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Review Article

Preliminary study about the application of finite elements method to describe the shoulder joint

Estudio preliminar sobre la aplicación de modelos de elementos finitos para describir la articulación del hombro

Estudo preliminar sobre a aplicação de modelos de elementos finitos para descrição da articulação do ombro

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Abstract

Computational biomechanics uses computational methods and simulations to study realistic biomechanics processes in a relatively long-time scale. The shoulder is the most complex joint on the human body. It is fragile and the slightest bone or ligament injury makes it unstable. Biomechanics of the shoulder and injury analysis are complex. To study these issues, numerical models can be used. Particularly, continuum mechanics models based on a finite element method (FEM) offer a powerful tool to assess the internal loading conditions of the shoulder musculoskeletal structure. Here it is presented a preliminary State of the Art focus on the application of FEM to describe the shoulder joint. General characteristics, parameters, vantages and limitations of these models and some representative examples are explained.

Keywords: sport biomechanics, computational biomechanics, shoulder joint, finite elements method, computational simulations.

Resumen

La biomecánica computacional utiliza métodos computacionales y simulaciones para estudiar procesos biomecánicos realistas en una escala de tiempo relativamente larga. El hombro es la articulación más compleja del cuerpo humano, es frágil y la más mínima lesión ósea o ligamentosa la hacen inestable. La biomecánica del hombro y el análisis de las lesiones son complejos. Para estudiar estas cuestiones, se pueden utilizar modelos numéricos. En particular, los modelos de mecánica continua basados en el método de elementos finitos (MEF) ofrecen una poderosa herramienta para evaluar las condiciones de carga interna de la estructura musculoesquelética del hombro. Aquí se presentan resultados preliminares del Estado del Arte focalizado en la aplicación del MEF para describir la articulación del hombro. Se explican las características generales, parámetros, ventajas y limitaciones de estos modelos y algunos ejemplos representativos.

Palabras clave: biomecánica deportiva, biomecánica computacional, articulación del hombro, método de elementos finitos, simulaciones computacionales.

Resumo

A biomecânica computacional utiliza métodos computacionais e simulações para estudar processos biomecânicos realistas em uma escala de tempo relativamente longa. O ombro é a articulação mais complexa do corpo humano, é frágil e a menor lesão óssea ou ligamentar o torna instável. A biomecânica do ombro e a análise de lesões são complexas. Para estudar essas questões, modelos numéricos podem ser usados. Em particular, os modelos de mecânica contínua baseados no método dos elementos finitos (MEF) oferecem uma ferramenta poderosa para avaliar as condições de carga interna da estrutura musculoesquelética do ombro. Apresentamos aqui resultados preliminares do Estado da Arte focado na aplicação do MEF para descrever a articulação do ombro. São explicadas as características gerais, parâmetros, vantagens e limitações destes modelos e alguns exemplos representativos.

Palavras-chave: biomecânica esportiva, biomecânica computacional, articulação do ombro, método dos elementos finitos, simulações computacionais.

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Introduction

Application of computation and informatics in sport sciences have been increasing in the past 20 years. Sport Informatics (SI) mainly uses computer technologies and computational biology methods to explore and manage data in health and sports setting. SI derives knowledge by mixing, matching, and selecting from bioinformatics, medical informatics, cognitive science, statistics and sports/exercise science (Chnmait y Westerbeek, 2021). Particularly, artificial intelligence (AI) and machine learning (ML) have left their footprints in the world of sports (Chnmait y Westerbeek, 2021) y (Beal et al., 2019). Also, numerical methods have been intensively used to study the biomechanics oft he human body. (Zheng et al., 2016)(Huiskes y Hollister, 1993)

According to the Encyclopedia Britannica biomechanics study “biological systems, particularly their structure and function, using methods derived from mechanics, which is concerned with the effects that forces have on the motion of bodies” (Aruin, 2023). By obvious reasons, biomechanics is a critical discipline in modern science sport, mainly for two reasons:

- To help people perform their chosen sporting activity better. This does not just apply to the elite athlete but to any sportsperson who wants to improve his or her performance,
- To help reduce the risk of injury (Bartlett, 2007).

A search carried out by the authors of this project in the SCOPUS database, using as keywords "Sport Biomechanics" and as criteria the first author and the corresponding author, yielded more than 800 authors in the period 2018-2023 (ending in April 2023) Biomechanics works with simplified models of the human body (most popular and successful are single-axis models and multi-segment models) (Pecolt et al., 2022) (Nagano et al., 2005). The application of computational techniques has become critical in the field of the sport biomechanics. Computational biomechanics uses computational methods and simulations to study realistic biomechanics processes in a relatively long-time scale.

Usually, solid models are used to simulate kinematic behaviors, as well as finite element method (FEM) to simulate deformation and resistance properties of tissues and biological elements (Martins et al., 2006) (Yang et al., 2023). The FEM is used to solve partial differential equations and it is based on subdivides a large system into simpler parts (finite elements). This FE are obtained by a space discretization in the space dimensions, which is implemented constructing a mesh of the object (the domain for the solution, which has a finite number of points). The FEM formulation of a boundary value problem results in a system of algebraic equations. The method approximates the unknown function over the domain (Logan, 2011). There are advanced programs that can be implemented to build human models. These programs are based on mathematical analyses, have additional visualization, and can explore many kinematic and dynamic options. They allow building spatial models with many degrees of freedom. An example of such a software is the MATLAB- based tool BoB (Mihcin, 2019).

Development

The shoulder is the most complex joint on the human body. The complexity of the joint shoulder (also named Glenohumeral) is due to it permits the greatest range of motion of any joint in the human body. It is fragile and the slightest bone or ligament injury makes it unstable (Zheng et al. 2016). This joint includes four bones (the thorax, clavicle, scapula and humerus). Biomechanics of the shoulder and its injury analysis are complex. Traditional biomechanical measurements are limited by the existing measuring techniques and ethical issues, and the in vivo internal loading condition of the shoulder musculoskeletal complex is almost unmeasurable [16]. In spite of the advances in experimental techniques, such as ultrasound imaging and MR-based diffusion tensor imaging (DTI) (Damon et al., 2002), understanding of the in vivo biomechanical functioning of the shoulder complex is still very limited. For example, little is known about the individual contribution of each component of the shoulder musculoskeletal structure to joint stability and mobility and their relationship with each other (Zheng et al. 2016)(Astier, 2008). To study these questions, numerical models have been used.

A brief introduction of the models based on FEM to study the shoulder joint

Overall, the shoulder complex models are classified into two types: the human shoulder model and the humanoid shoulder model. The first type focuses on the reality of the human shoulder complex. It takes into account the motion of the bones, muscles, ligaments and skin. The second type focuses on the similarity and equivalency to the human shoulder complex (Feng et al., 2008). Others classifications used in the literature are: skeletal model, musculature model, musculoskeletal model, kinematics model, dynamics model, joint boundary model and topological model.

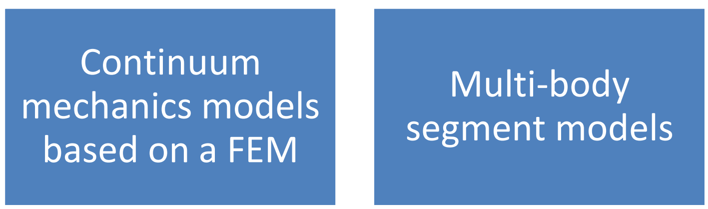
Simulation offers the possibility to analyze the reactions and the efforts produced by different anatomical elements, including dataset which cannot be recorded experimentally. Injuries in shoulders are very common in sport disciplines such as baseball and athletics (e.g., javelin) (Braun et al., 2009). In the last case, injuries occur due to excessive external rotation of the shoulder during the throw without sufficient strength and range of motion (Chnmait y Westerbeek, 2021).

Continuum mechanics models based on a FEM offer a powerful tool to assess the internal loading conditions of the shoulder musculoskeletal structure (Favre et al., 2009). They can provide valuable estimates of stress and strain distributions in the bones and soft tissues, which are usually not measurable in vivo. The FEM can simulate working conditions that are difficult to carry out in biomechanics and obtain the corresponding mechanical results. Its basic concept is the discretisation of complex mechanical structures into finite numbers of separate components with simple geometry called elements (Reddy, 2006). The FEM has been widely used in different engineering fields for system design and analysis. In the case of shoulder joint, models based on finite element (FE) have been developed for glenohumeral joint stability (Büchler et al., 2002). rotator cuff tears capsular (Luo et al., 1998) and labral defects (Drury et al., 2010) and for shoulder arthroplasty (Quental et al., 2014).

Other approximation to study joints in biomechanics is using multi-body segment models (Pecolt et al., 2022) (Stops et al., 2012) (Figure 1). In these models, body segments are assumed to be rigid bodies without deformations and muscles are simplified as single line actuators without 3D volume (Dickerson et al., 2007). The body segment models and inverse dynamics (ID) calculations (Köhler et al., 2023). are commonly used for analyzing throwing movements to identify potential risks of injury and enhance performance (Köhler et al., 2023) (Köhler et al., 2021). A prerequisite for doing such an analysis is the recording of kinematic data and obtaining information about the body segment inertia parameters (BSIP) (Köhler et al., 2021). Besides, the calculation of ID solutions is widely used to examine potential injury risks and sources for performance enhancement (Köhler et al., 2023) (Köhler et al., 2021). The results of these calculations are influenced, among others, by the chosen set of the BSIP. In this proccess the estimation methods on BSIP and joint moments became critical. From a practitioner's perspective is critical to evaluate the impact of different estimation methods on the results of individual athletes (Köhler et al., 2021) (Bezodis et al., 2010).

Figure 1

Models of the human body to study joints in biomechanics.



Combination of simulations based on both the FEM and the body segment models and inverse dynamics (ID) calculations can be useful in order comparing parameters obtained from these approximations. Simulations based on FEM can assits to the ID calculations by improving the parameters of the BSIP, particularly in the study of injuries.

Following the reference 3, we will consider the application of FE models taking into account the physiological and clinical problems addressed: glenohumeral joint stability, rotator cuff tears, joint capsular and labral defects, and shoulder arthroplasty. Recently, Yang et al. (2023), reported a finite element model of the shoulder joint was constructed to analyze the mechanical index changes of shoulder joint abduction under different loads. The proposed model avoind different degrees of simplification of previous shoulder models (Filardi, 2020) (Islán-Marcos, 2019), among them: incomplete construction of the anterior, middle, and posterior deltoid bundle, joint capsule, ligament and other soft tissues, which fails to simulate biological mimicry realistically, affecting the accuracy of the simulation results. It containing component such as the clavicle, scapula, humerus, deltoid muscle, rotator cuff, coraco-clavicular ligament, acromio-clavicular ligament, glenohumeral ligaments, including: superior glenohumeral ligament, middle glenohumeral ligament, inferior glenohumeral ligament and joint capsule. The results of simulations indicate that load increases the stress difference between the articular side and the capsular side on the supraspinatus tendon and increases the mechanical indices of the middle and posterior deltoid muscles, as well as the inferior glenohumeral ligament. The increased stress and strain in these specific sites can lead to tissue injury and affect the stability of the shoulder joint.

Conclusions

Biomechanics of the shoulder and its injury analysis are complex. The preliminary study of the state of the art has shown that computational models are increasingly used to study the biomechanics of the shoulder joint. In particular, the FEM has made it possible to investigate different aspects of the physiology and clinics of this joint. The combined use of FEM and BSIP can be very useful in the study of common injuries affecting the shoulder joint, for example, in throwing disciplines, or in baseball.

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