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A novel objective function for predicting reasonable muscle forces in subject-specific model*

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Abstract— **Objective functions in adjusting model parameters have been widely used to minimize the variance of joint moments, but it may be insufficient to estimate reasonable muscle forces. The purpose of this study was to introduce a novel objective function based on a correlation coefficient for predicting reliable muscle forces, and compare its performance to the existing objective function. A man with right-sided hemiparesis after stroke participated in the study, and performed the maximum voluntary isometric contractions with a dynamometer at an angular velocity of 30°/s. To compare the effects of the existing and the new objective functions on prediction of muscle forces, the relative root-mean-square error and correlation coefficient were calculated for joint moments and individual muscle forces. The new objective function yielded promising results, implying that it could potentially be used to estimate reliable muscle forces. In the future, this approach will be applied to various movements to determine the reliability of muscle forces and to understand mechanisms from the reliable muscle forces.**

I. Introduction

Musculoskeletal modeling is widely applied to understand muscle contributions of normal [1] and patient [2]. In the modified Hill-type muscle model, muscles are mathematically expressed as a set of spring and damper. Thus, muscle forces depend mostly on muscle length which can be determined from a musculoskeletal model [3]. Musculoskeletal geometry calculates muscle moment arms about a joint, and the joint moment is determined by given individual muscle forces [4]. In calculating muscle forces, elements such as muscle activation and contraction dynamics, and musculoskeletal geometry can be incorporated. A number of model parameters are involved to define the muscle properties, and often adopted or scaled from the literature [5]. However, joint moments calculated by the above procedure (referred to as model joint moments) differ from joint moments measured by a dynamometer (referred to as reference joint moments). The discrepancy between computational and experimental data stems from individual differences, as people inherently possess unique parameters. Sensitivity analysis shows that muscle forces are highly sensitive to the values of these parameters [6]. Therefore, they must be adjusted on a subject-specific basis.

Recently, many studies have developed subject-specific models to predict reasonable model joint moments that might be well matched to reference joint moments [7-9]. Although the EMG-driven model with numerically adjusted parameters predicts joint moments well, confirming whether individual muscle forces are also predicted correctly is not possible. In this regard, Heine et al. [10] reported that models with a large number of adjustable parameters predict unrealistic individual muscle forces. R^2 values (correlation determination coefficient) for joint moments (the reference and the model) might not be a good indication of reliable estimations of muscle forces, since incorrect muscle force combinations could increase R^2 values for joint moments. This means that the objective function, variance of joint moments, used in most previous studies might not be sufficient to estimate reasonable muscle forces. The determination of muscle forces provides more complete information about human movements. Also, since insufficient muscle forces mean that muscle-related activities cannot be properly performed, measurements of muscle forces could be clinically useful to allow clinicians to judge a patient's potential for function [11]. Thus, the prediction of reliable muscle forces is as important as the estimation of joint moments.

The purpose of this study was to introduce a new objective function for predicting reasonable muscle forces and investigate its performance compared to the existing objective function.

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II. Methods

A. Subject-specific model

Our subject-specific model consists of two modules [9]. One is the EMG-driven module that estimates individual muscle forces and joint moments, and the other is a parameter calibration module that minimizes the value of arbitrary selected objective functions. The EMG-driven module is used to predict forces and moments, and the parameter calibration module is used when adjusting model parameters. The EMG-driven module, excluding anatomical model, and the parameter calibration module were written in MATLAB R2009a (The MathWorks, Inc., USA). The anatomical model was developed using the Stanford VA Upper Limb Model [12], which includes an elbow joint with six muscles, biceps brachii long head (BIClong), biceps brachii short head (BICshort), brachioradialis (BRD), triceps brachii lateralis (TRIlat), triceps brachii long head (TRIlong), and triceps brachii medialis (TRImed).

B. Objective functions

The goal of the existing objective function (EOF) is to minimize the variance between the reference and the model joint moments, described numerically as:

$$\min \sum_{i=1}^{n} \left(M_i - \sum_{j=1}^{m} r_{ij} \times F_{ij} \right)^2 \quad (1)$$

where M is the reference joint moment, r is the muscle moment arm, and F is the muscle force. Index i indicates the time frame, j the muscle, and m the number of muscles.

The new objective function (NOF) proposed in this paper was designed to satisfy two objectives. One was to strengthen the linear relationship between the reference and the model joint moments. This condition becomes

$$\min \left(1 - \mathrm{corr}(M_r, M_m)\right)^2 \quad (2)$$

where corr is the function to find a correlation coefficient between M_r, the reference joint moment, and M_m, the model joint moment. To predict reliable muscle forces, the other function assumed that muscle activation contributes to active force and its corresponding muscle force have a similar pattern over time, because passive force is much smaller than active force [13]. This condition will be

$$\min \sum_{j=1}^{m} \left(1 - \mathrm{corr}(a_j, F_j)\right)^2 \quad (3)$$

where a is the muscle activation and F the muscle force. Other variables are the same as above. Finally, the proposed objective function aimed to make the shape of the model joint moment similar to that of the reference joint moment by ensuring that the relationship between the muscle activation and its corresponding muscle force is linear:

$$\min \left(\left(1 - \mathrm{corr}(M_r, M_m)\right)^2 + \sum_{j=1}^{m} \left(1 - \mathrm{corr}(a_j, f_j)\right)^2 \right) \quad (4)$$

C. *Evaluation procedures*

A man with right-sided hemiparesis after stroke (age: 18 years; mass: 78 kg; height: 178 cm) participated in this study with the informed consent prior to commencing the experimental trials. His modified Ashworth score was 1. Before experiments, bipolar surface electrodes were attached to record EMG signals from four of six selected muscles excluding BICshort and TRImed, using an eight-channel surface EMG system (MyoSystem 1200, Noraxon Inc., USA) based on positions suggested by [14]. A reference EMG electrode was placed on the skin surface of the olecranon. A dynamometer task was performed on a Biodex System 3 Pro (Biodex Medical Systems, New York, USA) to measure elbow joint moments. Range of motion for the elbow was 0° (fully extended) to 130° (fully flexed). After set up, the participant was asked to perform three MVICs for the muscle group of interest, separated by a 30-second rest, with an elbow joint angle of 90°. The middle 5 seconds of a 10-second contraction were then averaged over three MVIC trials [14]. The subject then generated an elbow flexion moment for 4 seconds, rested for 3 seconds, and generated an elbow extension moment for 4 seconds at an angular velocity of 30°/s three times. During the tasks, elbow joint moments and angles were measured by the Biodex system. The data from the Biodex system and EMGs were simultaneously collected at 1 kHz using MyoResearch XP software v1.06.35 (Noraxon Inc., USA). The activation of two muscles that could not be obtained by surface EMGs was estimated; the BICshort and TRImed were assumed to have the same activation as the BIClong and TRIlong, respectively. After all Biodex tasks, to scale the anatomical model, reflective markers attached to the subject's skin were collected by a six-camera Vicon motion capture system (VICON 612, Oxford Metrics Ltd., UK)

Muscle parameters were tuned to each of the dynamometer tasks with each of two objective functions. Once the parameters were adjusted for a certain trial, the EMG-driven module with the adjusted parameters was used to predict the joint moment for other trials. The data used in the parameter calibration module and EMG-driven module were down-sampled at 50 Hz to reduce the computational burden. To evaluate the effects of the objective functions for joint moments, we calculated the relative root-mean-square error (rRMSE) normalized by the peak-to-peak value of the reference joint moment and the correlation coefficient (CC) between the reference and the model joint moments. We also calculated the rRMSE between the muscle activation and the corresponding muscle forces normalized to maximum isometric forces of the muscle and the CC between the reference and the model joint moments.

III. Results and Discussion

Model joint moments with no parameter calibration showed undesirable negative offset during the 3-second-rest period between flexion and extension movements (Fig. 1). This resulted from unreliable muscle force prediction, especially for the TRIlong muscle force, due to improper values for model parameters (Fig. 2e). This problem was resolved by parameter calibration with EOF and NOF. For every trial, for joint moments, parameter calibration modulewith EOF reduced the rRMSE, and increased the CC; specially, the rRMSE for EOF decreased over 34.3% (average: 54.9%). This might be acceptable because the purpose of EOF was to reduce the variance between reference and model joint moments. The proposed objective function based on the CC showed relatively low performance; it caused a decline in the rRMSE about 31.9% and an increase in the CC of 3.3%. These results implied that the adjusted parameters could predict joint moments of other trials once the parameters

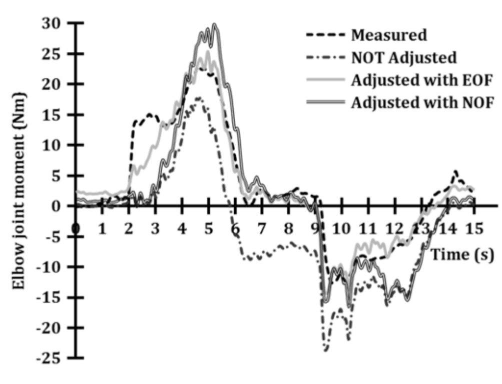

Figure 1. Measured and predicted elbow joint moments

were adjusted to a certain trial by a parameter calibration module with one of two objective functions. Even though the parameter calibration module with EOF gave a good estimation of joint moments, it resulted from a combination of unrealistic muscle forces (Fig. 2). In particular, the BIClong muscle generated no force between about 5 s and 11 s despite muscle activity, and the BICshort muscle generated too much force before the beginning of the task (0 s ~ 2 s). The rRMSE between muscle activation and corresponding normalized muscle force increased about 14.8%, but the CC between muscle activation and muscle force decreased by about 59.3% in the BIClong muscle . In contrast, the parameter calibration module with NOF predicted very similar muscle forces to the corresponding muscle activations (Fig. 2). The CC between muscle activation and muscle force increased approximately 40.8% in the BIClong muscle. This might be natural since the purpose of NOF is to approximate the CCs for joint moment and each muscle force to one. However, our results showed that the rRMSE between muscle activation and corresponding normalized muscle force also decreased about 43.9% in the BIClong muscle. The largest decrease occurred in the TRIlong muscle (the rRMSE decrease of 85.4%, and the CC increase of 15.7%), which resulted in discrepancy between the model and reference joint moments. This is a promising result, implying that the developed objective function could potentially be used to estimate reliable muscle forces.

This study has some considerations. First, we assumed that the muscle activation and its corresponding muscle force have a similar pattern over time, to predict reliable muscle forces. According to previous studies, EMG activity in concentric actions might be greater than in eccentric actions, even though muscle forces in eccentric actions are greater than in concentric actions [15]. This means that muscle activations

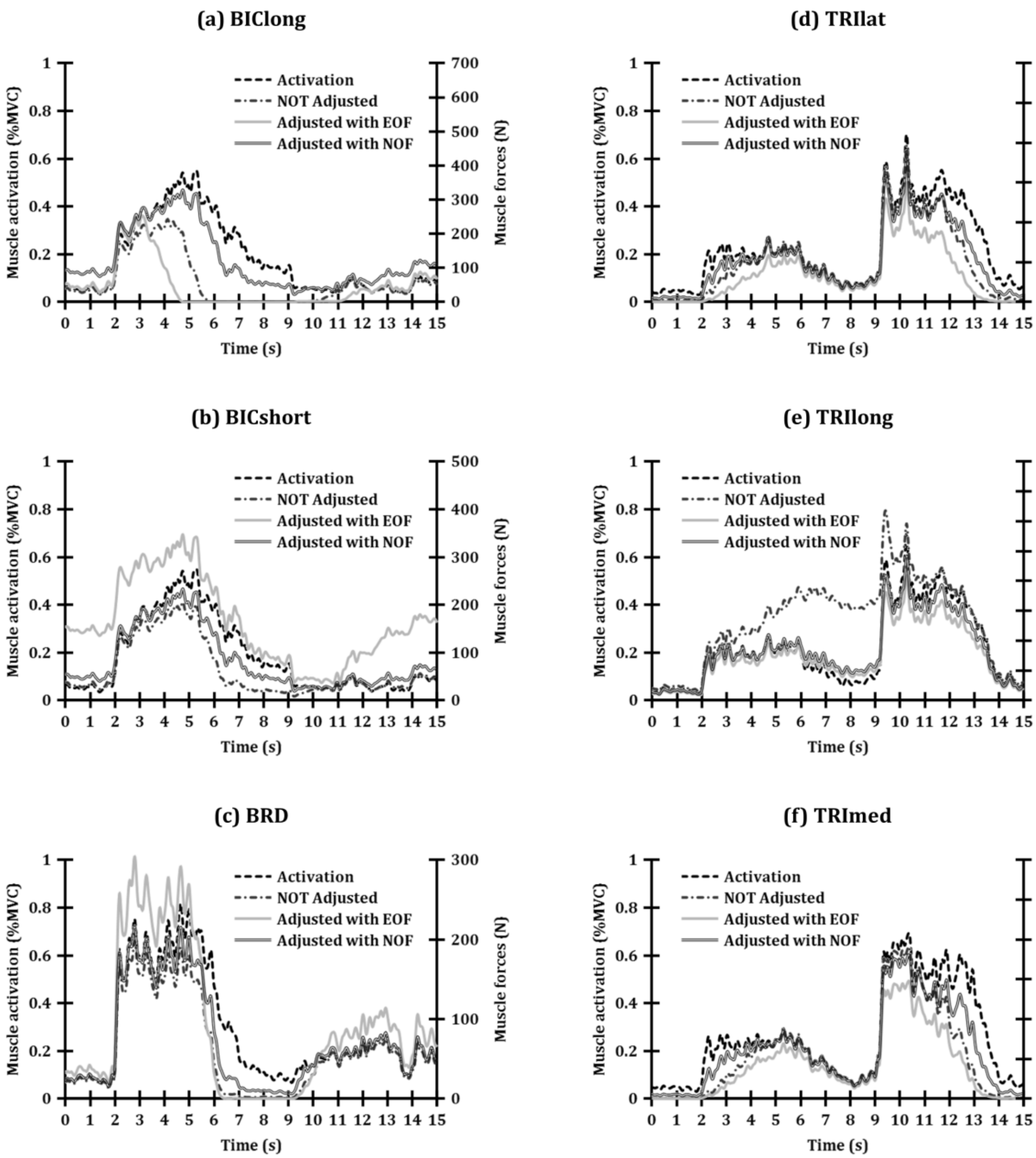

Figure 2. Muscle activations and forces calculated through the EMG-driven module

involving eccentric contraction might not have patterns similar to corresponding muscle forces. Some studies have examined the relationship between EMG amplitude and eccentric muscle force combined with musculoskeletal simulation. However, this is a problem not only in our proposed algorithm but also in musculoskeletal modeling area. Nonetheless, the results of this study are reliable since only concentric contraction was evaluated in this study. Further studies will be needed to evaluate eccentric contraction. Second, NOF showed CC and rRMSE for muscle forces that were more desirable than EOF, but that accuracy in predicting joint moments was relatively low. This could mean that the number of possible value of model parameters by NOF are limited compared to EOF, since muscle forces that determine joint moments are constrained. This might be considered as a trade-off problem; why joint moments must always be compared and matched is questionable. In this regards, Li et al. [16] mentioned that additional validation must be done before an EMG-driven model can be used as a reliable tool to estimate muscle forces. They suggested joint trajectories as a reliable tool, and compared joint trajectories predicted from forward dynamics with adjusted parameters to measured joint trajectories. We are currently developing a forward dynamics module, and will validate the developed algorithm by additional biomechanical variable, i.e. joint trajectories.

IV. CONCLUSION

In conclusion, the developed objective function yielded relatively low performance in joint moment prediction, but estimated muscle forces well under an assumption that the muscle activation and its corresponding muscle force have a similar pattern over time, at least. In the future, this approach will be applied to a research to determine the reliability of muscle forces and to understand mechanisms from the reliable muscle forces.

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