NUMERICAL ANALYSIS OF COOPERATIVE ABDUCTION MUSCLE FORCE IN A HUMAN GLENOHUMERAL JOINT

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INTRODUCTION

It is difficult to directly examine the muscle force in living subjects. Many muscles are acting cooperatively in a human shoulder, therefore, computed simulation may be useful in analyzing the muscle force. In this study, a method of numerical analysis of muscle force during shoulder abduction was described.

METHODS

Computer tomography (CT) data of the shoulder of a normal volunteer were prepared for creating a three-dimensional muscloskeletal model. Axial CT images of the shoulder, elbow, and forearm were obtained by a high-resolution helical scanner (CT Highspeed Advantage; GE Medical System, WI). Obtained images were transferred to a computer and a three-dimensional skeletal model was created using a medical image analyzing software Analyze 3.0 (Biomechanical Imaging Resource, MN). Three-dimensional coordinates of the origin and insertion of each muscle were manually determined on the skeletal model. The analyzed muscle were as follows; F1; anterior fiber of deltoid, F2; middle fiber of deltoid, F3; posterior fiber of deltoid, F4; supraspinatus, F5; infraspinatus, F6; subscapularis, F7; teres minor, F8; teres major, F9; long head of biceps, F10; short head of biceps, and F11; triceps. Muscles were modeled by a straight-line vector from its insertion to the origin. In muscles that originated from wide area (F1-F6), the adequate origin point was selected from several points in each abduction angle using the optimization method. Finally obtained muscloskeletal model was shown in Figure 1. The triangle shape demonstrated the muscles with wide area of origin (F1-6).

The analyzed motion was abduction of the glenohumeral joint in a scapular plane (a vertical plane 30º from a frontal plane) ranged from 0º to 100º. The glenohumeral joint was assumpted as a ball joint, and the center of the humeral head approximated to a sphere as the center of rotation. No friction at the articular surface was considered. Upper extremity was assumed to be a rigid body, of which elbow joint was fixed in full extension and wrist in neutral rotation and neutral flexion. The self-weight of the upper extremity, that is 5% of the body weight, was applied to the middle point between the shoulder and the wrist and was considered to be the only external force acting on it. Internal forces acting on the upper extremity were muscle forces and joint reaction forces. Any ligament forces were not considered in this model.

Three-dimensional biomechanical model for formulation was established as Figure 2. O stands for the center of rotation, $\boldsymbol{F_i}$ (i=1-11) for each muscle force, $\boldsymbol{R}$ for joint reaction force, and $\boldsymbol{W}$ for self-weight of upper extremity. Unknown quantities we handled here were 14 in all; 11 muscle forces and 3 joint reaction forces. Denoting the unit vector of the forces by u_i, the gravity vector of the self-weight of the upper extremity by u_w, the positional vector of the action points of the muscle forces by r_i, and the positional vector of the action point of the self-weight by r_w, force and moment equilibrium equations can be written as follows:

$$\sum_{i=1}^{11} F_i u_i + W u_w + R = 0 \tag{1}$$

$$\sum_{i=1}^{11} \left(r_i \times F_i u_i \right) + r_w \times W u_w = 0 \tag{2}$$

Since muscles have physiological features that they act only for contraction, the value of muscle forces must not be negative and the following expression can be indicated:

$$F_i \geq 0 \tag{3}$$

There are six equations ((1) and (2)) with 14 unknown quantities, therefore, to find a unique solution, optimization by successive quadratic programming (SQP) method was applied. Objective function used in this study is determined as the total sum of the square of the muscle force divided by the physiological cross sectional area (PCSA) [1]. Muscles surrounding shoulder girdle were rather varied with their volume, therefore, reciprocal of PCSA was introduced as a weighting factor for the purpose of reducing the excessive effect of the muscle volume, which should be correlated with muscle force, on the objective function. Therefore, objective function ***U*** can be summarized as follows:

$$U = \sum_{i=1}^{11} \left(F_i^{\,2} / PCSA_i \right) \quad (4)$$

To solve the optimization problem, function ***U*** was minimized using expression (1), (2), and (3) as constraints.

To evaluate the validity of the results of the analysis, we performed electromyography (EMG) examination on the same volunteer. Platinum fine-wire electrodes were used for the supraspinatus, infraspinatus, subscapularis, teres minor, and teres major, and disposable surface electrodes were used for the other muscles. Abduction movement in a scapular plane from 0º to 150º was investigated in every 10º and integrated EMG value for 3 seconds was calculated in each muscle. To study the correlation between the integrated EMG and the analyzed muscle force quantitatively, simple regression analysis was performed in each muscle. The regression functions were considered significant for $P<.05$.

RESULTS

Results of the muscle force analysis were shown in Figure 3. Middle fiber of deltoid (F2) demonstrated remarkably large force. Supraspinatus (F4), anterior fiber of deltoid (F1), and infraspinaus (F5) followed it. Subscapularis (F6), and teres minor (F7) were acting at the late phase of abduction. The statistical analysis showed significant regression function between the analyzed muscle force and the integrated EMG in all muscles.

DISCUSSION

Optimization method has been used to solve numerical muscle force analysis [2]. Many objective functions have been reported, however, there is no multi-functional function. We determined the total sum of the square of the muscle force divided by PCSA as an objective function to obtain analysis better correlated with EMG. Several methods of modeling the wide muscles have been reported [3,4]. We developed an original method to determine the muscle vector in each abduction angle. To obtain reasonable results that reflect actual muscle activities in living subjects, we believe that it is important to select the adequate objective function and constraints fit for the purpose of the analysis as well as to creating anatomically delicate geometrical model.

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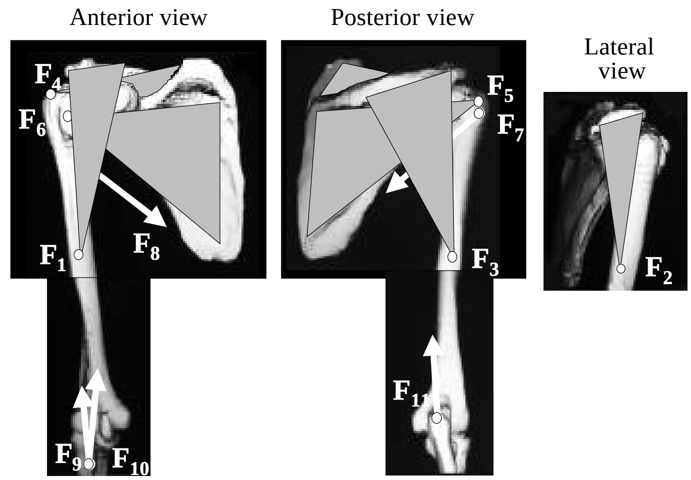

Fig. 1 Three-dimensional musculoskeletal model

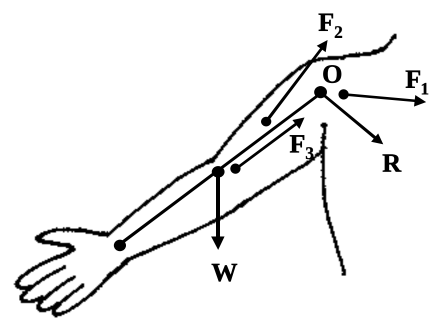

Figure 2: Three-dimensional biomechanical model of upper limb

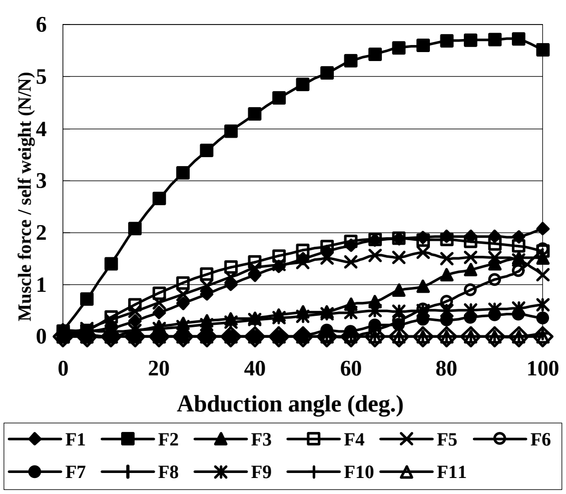

Figure 3: The results of the muscle force analysis