of inversion and plantarflexion at the ankle joint[3].

The above-mentioned ankle sprain injury mechanism is the common clinical presentation, which is rather qualitative in nature. Researchers have used free-fall platforms to simulate an injury-like motion in order to study its biomechanics[4] and develop a mathematical method to identify a simulated ankle sprain motion from common sporting activities through dorsal foot kinematics data[5]. However, the injury-like motions - or the sub-injury motions - were not real injury incidents, and it is questionable whether they could really contribute to data for understanding of the ankle sprain injury mechanism.

In rare circumstances, an ankle sprain injury happened in the laboratory in a calibrated setting which allowed the collection of biomechanical data[6,7]. These reports documented kinematics data from video analysis, as well as plantar pressure[6] and ground reaction force data[7]. By comparing the ankle kinematics data from these reports and from other common sporting activities, we could establish a threshold so as to identify hazardous ankle joint motion[8] and further develop a wearable system to monitor the ankle spraining injury risk[9]. However, these studies do not address the *in vivo* ankle ligament strains that accompany excessive foot motions and which may be the direct causal factors of ankle sprains. In addition, one might question whether the data from two injury cases could really represent the injury, as the incidents happened in a laboratory and the injured subjects may not have performed the sporting motion as vigorously as in real sports. Moreover, a sporting injury could be caused by awkward joint motion which would greatly differ in each case. Therefore, there is a need to obtain data from more real injury incidents in order to better understand the injury mechanism. Researchers then have to collect videos and develop new methods for systematic analyses.

This article presents a model matching video analysis technique to study ankle joint kinematics from actual injury incidents and a computational simulation method to further study *in vivo* ligament strains and ankle joint moments.

2. Model matching video analysis for studying ankle kinematics

One of the ways to obtain more real injury incidents for analyses is to collect video sequences of an injury captured during televised sporting events. By carefully viewing each incident on the video sequence, Andersen and colleagues[10] presented the ankle sprain injury mechanism in football, but only qualitatively since the videos were not taken in a calibrated setting and, therefore, a biomechanical analysis of the motion was not possible. In order to conduct a quantitative analysis, an ankle joint model-based image-matching motion analysis technique was developed[11].

2.1 Processing the video sequence of the injury incident

Video sequences from two or more different views which clearly show incidents and the ankle joint of the injured athlete are necessary. A zoomed-in camera view of the injured athlete, if available, would provide a better and clearer video sequence for processing. However, if the video is zoomed-in too much, we may not be able to identify the perpendicular lines on the sports ground, which are essential in setting up the virtual environment for estimating the position of the athlete during the model matching procedure. In a camera overview - which often shows the whole sports ground - the ankle joint of an injured athlete would occupy only a very small portion of the whole picture size, which would not facilitate the model matching. However, such a view is also useful as we have to identify the perpendicular lines on the sports ground for estimating the relative position of the injured athlete. Therefore, it is always preferable to obtain as many views (whether zoomed-in or not) as possible.

High-definition videos are available nowadays, and they are to be preferred as their quality can greatly facilitate the process. It may also be necessary to equip a computer with two or more large, high-resolution monitors to display high definition videos in full size (i.e., 1920 x 1080 pixels). Otherwise, the quality of the videos would not have been fully utilized. For obtaining such high-definition videos, researchers may have to contact the broadcasting company of the sporting event by themselves. It is also important to know the framing rate of the video sequence, which does not often come with the video file unless specifically requested. If a video with an unknown framing rate is to be used, the researchers would have to estimate the framing rate by observing the total number of frames elapsed during a certain motion and assume the total span time of that motion. For example, and from the literature, the duration of a gait cycle is around 1.1-1.3s. If a gait cycle elapsed at around 55-65 frames in a video, we would estimate the framing rate to be 50Hz.

The videos have to be transformed from their original format into an uncompressed AVI image sequence, de-interlaced and then rendered into a synchronized video sequence. These procedures could be done with many different image processing software products. One of the recommendations is the Adobe series, including Adobe Premiere Pro, Photoshop and After-Effects (Version CS4, Adobe Systems Inc.). If there are multiple views with different framing rates – e.g., one view of 50Hz and two views of 100Hz - one should keep all of the available frames and render them into the highest framing rate - i.e., 100Hz, but not trim them off to the lowest framing rate - i.e., 50Hz. After this process, there will be blank frames in the views with lower framing rate.

2.2 Information of the injured athlete for building a model

There is often some unavailable but essential information. The most critical would be that relating to the medical diagnosis and informed consent. Most injured athletes from televised sport events are famous sport stars, and it would be difficult for researchers to contact them to obtain their medical diagnoses and informed consents. On the other hand, since the medical diagnosis is not available to researchers, one might question how they could define the injury as an ankle ligamentous sprain injury. In a recent study that presented two cases from the 2008 Beijing Olympics[12], the research group defined the injury as being when the athlete was unable to continue the match or competition after the ankle inversion sprain motion. It would also be necessary to obtain ethical approval from the institutional review board, especially when informed consents could be unavailable in a study of this nature.

Other information that is often unavailable is the patient's anthropometric data, which would help build a skeleton model for the model matching procedure. If such information is available - usually by direct contact and measurement of the injured athlete - one could utilize the data to build subject specific models with the correct dimensions for the shank and the foot segment. If such information is unavailable, one might obtain the basic anthropometric data of the athlete - such as the height, as reported by their official sports club or federation website - and scale a pre-set skeleton model to fit that height. In our practice, the skeleton model from Zygote Media Group Inc. (Provo, Utah) was employed.

2.3 The matching of the skeleton model to the video sequence

The matching is performed with the Poser 4 and Poser Pro Pack (Curious Labs Inc., Santa Cruz) software. Details are published in a previous study[11]. First, the dimensions of the sports ground in which the injury occurred should be obtained, if possible. If not, one shall have to obtain the dimensions of a standard sports ground from the available literature. With this information, a virtual environment of the sports ground with perpendicular lines is built. The skeleton model from Zygote Media Group Inc. contains nine rigid segments with the pelvis as the primary parent segment, and the matching begins with the pelvis segment and then distally to the left and/or right femur, the shank, the foot and the toe. To investigate the ankle kinematics, the essential body segments to be matched are the shank and the foot. The ankle motion is presented by the foot segment orientation relative to the shank segment orientation.

The quality of the matching depends upon the knowledge of the researcher, and it might also affect the kinematics

data to be determined. To ensure quality, a protocol was also suggested as the instruction for the model matching procedure[11]. The femur and the tibia segments are somewhat alike with a cylindrical shape and, therefore, the alignment along the longitudinal axis of rotation has to be carefully matched by identifying the patellar position and the anterior edge of the shank as the decisive landmarks in the video sequence. In matching the foot segment, one could regard the foot segment as a rectangular board, and match it along the long axis of the foot. After the matching, one should ensure that the skeleton model is always within the image boundaries and that it is anatomically correct. Lastly, one should re-assess the motion with the matched skeleton model frame-by-frame - adjusting the matching if necessary - and ensure a smoothly-matched motion for all camera views. Figure 1 shows a matched video sequence of an ankle sprain injury sustained during a high jump event during the 2008 Beijing Olympics.
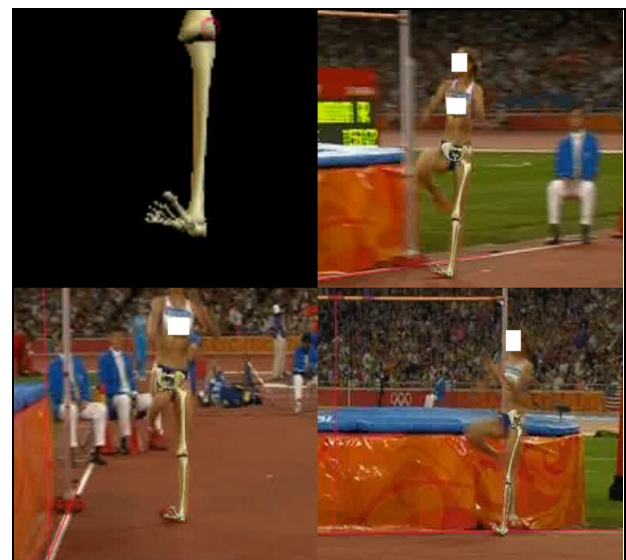

Figure 1. An ankle sprain injury event during the 2008 Beijing Olympics, analysed by the model-based image-matching technique. The kinematics data was reported previously.[12].

Our previous study showed good validity when compared to bone-pin marker-based motion analysis on a cadaveric specimen and good reliability between 5 different trials on the same cadaveric specimen, 5 different cadaveric specimens, 2 different researchers for matching, and 2 different shod conditions (shod and barefoot) [11]. The technique is novel and validated, but it currently utilizes four different items of software, and involves very tedious and time-consuming procedures which have to be performed manually. Further development should involve automatic camera position estimation and an edge detection technique for model matching.

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2.4 Determination of ankle kinematics data

After the model matching procedures, the joint angle time histories are exported from the Poser 4 and Poser Pro Pack (Curious Labs Inc., Santa Cruz) software. There are many methods to determine the ankle kinematics data. One of the recommendations is the ankle joint measurement standard, as recommended by the International Society of Biomechanics[13]. A proper filtering procedure may have to be conducted if the fluctuation of the data is not acceptable. This might happen when the injury motion is fast and abrupt, and when the framing rate is too low, e.g., 50Hz. Since a force plate or plantar pressure sensor would be absent, the foot touchdown - which normally happens just before the ankle sprain injury - has to be determined visually.

3. Computational simulation to investigate *in vivo* ankle ligament strains and joint moments

Computational models of musculoskeletal joints and limbs can provide useful information about joint mechanics[14]. Validated models can be predictive tools to understand normal joint function and serve as clinical tools for predicting and helping prevent sports injuries. While finite element modelling yields useful information about stresses and strains in bones and ligaments, an advantage of multibody rigid modelling is the ability to rapidly solve for motion-based mechanics in large structures[15]. To simulate motions documented from the model matching video analysis of ankle sprain events, a three-dimensional (3D) multibody dynamic foot model was developed and validated against several cadaveric and *in vivo* studies.

3.1 Ankle bones' reconstruction

A fresh frozen, left cadaver foot (male, aged 19 years, height of 1.88 m, weight of 86 kg), showing no signs of abnormal anatomy, was transected approximately 15 cm distal to the knee centre. The specimen was fully thawed overnight and a computed tomography (CT) scan was conducted to obtain 3D joint anatomy. Detailed features of the ankle were transferred from Digital Imaging and Communications in Medicine (DICOM) files into Materialise's Interactive Medical Imaging Control System (MIMICS) (Materialise, Ann Arbor, MI). The individual bones of the foot were computationally separated and meshed as solid bodies. This yielded a 3D surface model of each bone as Stereolithography (STL) files for export. To reduce the size of surface files and subsequent models, the STL files were re-meshed in MIMICS to smooth the surface of each bone. The re-meshed STL files were then imported into a 3D solid modelling program (SolidWorks, TriMech Solutions, LLC, Columbia, MD). In SolidWorks, the ScanTo3D package was used to reconstruct each bone and simplify the bone surfaces. The

individual bones were then assembled into a lower extremity and registered with respect to one another in the anatomical position (Figure 2). Since toe involvement is minimal in the experimental cadaver foot, the phalanges were excluded in the model. All other joints of the foot and ankle were constrained only by joint geometry and ligament stability.

3.2 Model formulation

SolidWorks Motion (SolidWorks, TriMech Solutions, LLC, Columbia, MD) was implemented to apply ligamentous restraints, prescribe force/motion constraints and to simulate the ankle dynamics. Ligaments were represented as linear, elastic spring elements, with stiffness values from the literature[16,17]. The origin and insertion locations of the ligaments were determined from dissection and anatomical atlases[18]. Ligament preloads were induced by reducing the lengths by 2%[14]. Each bone was allowed to move in all six degrees of freedom, leaving body motion as a function of ligament behaviour, surface contact and external constraints. 3D contacts[19] were implemented between adjacent bones in order to prevent overlap during the simulation. Friction was neglected to simulate cartilage effects. In the model, the tibia was allowed to move only in the vertical direction (one degree of freedom), and the fibula, the talus and the calcaneus were free to move. The remaining bones of the foot were fused together and moved as a unit for the purpose of simplification. The simulated body weight was applied to the proximal end of the model, proportionally distributing it between the tibia and the fibula as to a one-sixth loading on the fibula[20]. Ligament strains, defined in percentages as the relative elongations of ligaments, were determined from the computational model. Resistive moments, deduced by inverse dynamics along the axes of rotation, were also estimated from the model analysis.
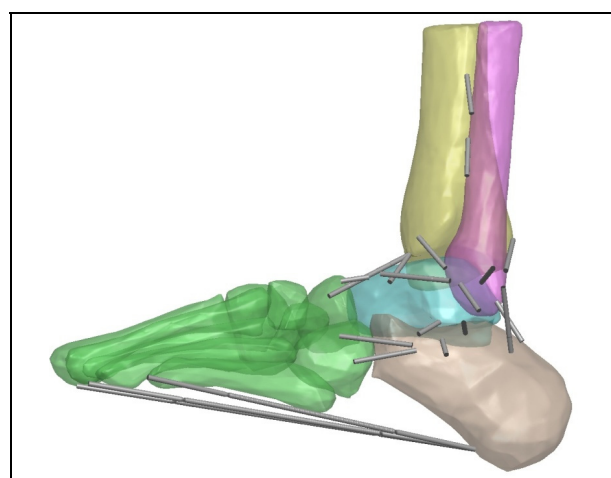

Figure 2. Lateral view of the ankle model showing transparent bones and the locations of 20 simulated ligaments. Ligament definitions and stiffness have been documented previously[16].

3.3 Model validation

The model was validated against two cadaveric studies for ankle ligament strains and ankle joint moments. The first validation recreated the experimental study performed by Colville et al.[21] to investigate the strains present in lateral ankle ligaments while moving the foot and applying stress in a variety of ways. To simulate this cadaver study using the computational model, continuous dorsi–plantar flexion was applied to the foot with the axis of rotation through the talus. A rotational moment of 3 Nm was then internally or externally applied to the talus with the axis of rotation along the tibia for various dorsi–plantar flexion angles. The results showed that the ligament strains of the model during this range of motion followed trends seen experimentally and that the average difference in strain was within 0.005 mm/mm (0.5%)[16].

A second validation of the ankle model was performed while simulating a cadaver study[22] that investigated ankle injury due to excessive external foot rotation. To simulate this cadaver experiment in the computational model, an input external foot rotation of 40° was used, based on the average failure rotation documented in the cadaver study. A comparison of the model with the experiment demonstrated a similar moment–rotation behaviour during this level of external foot rotation, with a correlation coefficient (R^2) equal to 0.950[16].

3.4 Model sensitivity analysis

An additional variable that may control the biomechanics of the ankle joint is the stiffness of ligaments. Reported ligament stiffness values have a relatively large range[23]. To assess the sensitivity of simulations and in order to further validate the computational model, the effect of variations in ligament stiffness on model outcomes was studied by performing an additional simulation that mimicked a previous experimental setup[22]. To quantify the effect of ligament stiffness, first, all of the ligament spring stiffness were together either increased by 25% or decreased by 25%. Second, the strains of each ligament at 40° external foot rotation were compared and those ligaments that had more than 10% strain were selected to individually vary their stiffness by ±25%. Finally, the selected ligaments were randomly combined and a variation of stiffness by ±25% was performed at the same time. These sensitivity analyses resulted in small changes in the maximum moment (< 3%) and rotational stiffness (< 7%) generated from the computational ankle joint[16]. While these results demonstrated a trend of stiffer joints with stiffer ligaments, both parameter variations caused a change lower than the experimental standard deviations reported in the cadaver study[22]. This suggested that moderate parameter variations do not significantly alter the conclusions that could be drawn from this model.

3.5 Model simulation of cadaveric studies

The validated model has been utilized to help investigate motions of the talus during external foot rotation. One biomechanical study[24] externally rotated six pairs of cadaver limbs in two different football shoe designs, a flexible shoe and a rigid shoe. Vicon motion capture (Oxford Metrics Ltd., Oxford, UK) was performed to track the movement of the talus with a reflective marker array screwed into the bone. These talar motions - relative to the tibia in three directions - were determined for each limb and input to drive the computational model for the estimation of ankle ligament strains. The results showed that while the moments developed with the more flexible shoe were lower than those with the rigid one, more talus eversion resulted in a significant increase (200%) in the anterior tibiofibular ligament strain, predisposing the ligament to injury and forming a basis for high ankle sprains. This effect of talus eversion was supported by a later cadaver study that produced, for the first time, a high ankle sprain in a laboratory setting by the external rotation of a highly everted foot[25].

3.6 Model simulation of an actual injury event

While this computational model demonstrated its ability to simulate *in vivo*, physiological motions[17], it also provided insightful information for the understanding of the biomechanics of injury-producing events. In a case report[6], a male athlete (aged 23 years, height of 1.75 m, weight of 62.6 kg) wore a pair of high-top basketball shoes and performed a series of cutting motion trials in the laboratory. In one trial, the athlete accidentally sprained his right ankle and the injury was immediately diagnosed as a grade I sprain of the anterior talofibular ligament. The injury occurred in a laboratory that utilized the model matching video analysis system, enabling the measurement of 3D, temporal kinematic data. These data - i.e., inversion-time, plantarflexion-time and internal rotation-time - were inputted into the computational ankle model for simulation[26], as shown in Figure 3.
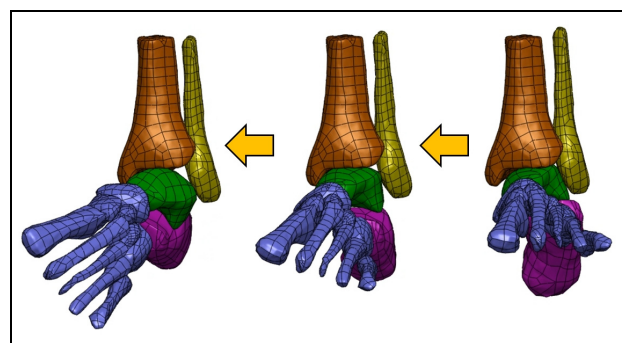

Figure 3. Model simulation of a previously reported injury incident with a diagnosed grade I sprain of the anterior talofibular ligament[26]. The images shown are of the initial, intermediate and final position (right to left) during the simulation.

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Three motor elements were used to drive the motion of the bones, two on the talus for plantarflexion and internal rotation, respectively, and one on the calcaneus for inversion. The three axes of rotation were set as: (1) dorsi-plantarflexion – fixed to the talus through its estimated centre (initially-oriented medial-lateral); (2) internal-external rotation – along the tibial axis; and (3) inversion-eversion – fixed to the calcaneus through its estimated centre and perpendicular to the previous two (initially-oriented anteroposterior). The Akima Spline interpolation method was used to input continuous rotation-time data into SolidWorks Motion to drive the talus and/or the calcaneus movement.

The simulation results showed that the anterior talofibular ligament was strained the most at 20.5%, followed by the calcaneofibular ligament at 16%. This was consistent with the diagnosed sprain location[6]. Additionally, the highest moment was calculated to be 23 Nm for inversion, followed by 11 Nm for internal rotation[26]. The study indicated that a 23 Nm ankle moment may produce 16-20% ankle ligament strains which might cause a grade I ankle sprain.

4. Conclusion

This article reviewed procedures of a model matching video analysis that was used to obtain kinematics data from injury-producing events, and the development and validation of a computational ankle model that was used in various *in vitro* and *in vivo* studies for the estimations of ankle ligament strains and ankle joint moments. The combination of these two novel techniques, aiming at exploring the biomechanics of actual ankle sprains, is encouraging. The development of new prophylactic measures and targeted rehabilitation therapies will hinge upon an accurate understanding of the injury mechanisms and knowledge of the injury-causing factors. These techniques have the potential to provide a better understanding of ankle sprains which may help reduce their incidence and accelerate recovery from this type of injury.

5. Acknowledgments

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