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A simulation framework for humeral head translations

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ABSTRACT

Humeral head translations (HHT) play a crucial role in the glenohumeral (GH) joint function. The available shoulder musculoskeletal models developed based on inverse dynamics however fall short of predicting the HHT. This study aims at developing a simulation framework that allows forward-dynamics simulation of a shoulder musculoskeletal model with a 6 degrees of freedom (DOF) GH joint. It provides a straightforward solution to the HHT prediction problem. We show that even within a forward-dynamics simulation addressing the HHT requires further information about the contact. To that end, a deformable articular contact is included in the framework defining the GH joint contact force in terms of the joint kinematics. An abduction motion in the scapula plane is simulated. The results are given in terms of HHT, GH joint contact force, contact areas, contact pressure, and cartilage strain. It predicts a superior-posterior translation of the humeral head followed by an inferior migration.

1. Introduction

Several musculoskeletal models are available for the human shoulder that provide reliable predictions of both the muscle and joint reaction forces e.g. [1,2]. A vast majority of these models have been developed based on inverse dynamics, e.g. [2–7]. In inverse dynamics, measured joints kinematics (rotations and translations) are required as inputs to calculate muscle and joint reaction forces. However, with the available measurement techniques, it is not straightforward to measure the translational DOF of the GH joint [8]. Therefore, it is often approximated as an ideal ball-and-socket joint in the musculoskeletal models, neglecting its translation [9]. A so-called stability constraint is also often considered in the load-sharing scheme of the models to restrict the GH joint reaction force to point into the glenoid fossa, avoiding subluxations by enforcing more physiological contributions from the rotator cuff muscles [1]. Nonetheless, the GH joint translations have a role to play in the GH joint stability mechanism [1,10]. Furthermore, predictions of the GH joint translations, the contact pressure, and the contact areas are required in designing shoulder prostheses [11,12].

Indeed, few studies have investigated the HHT using biomechanical models. To this end, they tailored either available musculoskeletal models [12,13] or developed finite element models [9,11,14,15]. Other studies mainly used cadaveric [16,17] or clinical [8,18-23], approaches to address the GH joint translations. However, there are limitations associated to each of these studies. The Anybody shoulder model [6] was tailored using the force dependent kinematic method, introduced by Andersen et al. [24], to address the HHT after total shoulder arthroplasty (TSA) [12]. The dynamic effects of motion were neglected although their influence on the HHT has been already highlighted [18]. A shoulder model, developed and adapted by Quental and colleagues [13,25] to address the HHT using a novel inverse-dynamics framework. The HHT was considered as an extra design variable in an optimization scheme within this framework. Despite the report by Sins et al. [12], the dynamic effects of motion were partially considered. However, the articular contact was approximated by an elastic potential function. This deviates from the nonlinear and viscoelastic behavior of the cartilage [26] and does not account for the moment applied on the humerus due to the articular contact. The various 3D finite element models reported in the literature [9,11,14,15] share the same attributes. They include more realistic estimation for the articular contact although they were simulated under a sequence of static conditions, neglecting the dynamics of motion. Furthermore, they all lack a physiological muscle force load-sharing. The 3D finite element model developed by Terrier et al. [9] has been employed in similar studies [10,27,28] to further study the HHT after the TSA.

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The *in vivo* or *in vitro* measurement of the HHT remains a challenging task [8]. Specifically, *in vitro* studies cannot accurately simulate the *in vivo* conditions in terms of the muscle and joint contact forces. The *in vivo* studies are also either limited to 2 dimensional analysis [18,19] or otherwise their accuracy is limited by the 3D reconstruction of the bones [8,22,23]. Furthermore, they are not developed to assess the GH joint translations during dynamic activities [20,21].

The aim of this study is to develop a simulation framework for a shoulder musculoskeletal model that allows simultaneous predictions of HHT, joint reaction forces, and contact pressure. To that end, a forward-dynamics simulation coupled with a nonlinear viscoelastic approximation of the articular contact is used. The dynamic equations of motion are therefore solved forward in time, allowing a straightforward consideration of the dynamic effects of the motion. To the best of our knowledge this has not been addressed elsewhere. This simulation framework provides addressing the GH joint kinematics (HHT) and mechanics (reaction forces and contact pressure) either in its physiological form or after the TSA. The outcome of this simulation framework will be translated for future patient-specific clinical applications related to the treatment of osteoarthritis by TSA.

2. Methods

A musculoskeletal model of the GH joint with 6 DOF is developed. The 6 DOF correspond to 3 rotational and 3 translational (HHT) generalized coordinates. We show that the equations of motion of the GH joint with 6 DOF is indeterminate, i.e. there are fewer equations than the number of unknown forces and unknown generalized coordinates (Section 2.1). Therefore, defining the HHT requires solving the indeterminate equations of motion of the GH joint. In order to resolve the indeterminacy, we develop a framework that maps the unknown forces to the unknown generalized coordinates and velocities (Sections 2.3 and 2.3). This leads to a set of transformed equations of motion that no longer is indeterminate. We then simulate an arm motion in the scapula plane. The resulted HHT, GH joint contact force, contact areas, contact pressure, and cartilage strain are compared to those from the *in vitro*, *in vivo*, and numerical studies.

2.1. Indeterminacy in HHT

The surfaces of humeral head and glenoid fossa are both approximated as spheres with radii r_h and r_g equal to 30 [mm] and 32 [mm], respectively [29] (Fig. 1). The arm weight is 35.7 [N] that corresponds to 5% of the bodyweight. All the 11 major muscles spanning the GH joint are included, and their forces applied on the humerus are replicated by a resultant force $\boldsymbol{F}_m$ and a resultant moment $\boldsymbol{M}_m$ acting on the humeral head center. Muscle paths are defined using the algorithm introduced by Charlton and Johnson [4]. $\boldsymbol{F}_c$ represents the GH joint contact force applied on the humerus. The contact point on the humeral head and its associate point on the glenoid fossa are denoted by $\boldsymbol{C}_h$ and $\boldsymbol{C}_g$, with velocities of $\boldsymbol{V}_{C_h}$ and $\boldsymbol{V}_{C_g}$, respectively. x_h, y_h, and z_h are the humerus body-fixed coordinates at the humeral head center (***HH***). The scapula motion is included by the scapulohumeral rhythm [30].

The GH joint equations of motion are derived using the Lagrange's equations. A compact form of these equations is

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\boldsymbol{q}}}\right) - \frac{\partial L}{\partial \boldsymbol{q}} = \boldsymbol{\tau}(\boldsymbol{F}_m, \boldsymbol{F}_c) \tag{1}$$

The generalized coordinate vector $\boldsymbol{q}$ consists of three rotational DOF (ψ, θ, and ϕ) and three translational DOF (x, y, and z). The generalized force vector $\boldsymbol{\tau}$ is a function of applied external forces

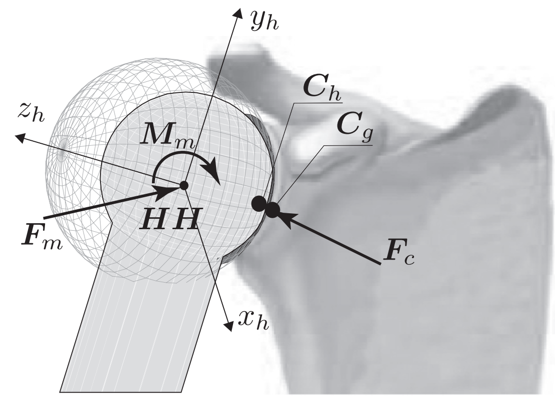

Fig. 1. A schematic view of the GH joint. The surfaces of humeral head and the glenoid fossa are both approximated as spheres. x_h, y_h, and z_h are the humerus body-fixed coordinates attached to the humeral head center ***HH***. $\boldsymbol{F}_m$ and $\boldsymbol{M}_m$ are resultant force and moment due to the muscles, and $\boldsymbol{F}_c$ is the contact force. The contact points on the humeral head and the glenoid fossa are denoted by $\boldsymbol{C}_h$ and $\boldsymbol{C}_g$, respectively.

($\boldsymbol{F}_m$ and $\boldsymbol{F}_c$) [31]. A holonomic constraint is also considered to account for the contact between the surfaces of humeral head and glenoid fossa

$$(\boldsymbol{V}_{C_h} - \boldsymbol{V}_{C_g}) \,.\, \hat{\boldsymbol{n}} = 0 \tag{2}$$

The unit vector $\hat{\boldsymbol{n}}$ is perpendicular to the plane of contact that is tangential to the contact point. The constraint equation assures no relative velocity between $\boldsymbol{C}_h$ and $\boldsymbol{C}_g$ in the direction of $\hat{\boldsymbol{n}}$ [32].

There are 12 unknowns in Eqs. (1) and (2), including the 6 generalized coordinates (ψ, θ, ϕ, x, y, and z), the 3 components of the contact force ($\boldsymbol{F}_c$), and the 3 components of the resultant muscle force ($\boldsymbol{F}_m$). However, Eqs. (1) and (2), respectively, provide 6 and 1 equations (7 in total) that are not sufficient to uniquely determine the 12 unknowns. Therefore, the equations of motion of the GH joint with 6 DOF is indeterminate.

2.2. Resolving the indeterminacy: deformable articular contact

Our approach to resolve the indeterminacy is to define the unknown muscle and contact forces and their associated moments as smooth function mappings of the generalized coordinate and velocity vectors. This leads to a set of transformed equations of motion that is no longer indeterminate.

Using the definition of virtual work [31], the generalized force vector ($\boldsymbol{\tau}$) on the right-hand side of (1) can be expressed as

$$\boldsymbol{\tau} = (\boldsymbol{F}_m + \boldsymbol{F}_c)\frac{\partial \boldsymbol{V}_{HH}}{\partial \dot{\boldsymbol{q}}} + (\boldsymbol{M}_{HH_m} + \boldsymbol{M}_{HH_c})\frac{\partial \boldsymbol{\omega}}{\partial \dot{\boldsymbol{q}}} \tag{3}$$

where $\boldsymbol{V}_{HH}$ is the velocity of the humeral head center, and $\boldsymbol{\omega}$ is the angular velocity of the humerus. $\boldsymbol{M}_{HH_m}$ and $\boldsymbol{M}_{HH_c}$ denote the resultant moments about the humeral head center due to the muscle and the contact forces, respectively.

Substituting $\boldsymbol{F}_c$, $\boldsymbol{F}_m$, $\boldsymbol{M}_{HH_c}$, and $\boldsymbol{M}_{HH_m}$ in (3) with smooth function mappings (to be defined) of $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$ and introducing the resulting generalized force vector into (1), we obtain

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\boldsymbol{q}}}\right) - \frac{\partial L}{\partial \boldsymbol{q}} = \mathscr{F}_c(\boldsymbol{q}, \dot{\boldsymbol{q}})\frac{\partial \boldsymbol{V}_{HH}}{\partial \dot{\boldsymbol{q}}} + \mathscr{M}_{HH_c}(\boldsymbol{q}, \dot{\boldsymbol{q}})\frac{\partial \boldsymbol{\omega}}{\partial \dot{\boldsymbol{q}}} + \mathscr{F}_m(\boldsymbol{q}, \dot{\boldsymbol{q}})\frac{\partial \boldsymbol{V}_{HH}}{\partial \dot{\boldsymbol{q}}} + \mathscr{M}_{HH_m}(\boldsymbol{q}, \dot{\boldsymbol{q}})\frac{\partial \boldsymbol{\omega}}{\partial \dot{\boldsymbol{q}}} \tag{4}$$

where $\mathscr{F}_c$, $\mathscr{F}_m$, $\mathscr{M}_{HH_c}$, and $\mathscr{M}_{HH_m}$ are the smooth function mappings from $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$ to $\boldsymbol{F}_c$, $\boldsymbol{F}_m$, and their associated moments. Once these function mappings are defined, solving the transformed equations of motion (4) is trivial.

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