Development and Validation of a Detailed Finite Element Model of the Hand and Wrist for Biomechanical Simulation

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Summary

In this study, an optimization method based on muscle tissue interactive modeling was developed to construct a 3D finite element (FE) model of the upper limb, which includes 31 bones, 32 skeletal muscles, 88 ligaments, and 16 joints (22 degrees of freedom). Based on multibody dynamics results, gestures and postures were simulated, and mechanical parameters were calculated. Compared with experiments, the active muscle force change curve closely matched the corresponding electromyographic (EMG) signal data.

Introduction

The anatomical redundancy of the hand and arm muscles provides them with flexible movement capabilities. However, it also brings multiple challenges to system modeling, including the nonlinear characteristics of joint kinematics and the dynamic coupling of soft tissue deformation[1].

The aim of this study is to develop and validate a finite element (FE) musculoskeletal model of the hand and arm, which includes deformable models of muscles, ligaments, and cartilage, in incorporating inverse-dynamics-based optimization for the simulation of muscle changes during different movements.

Methods

MRI data of a healthy subject's relaxed palm position (with a slice thickness of 0.5 mm) were collected. MR images were imported into Mimics to construct the initial anatomical model(31 bones and 32 muscles). Muscular tissues modelling was optimized in Blender based on the anatomical orientation characteristics of muscle fibers. In addition, ligament models were created based on their anatomical origin and insertion points. The complete model as shown in Figure 1.

Figure 1. Upper limb FE models of healthy subject

Both active and passive properties of the muscles were considered. Incompressible transversely isotropic Mooney–Rivlin material incorporating fibres was adopted to represent the tendons and passive properties of the muscles.

This study uses the model previously developed by McFarland et al. for the analysis of multibody dynamics[2]. The captured motion capture data are imported into OpenSim for dynamic analysis to obtain the total muscle force.

The upper arm is fixed in all degrees of freedom, and flexion is applied to the wrist joint, gradually increasing from 0° to 43° (angle derived from kinematic results) within 0.3 seconds to simulate the process of wrist flexion. The ulnar flexor muscles, which play a major role in this process, are selected for analysis.

Results and Discussion

The distribution of the stretching stress of the ulnar flexor muscles during wrist flexion is shown in Figure 2(a). The stretching stress was concentrated around the tissue areas connecting the carpal bones and the regions where the muscle contacts the bone during deformation. Extracting the reaction force of the ulnar flexor muscles, showing the applied force gradually increasing during the wrist flexion process (Figure 2(b)).

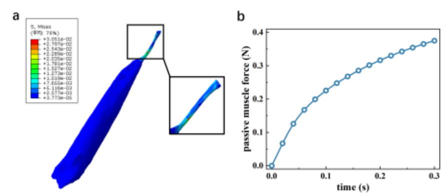

Figure 2: The stress contour map and reaction force of the ulnar flexor muscles during the wrist flexion process.

Conclusions

This study established a relatively complete and accurate finite element model of the upper limb and validated it. It is expected that this model will provide significant support for future research on upper limb motion.

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