Biomechanical Measurement Methods to Analyze the Mechanisms of Sport Injuries

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Introduction

The performance of an athlete is affected by numerous factors. These can be roughly grouped into three categories which are physiological, biomechanical, and psychological factors. Biomechanical factors have a profound effect on how an athlete controls and compensates movement patterns during the performance of a movement or series of movements. From a biomechanical point of view, these compensations often lead to faulty movement patterns, which decrease the sports performance. For example, if a javelin thrower had an overactive infraspinatus muscle in the shoulder, it would significantly affect the thrower's ability to deliver a consistent high velocity throw. This is due to the shoulder's inability to control the arm at high speed before and after the throw. The same concept applies to all arm-related events, such as golf and tennis.

Video Analysis Software

In order to overcome such a problem, a video analysis system can be a simple solution for athletes and their medical and training team. It helps them come to a common place in an effort to collaborate in accomplishing an athlete's biomechanical needs. The main purpose of such an analysis is to identify an athlete's biomechanical or movement dysfunction by using video analyses of his/her sport as well as breaking down the fundamental parts of the movement to expose the problem part that is contributing to injury and/or decreased performance.

Video analysis software is one of the common tools that is used to capture, edit, and analyze various sport motions to find the weak parts in the movement which may cause injury, pain, or a drop in the performance. By using stroboscopic image extraction method in the video analysis, an athletic movement can be unfolded in time and space by compounding video images into a frame-by-frame of static images along the athlete's trajectory. A typical output of video analysis software can be seen in Fig. 1. From this information, athletes can develop the strength and conditioning specific to

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Fig. 1 Stroboscopic image extraction of triple jump movement from video recording

their movements and their sport. They can also receive suggestions and corrective exercises from the medical team to decrease the risk of injury.

There are, however, shortcomings of the video analyses that cannot be ignored in some cases. Video analysis software happens to be an ineffective tool if exact position, velocity, or acceleration of an athlete's body or his/her equipment is required for a biomechanical analysis.

Motion Analysis Software

A motion analysis system enables one to record movement and then to measure positions, angles of joints, speed and distance of movement, and to compare the same movements performed at different times. Such an analysis gives the athlete or the physician clear information on the reasons of injury, muscle weakness, and degree of improvement. In general, this methodology is called Human Motion Analysis (HMA). Nowadays, the methods can be brought together as whole under the definition of marker-based methods, which are the main methods in the laboratory and clinical environments. Marker-based methods are defined as methods that rely on anatomically positioned markers recorded by camera systems. These systems work by measuring the location of markers attached to the subject. Then, in the case of a three-dimensional (3D) system, using a mathematical procedure the views from several cameras are integrated to form a 3D representation of those markers in space. Camera systems can also be classified into two main streams, which are near-infrared spectrum (it is commonly called as infrared – IR) and visible spectrum cameras. Depending on the camera type, tracing of the markers can be done manually or automatically. Because of the ease in using threshold processing in the IR cameras, infrared reflective markers are used to collect spatial–temporal and kinematic data in the most modern commercial IR camera-based motion capture systems. Whether these modern systems use automatic tracking or manual, their output is the 3D positions of the markers (e.g., ProReflex from Qualisys, Sweden; Motion Analysis from Motion Analysis Corporation, USA; Simi Motion from SIMI Reality Motion Systems, Germany; HUBAG from Hacettepe University, Turkey). This allows the calculation of marker displacement, angles, velocities, and accelerations, etc. A movement of the rendered 3D stick figure or skeleton representation of human body can be the typical output of HMA. As an example of HMA, a trajectory of selected anthropometric point during back somersault movement can be seen in Fig. 2.

The main disadvantage of the automatic tracking systems with IR cameras is that these systems can only work on controlled artificial lighting environment. The system does not work on direct or indirect sunlight, even though in the controlled environment reflective shiny spots in the camera view can be mistaken by the system as markers. Additionally, these systems are usually fixed in the laboratory environment and cannot be easily moved if an experiment requires a different location. Therefore, these systems are limited to some movements that can only be performed in the laboratory environment.

Biomechanical Modeling

It is, however, viable to obtain all kinematics variables in a movement by utilizing HMA; it is not possible to measure forces that caused the movement. In order to measure the force inside a human body, a surgical operation is required to implement a force transducer. In addition to technical complications and calibration problems of force transducer, the subject would also be at risk of surgical infections. Therefore, modeling in biomechanics works as an interface between the body and measurement settings.

In recent years, biomechanical modeling has become very popular in the area of sports biomechanics. Recent developments in software and hardware in the computer technology could potentially explain this popularity. Developing a biomechanical model itself improves the understanding of the mechanical system's dynamics and the structure. On the other hand, most of the biomechanical systems are so complicated that a satisfying modeling seems extremely difficult.

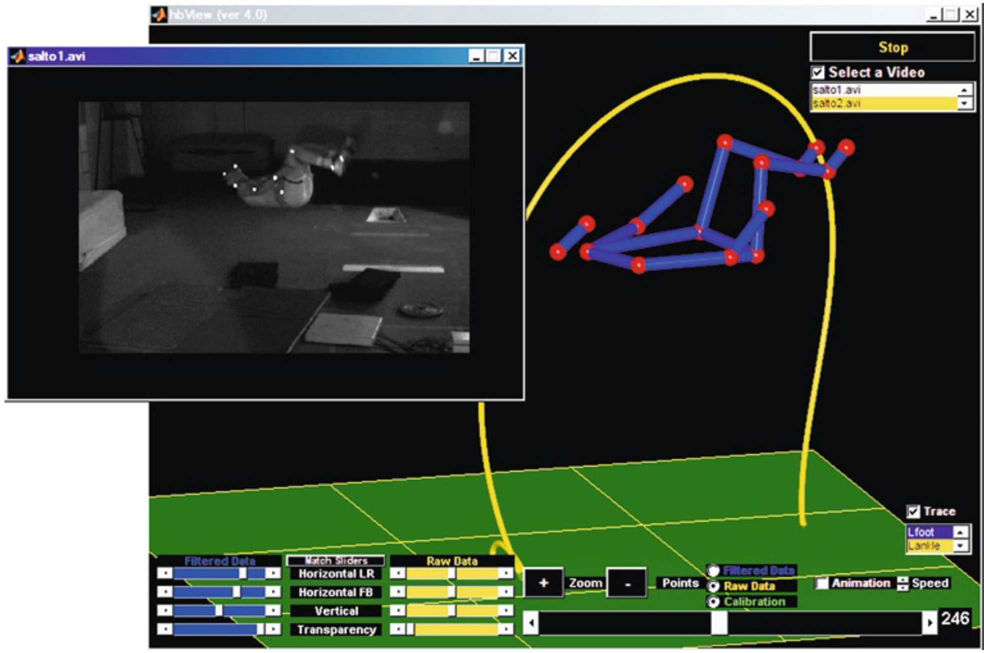

Fig. 2 Stick figure output of back somersault movement

One standard solution is that the complexity can be reduced by cutting down some part of the system to be modeled. A well-prepared model must be simple but yet adequately detailed to precisely represent the system.

Considering the system components (i.e., limbs of the human body) as a rigid body, rather than a deformable body also helps to reduce the complexity of the model. Although, in reality, no material is absolutely rigid, deformation of limbs in sports movement can be ignored, when compared to the gross motion of the system.

Basically, there are two types of approaches in biomechanical modeling. The first one is inverse dynamics and the second one is forward dynamics or direct dynamics. Inverse dynamics calculation is used to determine joint forces and torques based on the physical properties of the system being modeled and a time history of displacements from experimental kinematic data, including velocities and accelerations. Ground reaction forces, mass and inertial characteristics of segments are also required in this method. In a forward dynamical analysis, the joint torques are the inputs and the body motion is the output. It is critical to understand what generates this joint torques. Joint torques are the addition of internal body forces such as ligaments, joint constraints, and of course, muscle forces. Muscles are the actuators in this method. Therefore, the correct input into the model is definitely neural input, which drives the muscles.

Classical Mechanics

Whichever approach is used for modeling, first of all, the equation of motion has to be derived. The dynamics of biomechanical systems is based on classical mechanics. The simplest element of a multi-body biomechanical system is a free particle that can be treated by Newton's equations, which was published in 1686 in his "Philosophiae Naturalis Principia Mathematica" [15]. The rigid body that is a key element in the modeling was introduced in 1775 by Euler in his contribution entitled "Nova methodus motum corporum rigidarum determinandi" [10]. Euler already used the free body principle for the modeling of joints and constraints, which resulted in reaction forces. Thus the equations obtained are known in human body dynamics as Newton–Euler equations. In 1743, D'Alembert distinguished between applied and reaction forces in a system of constrained rigid bodies in his book entitled "Traité de Dynamique" [7]. He called the reaction forces "*lost forces*" having the principle of virtual work in mind. A systematic analysis of constrained mechanical systems was also established in 1788 by Lagrange [13]. The variational method applied to the total kinetic and potential energy of the system considering its kinematical constraints and the corresponding generalized coordinates result in the Lagrangian equations of the first and the second kind. Lagrange's equations of the first kind represent a set of differential algebraical equations in Cartesian coordinates with undetermined Lagrange multipliers, while the second kind leads to a minimal set of ordinary differential equations in generalized Lagrange coordinates.

Choosing a Method for Deriving the Equations of Motion

- Lagrangian Dynamics
  Lagrange's equations of motion are specified in terms of the total energy of the body in the kinematic chain. With this formulation, forces between bodies (equal and opposite) do not need to be considered because these forces do not add

energy to the system. Although the equations of motion are generally easy to formulate, this method is relatively inefficient for inverse dynamics calculations.

- Newton–Euler Dynamics
  In this method, the Newton–Euler equations are applied to each body in the model. All forces affecting each body must be considered, which makes this method difficult and tedious for complex systems. The overall equations of motion can be written in any suitable inertial reference frame. Recursive and non-recursive formulations are exist, which makes this method is effective for inverse dynamics.
- D'Alembert's Principle
  Equations of motion are derived by identifying all forces on each body go through an acceleration and writing equilibrium equations. These equilibrium equations are simultaneously solved to obtain the dynamic system response. The restriction of this method is that it can only be used for the systems which work at low speeds.
- Kane's Dynamics
  This method is a subset of the group of methods known as "Lagrange's form of D'Alembert's Principle." The Newton–Euler equations are multiplied by "special vectors" to develop scalar representations of the forces acting on each body. In this method, there is no need to take interbody forces into consideration. Closed kinematic chains can be directly calculated, but extensive symbol manipulations are required in the formulation of the equations of motion [12].

Methodology of Biomechanical Modeling

Bresler and Frankel established the method of determination of forces and torques at each joint by simple repetition of the free body model of each body segment [6]. This was a follow-up study of Elftman [9]. They measured ground reaction forces and torques using a force plate. Kinematical values of anthropometric points were determined by using photogrammetric techniques. The human body was modeled as a system of rigid body links. Kinematic and force platform data were combined to calculate the dynamics of each body segment by applying inverse dynamics with the Newton–Euler procedure. The method started at the foot and continued up the limb. Fourteen thousand calculations and 72 graphs were all manually produced. There were no computers which were used in the study. The work required a sum of almost 500 man-hours.

How to Calculate

Nowadays, all necessary calculations in modeling have been done automatically on computers. This can be achieved by writing a computer program or just using commercial software. Any approach is much faster than the manual calculation without a comparison.

Developing a computer program, which calculates dynamics joint software, demands a good knowledge in dynamics. Solving the equations of motion requires a great deal of time to perform the pencil-and-paper analysis of the system to put the equations into a form that can be solved numerically by computer.

To use the generalized simulation toolboxes, the biomechanist must have access to the general-purpose simulation software with a powerful computer to run the software. Extensive experience in dynamics and experience with the simulation software are also essential. Even with the required software, hardware, experience, and knowledge, running the generalized simulation codes may require too much computer time for some analyses.

The symbolic analysis software serves to aid the biomechanist in the development of simulation codes that may be done manually. However, a large amount of the work must still be done by the researcher, particularly in identifying forces and torques acting on bodies in the model, and in specifying constraints. Also, the symbolic programs produce only a portion of the complete simulation code.

Examples for Biomechanical Modeling

Forces and torques acting on the joints during takeoff phase in the long jump were investigated by Alptekin and Arıtan [1]. They modeled the jumper as a system of seven rigid bodies. Free body diagram of the takeoff phase in the long jump is shown in Fig. 3. Kinematics and force platform (kinetics)

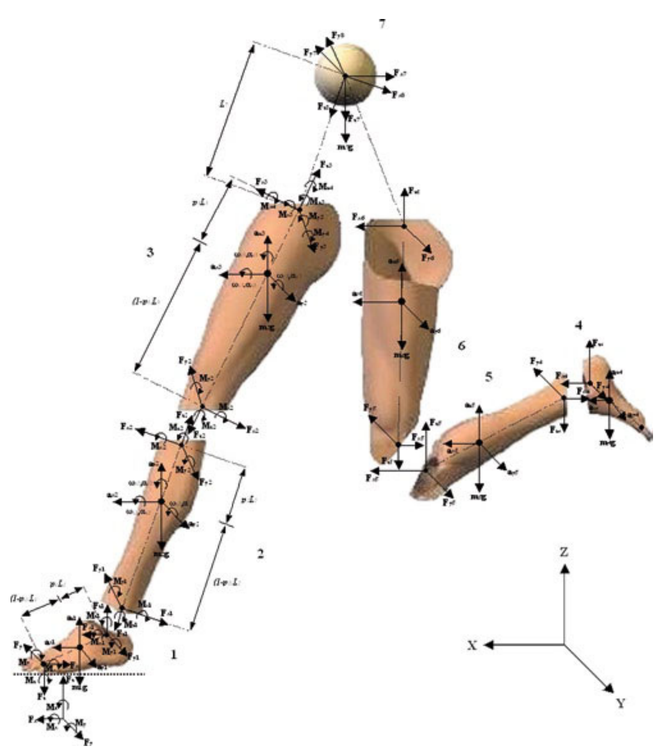

Fig. 3 Free body diagram of the take-off phase in long jump

data were collected to analyze the dynamics of each body segment by applying inverse dynamics. In their study, the Newton-Euler equations were applied to each body in the model to calculate the joint forces and torques.

Modeling of pull phase in Olympic snatch (weight lifting) was accomplished by using physical modeling tools [2]. The term "physical modeling" is somewhat confusing. A physical model can be interpreted as a real wood, clay, or metal copy of a real object. In the context of biomechanics, it refers to modeling techniques that better represent the physics and the mathematics of a system. Amca and Arıtan [2] captured a successful snatch attempt of an elite weightlifter by using high speed cameras. To determine the angular kinematics of the joints and to create the model, selected points on the weightlifter and barbell were digitized. A 2D multi-body model was created on the sagittal plane of the weightlifters.

Instead of deriving and programming equations, they used a multibody simulation tool to build a physical model of the weightlifter by using SimMechanics, which is a physical modeling tool that works on top of Simulink [16]. SimMechanics model of weightlifter can be seen in Fig. 4. The joint torques was calculated during the pull phase of the Olympic Snatch by utilizing inverse dynamics solvers. In addition to developing multibody models straightforwardly in SimMechanics, it also works in both forward and inverse dynamics approaches.

Herrmann and Delp created a model by using OpenSim (Open-Source Software to Create and Analyze Dynamic Simulations of Movement) to analyze how the surgery will affect wrist extension strength [11]. They investigated the effects of the surgery of the transfer on wrist extensor strength by creating plots of the maximum isometric wrist moments before and after the simulated surgery. Screen shot of the wrist model in OpenSim software can be seen in Fig. 5.

OpenSim is a software system that enables you to create and analyze graphics-based models of the musculoskeletal system [8]. In OpenSim, a musculoskeletal model consists of a set of bones that are connected by joints. Muscle-tendon actuators and ligaments span the joints. The muscles and ligaments develop force, thus generating moments about the joints. OpenSim allows analyzing and testing a musculoskeletal model by calculating the moment arms and lengths of the muscles and ligaments. Given muscle activations, the forces and joint moments (muscle force multiplied by moment arm) that each muscle generates can be computed for anybody position.

As it can be noticed from the text, the classical mechanics modeling approach is based on the assumption that the body is rigid. This assumption can be acceptable when a body exposed to a set of forces, it mainly moves rather than deforms. As an example, bones can be assumed to act as rigid bodies during gait or other activities. Alternatively, when a body responds to force by not only moving but also deforming, it must be considered as deformable body. Soft tissues such as muscle, ligament, or cartilage cannot be considered as rigid bodies, they have to be regarded as deformable bodies.

Finite Element Modeling

The fundamental concept in deformable body analysis is that all structures may be considered a collection of springs. Together, this collection of springs imparts a characteristic elastic stiffness or resistance to deformation. Most biomechanists would accept that Finite Element Method (FEM) is the most appropriate method to analyze deformable biological

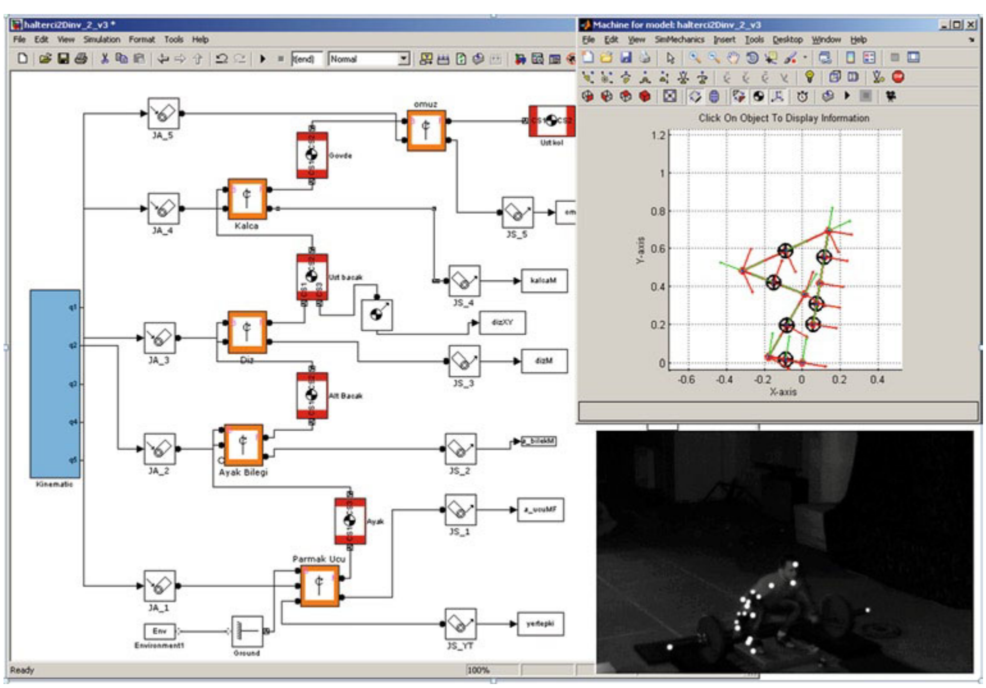

Fig. 4 SimMechanics model of weightlifter

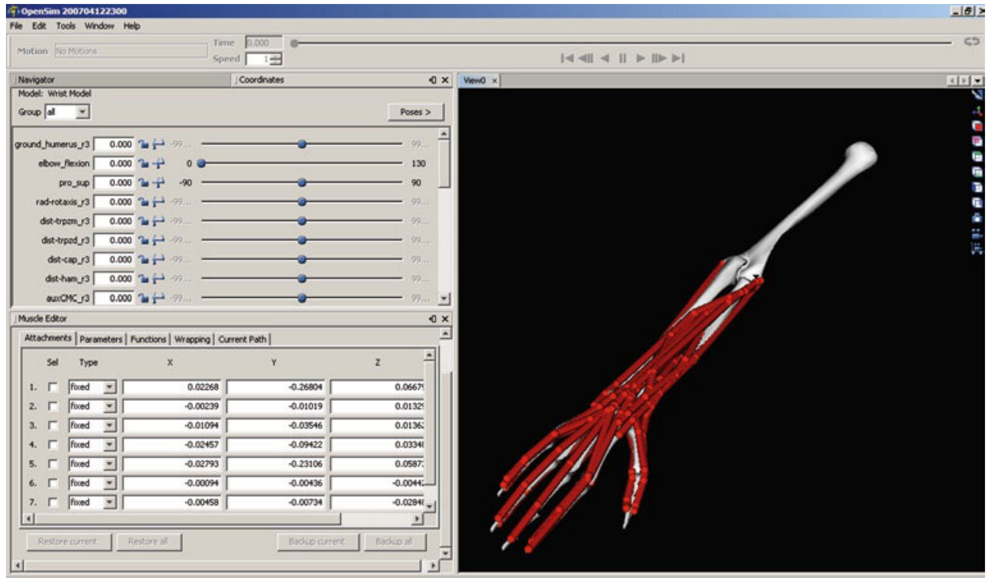

Fig. 5 Screen shot of wrist model in OpenSim software

systems. The FEM is generally referred to as finite element analysis (FEA). Although FEA is preferred in soft tissue biomechanics, it can be also used in the skeletal system (joint loads, bone stress analyses, artificial joints), modeling blood flow, and heat transfer in biological tissues [14].

FEA is simply explained by algebraic equations which are given as follows:

$$\{F\} = [K]\{u\}$$

where;

$\{F\}$ is the vector of nodal forces,
$[K]$ is the element stiffness matrix,
$\{u\}$ is the vector of nodal displacement.

FEA can be divided into three sections, which can be described as model creation, solution, result validation, and interpretation. The aim of the model creation phase is the mathematical formulation of the finite element model in terms of nodes and elements, material properties, boundary and interface conditions, and applied loads. Model creation is also called as discretization, the structure is divided into a finite number of discrete subregions, called elements that are interconnected at nodal points, or nodes. This interconnected network of elements and nodes constitutes the finite element mesh. The mesh acts like a spider web in that, from each node, there extends a mesh element to each of the adjacent nodes. Mesh generation is the most tedious and time-consuming step in FEA. Using magnetic resonance imaging (MRI) or computer tomography (CT) data can be the best way of generating 3D meshes of heterogeneous objects with complex geometry like the human body [4]. Visual procedure of generating 3D mesh of upper arm from MRI data can be seen in Fig. 6.

Elements are then assigned specific material properties that represent the elasticity of the real structure. Mechanical properties of the material must be known to establish the element stiffness matrix [3]. The time-dependent behavior of soft tissues has made it very difficult to obtain mechanical properties. In order to obtain viscoelastic material properties of soft tissue specific instrumentation and experimental setup [5] are required. This is why FEM in biomechanics has been dominated by bone and cartilage-based studies. FEM of bone enables researchers to use standard engineering testing machines to obtain the mechanical properties of bone, and bone has a comparatively simple geometrical shape.

Finally, virtual loads are added to the model, typically to nodal points (Fig. 7). Constraining anchors are also determined at this step and mobility may be restricted to particular degrees of freedom. These applied loads and constraints are collectively termed the boundary conditions. On running the analysis step, nodal displacements are calculated in response to the applied boundary conditions, taking into account structural geometry and the predefined elasticity of the structure. The solution phase consists of executing a finite element computer program using the previously generated model as the input data. Finally, a crucial part of FEA is the validation and interpretation of the results. Model validation and accuracy must be checked. In other words, does the FEM represent the geometry, loads, material properties, boundary, and interface condition of the real structure?

Conclusion

There are many causes of injury ranging from poor technique, not enough preparation, inadequate strength, insufficient range of movement in the relevant structures, and many others. Correct biomechanical function is a critical factor, but is generally less understood. Biomechanical measurement

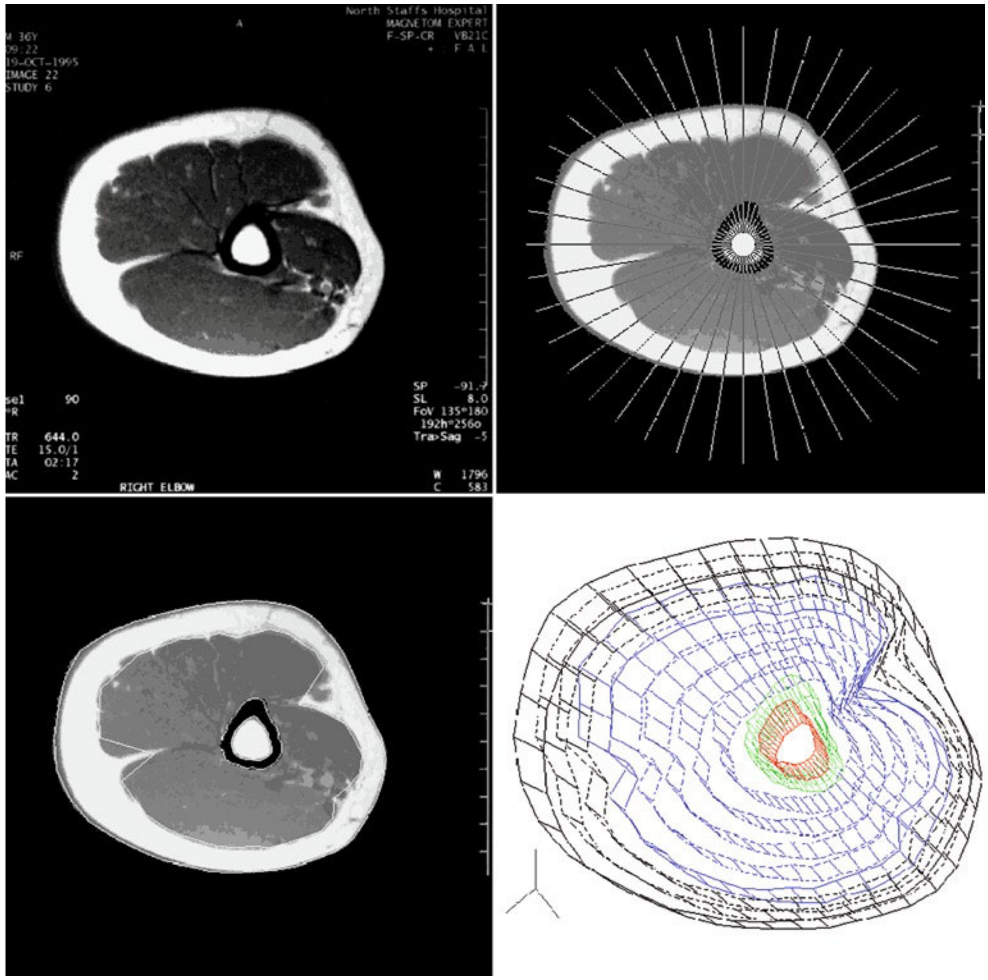

Fig. 6 3D mesh of upper arm from MRI data

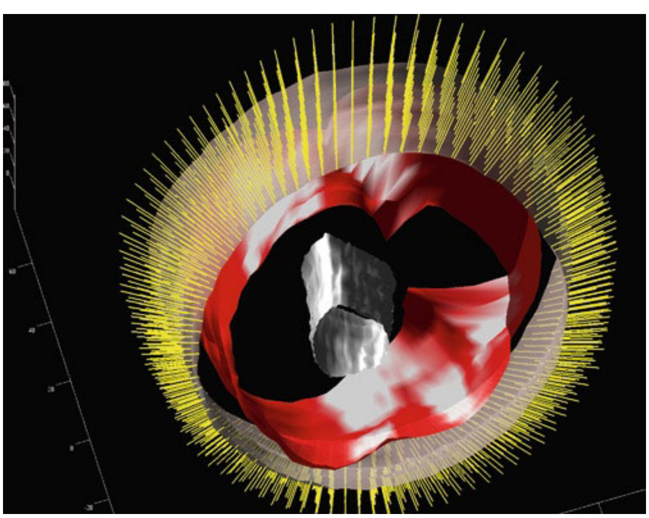

Fig. 7 Image of virtual loads that are added to the nodal points of 3D mesh of upper arm

methods and modeling play an important role in understanding the kinematics and kinetics part of the movement. In fact, advanced biomechanical modeling simulation tools can help model the physical world at sufficient speed with a desired accuracy. Finally, biomechanical screening can be used as an integral part of sports injury prevention and management program for optimal performance.

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