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Exploring novel objective functions for simulating muscle coactivation in the neck

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ABSTRACT

Musculoskeletal modeling allows for analysis of individual muscles in various situations. However, current techniques to realistically simulate muscle response when significant amounts of intentional coactivation is required are inadequate. This would include stiffening the neck or spine through muscle coactivation in preparation for perturbations or impacts. Muscle coactivation has been modeled previously in the neck and spine using optimization techniques that seek to maximize the joint stiffness by maximizing total muscle activation or muscle force. These approaches have not sought to replicate human response, but rather to explore the possible effects of active muscle. Coactivation remains a challenging feature to include in musculoskeletal models, and may be improved by extracting optimization objective functions from experimental data. However, the components of such an objective function must be known before fitting to experimental data. This study explores the effect of components in several objective functions, in order to recommend components to be used for fitting to experimental data. Four novel approaches to modeling coactivation through optimization techniques are presented, two of which produce greater levels of stiffness than previous techniques. Simulations were performed using OpenSim and MATLAB cooperatively. Results show that maximizing the moment generated by a particular muscle appears analogous to maximizing joint stiffness. The approach of optimizing for maximum moment generated by individual muscles may be a good candidate for developing objective functions that accurately simulate muscle coactivation in complex joints. This new approach will be the focus of future studies with human subjects.

1. Introduction

The musculoskeletal system of the human body is over actuated with an average of 2.6 muscles acting on each joint (Bottasso et al., 2006). This redundancy implies that a nearly infinite number of solutions is possible to predict individual muscle forces to produce a joint moment (Crowninshield and Brand, 1981). A common approach to overcome this problem is using an optimization approach with computational musculoskeletal modeling (Herzog and Binding, 1992). The premise for using optimization is that the human body functions to achieve a secondary objective (e.g., minimizing force, energy, pain, etc.) along with a primary objective of producing specific joint moments (Bottasso et al., 2006; Crowninshield and Brand, 1981; McKay and Ting, 2012). This secondary objective is expressed in a somewhat unclear objective function. Formulating objective functions that allow models to closely match experimental data is the focus of many studies with varying degrees of success (Bottasso et al., 2006; Monaco et al., 2011; Prilutsky and Zatsiorsky, 2002a; Thelen et al., 2003). Minimizing muscle activation, total muscle force, metabolic rate, muscle stress, and total work are common objective functions. These approaches have been validated for many situations including gait, load lifting, and isometric contractions (Prilutsky and Zatsiorsky, 2002b). However, how humans respond when efficiency is not the main objective has not been adequately explored. For example, situations where efficiency is overruled by the need for high-energy expenditure including unexpected slips, perturbations, and impacts.

Muscle coactivation is defined as opposing muscles generating force with a combined effect of zero net torque (Hogan, 1984). Muscle coactivation has been shown to increase joint stiffness, which is resistance to imposed movement (Madhavan and Shields, 2009; Milner et al., 1995; Pope-Ford and Jiang, 2013; Shadmehr, 1993; Shadmehr and Arbib, 1992). Coactivation increases for high accuracy movements (Lee and Terzopoulos, 2006; Madhavan and Shields, 2009; Pope-Ford and Jiang, 2013).

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Simulating muscle coactivation requires optimizing for a measure other than efficient movement. The minimum activation levels, muscle force, metabolic rate, muscle stress, and total work for a stationary joint that is not under load will result in near zero muscle coactivation. The classical objective functions can predict some coactivation levels, but generally only in complex systems and to a minimal degree (Herzog and Binding, 1992). In order to get realistic muscle forces during intentional coactivation, different objective functions are needed.

Four previous studies have sought to simulate stiffness in the spine through coactivation. Lee et al. created a computer model that mimics human neck behavior for computer graphics purposes (Lee and Terzopoulos, 2006). It was argued that the manner in which humans coactivate to produce stiffness remains an open question, and presented an intuitive approach based on maximizing total muscle forces with a constraint of zero net torque. Two additional studies used the same approach to investigate the effect of active muscles on neck injury thresholds (Chancey et al., 2003; Dibb et al., 2013). Another study investigated how the human body addresses the muscle redundancy problem in the lumbar spine by modeling joint stiffness as a function of activation, and then solved for maximum stiffness levels by maximizing activation levels (Rashedi et al., 2010). None of these studies explored how different objective functions compare in generating joint stiffness. Instead, it was assumed that maximizing total activation levels or force would result in the stiffest joints possible. This assumption may not be valid, due to differences in muscle capabilities resulting in non-symmetrical anterior-posterior movement and needs to be further explored.

The human response to potentially injurious scenarios from high impact sports such as American football, soccer, hockey and lacrosse, to automobile accidents could be better understood with an improved model of coactivation for neck muscles. It has been shown that awareness of impending impact affects head kinematics in car crashes and sports (Eckner et al., 2014; Fanta et al., 2013; Siegmund et al., 2003). Improved safety devices, equipment, physical training, and sport rules could arise from musculoskeletal models of the head and neck that incorporate an understanding of coactivation. In order to obtain this understanding, objective functions that can closely match experimental data are necessary.

In 2006, Bottasso et al. proposed that objective functions could be extracted from data numerically, using optimization techniques (Bottasso et al., 2006). Even with this sophisticated technique, a general idea of which parameters should be in the objective function is still required. Previous attempts at simulating coactivation have used an assumption that activation or force is the key component of the objective function. If this assumption is not valid, it will be difficult, if not impossible, to match experimental data.

The aim of this study is to investigate how different objective functions for modeling coactivation affect neck stiffness. We hypothesize that building on previous approaches and maximizing applied moment on joints in the direction of interest will result in a stiffer neck than previous objective functions are able to produce. We also hypothesize that it is possible to directly maximize stiffness with an objective function built on properties of individual neck muscles. The results of this study will direct which parameters should be used in extracting objective functions from experimental data in order to realistically model neck muscle coactivation. This study is meant to serve as theoretical background necessary for correctly modeling neck muscle coactivation.

2. Methods

We created a musculoskeletal model of the neck using OpenSim software based on the work done by Vasavada (Delp et al., 2007; Vasavada et al., 1998). We present four approaches to modeling coactivation in neck muscles. The Push-Pull method [PP], involves combining solutions obtained from resisting forces and minimizing activation levels. The Static Optimization method [SO], minimizes activation levels with specific muscles being constrained to full activation. The Maximum Moment method [MM], seeks to maximize the total moment about joints in the neck caused by each muscle. The Maximum Stiffness method [MS], seeks to maximize stiffness directly.

2.1. Musculoskeletal model

OpenSim has robust tools for inverse kinematics, inverse dynamics, muscle force computation, and forward simulation (Delp et al., 2007). A major advantage of using OpenSim is the ability for future research to use or recreate the results of this study easily. Vasavada's model contains 39 individual muscles attached in anatomically determined locations. The movements of individual cervical bones in this model are constrained to move together to allow for three degrees of freedom including flexion/extension, lateral rotation, and axial rotation. Vasavada's model required several modifications for our simulation study. We added muscles bilaterally in the model (Fig. 1) and mass and inertia properties obtained from Lee et al. (Lee and Terzopoulos, 2006). Lee's research also provided values for lumped stiffness between each joint to account for passive elements in the neck. Finally, the muscle model was updated from Thelen2003 type muscles to MillardAcceleration2012 muscles (Millard et al., 2013; Thelen, 2003). This allows for more accurate muscle modeling, especially in muscles that have little to no excitation (Millard and Delp, 2012).

2.2. Optimization setup

OpenSim software allows for interaction with MATLAB (Lee and Umberger, 2016). A function in MATLAB was created that calculates the net moment that is a resultant of all applied muscles for each degree of freedom according to the individual muscle activation levels, without considering the effect of gravity. This simplification allowed for efficient computation of the effect of different muscle activation schemes. The MATLAB function is described as:

$$M_d = \sum_{i=1}^{78} a_i f_i r_i$$

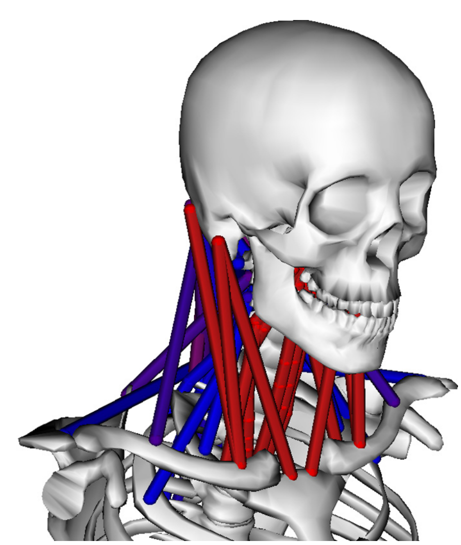

Fig. 1. OpenSim musculoskeletal model used for this study.

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