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Analysis of the musculoskeletal system of the hand and forearm during a cylinder grasping task

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A B S T R A C T

Musculoskeletal disorders of the hand are mostly due to repeated or awkward manual tasks in the work environment and are considered a public health issue. To prevent their development, it is necessary to understand and investigate the biomechanical behavior of the musculoskeletal system during the movement. In this study a biomechanical analysis of the upper extremity during a cylinder grasping task is conducted by using a parameterized musculoskeletal model of the hand and forearm. The proposed model is composed of 21 segments, 28 musculotendon units, and 20 joints providing 24 degrees of freedom. Boundary conditions of the model are defined by the three-dimensional coordinates of 43 external markers fixed to bony landmarks of the hand and forearm and tracked with an optoelectronic motion capture system. External marker positions from five healthy participants were used to test the model. A task consisting of closing and opening fingers around a cylinder 25 mm in diameter was investigated. Based on experimental kinematic data, an inverse dynamics process was performed to calculate output data of the model (joint angles, musculotendon unit shortening and lengthening patterns). Finally, based on an optimization procedure, joint loads and musculotendon forces were computed in a forward dynamics simulation. Results of this study assessed reproducibility and consistency of the biomechanical behavior of the musculoskeletal hand system.

Relevance to industry: This musculoskeletal model may be employed to predict internal biomechanical parameters during manual handling in the manufacturing industry. Subsequently workplace or tool design may benefit from this process by decreasing the risk of developing work-related musculoskeletal disorders.

1. Introduction

Musculoskeletal disorders of the hand and forearm are considered a public health issue (Burgess-Limerick, 2007; Picavet and Schouten, 2003). Consequently, understanding how the anatomical structures of the upper limb interact when moving is crucial for designing tools dedicated to industrial manual tasks and decreasing the incidence of work-related musculoskeletal disorders (Dickerson et al., 2007; Vignais et al., 2013). However, direct measurements of musculotendon and joint forces are invasive, and therefore impossible to be performed routinely (Chalfoun et al., 2005; Pfaeffle et al., 1999). As an alternative, methods based on mathematical modeling and computer simulations have been developed in order to analyze the musculoskeletal system of the hand and forearm (Brook et al., 1995; Lemay and Crago, 1996; Sancho-Bru et al., 2001; Wu et al., 2009a).

Computer-based musculoskeletal modeling can be divided into two approaches: inverse-based and forward-based simulations (Erdemir et al., 2007). Firstly, the inverse approach estimates musculotendon force by using external data (kinematics, forces, etc.) combined with inverse dynamics and static optimization (Tsirakos et al., 1997). Musculotendon forces assessed by researchers are then compared to electromyographic (EMG) activity patterns to validate their results (Erdemir et al., 2007). Due to complexity and redundancy of its anatomy, several sophisticated inverse models of substructures of the hand and forearm have been suggested (Sancho-Bru et al., 2001; Valero-Cuevas et al., 2003;

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Vigouroux et al., 2009). For instance, a three-dimensional biomechanical model of the thumb has been proposed (Wu et al., 2009b). In this case, different virtual scenarios have been designed, e.g. musculotendon forces in a thumb were virtually affected by osteoarthritis and analyzed. This model was verified by comparing the predicted musculotendon moment arms with experimental data (Wu et al., 2009a, 2009b). However, few models have taken into account the whole complexity of the musculoskeletal system of the hand and forearm (Johnson et al., 2009). Chalfoun and colleagues have designed an inverse model of the hand and forearm containing 38 musculotendon units and 17 joints with a total of 24 degrees of freedom (DOF). Based on an optimization method minimizing the square sum of the normalized musculotendon forces, these values were predicted for the closing/opening motion of the hand and pinching (Chalfoun et al., 2004, 2005). Nevertheless, these movements came from a numerical simulation not based on experimental data. Main shortcomings of the inverse approach have been identified as the inadequacy of kinematic models to represent the movement, and inaccuracies of experimental data (Erdemir et al., 2007).

Secondly, in the forward approach, an initial set of muscle activations are fed into a forward dynamics model of the musculoskeletal system to estimate the produced movement. Then the solution is compared against experimental data and the process is iterated by updating the muscle activations that best reproduce measured data. Complete musculoskeletal models of the hand and forearm have been proposed using the forward approach to provide realistic simulations (Albrecht et al., 2003; Li and Zhang, 2009). A musculoskeletal model of the hand and forearm defined by 41 musculotendon units and 16 joints providing 23 DOF has been developed, and was able to compute hand and finger positions with a given set of muscle activations specified by the user (Tsang, 2005). Nevertheless, the forward approach involves a high computational cost (due to multiple integrations to obtain optimal joint kinematics) and is therefore difficult to apply directly to industrial environment where a rapid output is often necessary (Erdemir et al., 2007).

Thus the aim of this study is to provide an alternative strategy for the musculoskeletal modeling of the hand and forearm. Based on measured hand motion capture data, this modeling tool includes an inverse-to-forward dynamics simulation in order to estimate subject-specific internal parameters such as musculotendon forces or joint loads. As a case study, the whole procedure has been developed and simulated during a cylinder grasping task.

2. Method

2.1. Overview

In order to analyze the biomechanical behavior of the system of the hand and forearm, a three-step process for musculoskeletal modeling is proposed (see Fig. 1). For pre-processing, the LifeMOD (Biomechanics Research Group, San Clemente, CA, USA) plugin has been used and for multi-body dynamics solver, the software

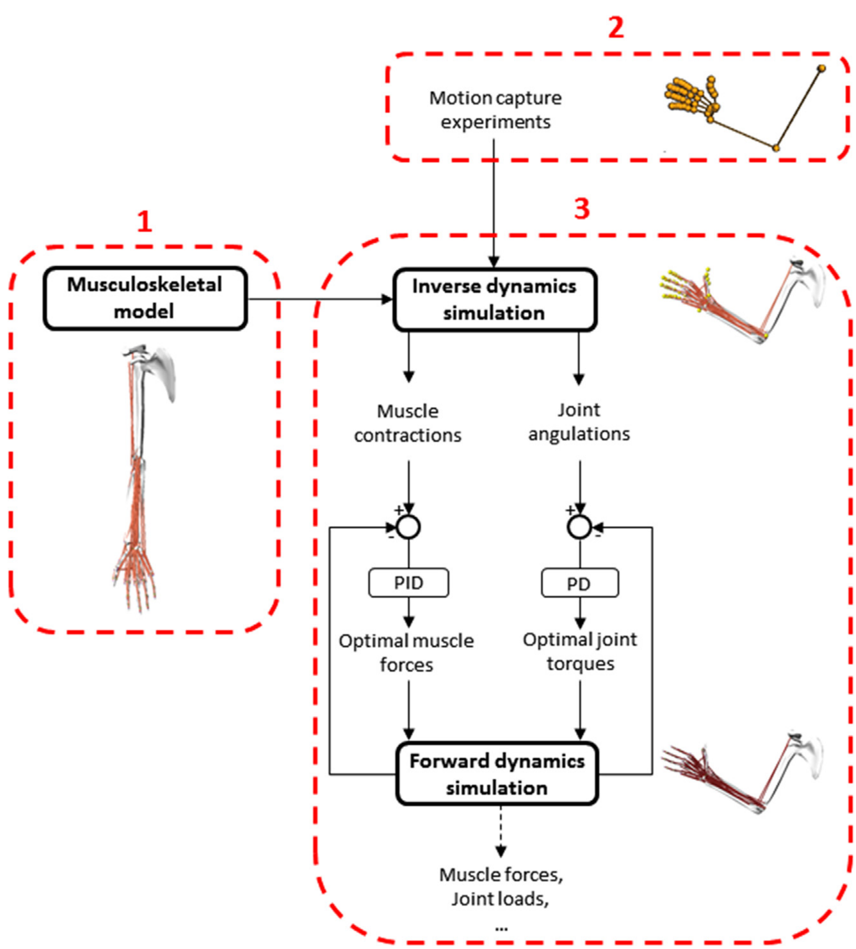

Fig. 1. A three-step process simulation to compute internal parameters. This process includes the musculoskeletal model development (1), the motion capture data experiments (2) and the calculation step with an inverse-to-forward dynamics simulation method using PD (proportional/derivative) and PID (proportional/integral/derivative) controllers (3).