Research on the motion characteristic of elbow joint angle based on the sEMG of single muscle

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Abstract: As the number of patients caused the stroke increase, there are many therapies applied to rehabilitation, but they lack scientific theoretical basis guidance. In the process of treatment, the muscle force analysis, and the movement of information to predict muscle activity, they can provide a theoretical basis for the design of rehabilitation exercise; the treatment is more targeted and efficient. According to the characteristics of upper limb motion, this article establishes a reasonable and effective mathematical model, and uses the Hill muscle model to establish the simplified musculoskeletal model. The simulation model of human upper limb is used to establish with anybody software. The subjects have an experiment with the elbow joint flexion and extension, and use the electromyography collection device to collect the sEMG of biceps brachii and triceps brachii. And the motion information is processed to obtain the motion angle, angular velocity and angular acceleration. After preprocessing the sEMG, the wavelet decomposition and reconstruction is used to deal with the sEMG. The reconstructed signal is compared with the motion information, and finds the relationship between sEMG signals and elbow joint motion and muscle force. The experiment confirms the sEMG of biceps brachii can directly reflect the changes of muscle force. It is concluded that the sEMG of a single muscle can directly reflect the information of elbow joint flexion and extension.

Subjects: Biomedical Engineering; Digital Signal Processing; Rehabilitation Medicine; Statistics for the Biological Sciences

Keywords: sEMG; elbow joint; single muscle; Hill model; upper limb motion; musculoskeletal model; innovative design and manufacturing

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PUBLIC INTEREST STATEMENT
During flexion of elbow joint, the angle is an evaluating reference in the rehabilitation of patients upper limb. The traditional method uses measuring instrument (protractor) to attain the limb angle information, it is easy to be affected by subjective factors of the patient and therapist. In this article, the sEMG of muscles related to elbow flexion was collected and processed, and find out the relation between muscle force and the flexion angle. According to the experimental results, the prediction results found that the brachioradialis muscle is significantly better than the biceps brachii and flexor carpi ulnaris muscle and flexor carpi radialis, and identify the angle error close to the rehabilitation of patients with elbow angle of the precision evaluation.
1. Introduction
In recent years, the cases of dyskinesia patients increased year by year, and they are mainly caused by strokes. To these patients, there are not effective treatment methods, usually apply rehabilitation plus medical expulsive treatment. Because the rehabilitation lack of scientific and accurate assessment and guidance, the assessment of muscle force base on sEMG analysis has become a research focus in the field. To the 0–1 level upper limb hemiplegic patients with stroke, the main method of rehabilitation is passive movement (Cai & Feng, 2009). Passive movement refers to the patients have some simple exercises with the help of the instrument or nursing staff. It can stimulate the lateral muscle, and make for the function recovery of limb. But the recovery is only speculated by the patient's movement conditions. If there is no qualitative change of movement, the recovery will not be able to detect. For the recovery, there is not the reasonable and reliable means of assessment.

This article selects the motion of elbow flexion and extension as the research object in the upper rehabilitation therapy. At present, the Fugl-Meyer assessment Scale is usually applied for the elbow rehabilitation, the flexion and extension angle is a parameter of the assessment, the value is measured by protractor or gyroscope, so it is difficult to ensure the therapy precision, and the effect cannot be timely detected. If the relation of sEMG between joint movements can be found out, the sEMG processing can be predicted for muscle and joint movement, which will provide scientific basis and direction for the rehabilitation therapy, develop more targeted treatments for the strokes patients, embodies the practical value of the study.

2. Related works
The research of musculoskeletal model forms a relatively complete system both in China and abroad. To upper limb disorders, develop a targeted musculoskeletal model, dynamic simulation is done on strokes patients, these have not been used and researched. The sEMG signals can reflect muscle force information, but through the sEMG signal, it has some drawbacks on forecasting the movement and the muscle force, so as to evaluate the human muscle function.

The calculation of muscle forces has become an important part of human motion analysis and rehabilitation therapy, but it is almost impossible to measure muscle force directly. The most accurate method is using musculoskeletal model for muscle force prediction. The key of muscle forces prediction is to establish an effective musculoskeletal model.

2.1. The musculoskeletal model of elbow joint
The human movement system is composed of bone, bone connection and skeletal muscles. The bone and bone connection are the implementation of the movement, and have the function of supporting and maintenance on human body, also provide the attachment for skeletal muscles. The upper extremity elbow (Kamavuako et al., 2013) is composed of distal humerus, ulna and the upper end of radius; it is a compound joint, including three joints: humeroulnar joint, humeroradial joint, and proximal radioulnar joint, such as shown in Figure 1.

The humeroulnar joint is composed of trochlea of humerus and semilunar incisure of ulna, belonging to articulationes cochlearisthe, it is the main part of the elbow joint. The humeroradial joint is composed of capitellum and fovea articularis capitis radiita, belonging to ball and socket joints. The and proximal radioulnar joint is composed of circumferentia articularis capitis radiita and Incisura radialis of ulna, belonging to pivot joints. The elbow joint can carry out the movement of flexion, extension, and involved in the movement of pronation and supination of the forearm.

2.2. The movement characteristics of elbow joint
The upper limb is a very complex structure, especially the palm part, the structure is complex and the activity is very flexible, the related research aimed at the palm part is enormous. But this article mainly focuses on the elbow joint, and without considering the internal and external rotation of the elbow, so its characteristics are as follows: the elbow has only a degree of freedom, which only considers flexing and stretching.
When the upper limbs move described above, the muscle mass provided forces is different, and the range of joint motion is not the same, the range of motion and the muscle mass are as bellow.

The flexion movements: the range is 135°–150°, the muscle mass involved are brachialis, biceps and brachioradialis. The extension movement: the range of motion is 0°–10°, the muscle mass involved is triceps brachii muscle.

2.3. The musculoskeletal model
Because the muscle is complexity, its physical and geometrical characteristics are constantly changing during the movements, so it is difficult to imitate the real human muscle. In order to make the simulation model more accurate, this article selects the Hill model, as shown in Figure 2.

CE represents the activity of muscle fiber; the elastic force of muscle depends on it. SE represents the elasticity caused by tendon, because the elastic coefficient of tendon is great different with muscle fiber, in order to calculation, they are distinction between CE and SE. PE is the passive stiffness of muscle fiber, it not only can generate the muscle force with contraction actively, but also can generate the muscle force in the process of contraction passively. So, this force is known as passive force, it takes up a large proportion, need to consider their role in the movement.

Notes: \( l_{mt} \) is the total length of tendon and muscle fiber. \( l_t \) is the length of tendon, \( l_m \) is the length of muscle fiber, and \( \alpha \) is the angle between muscle fiber bundle and tendon. This model is composed of three main components, respectively is the series elastic element (SE), the parallel elastic element (PE) and the contractile element (CE) (Wu, Sun, Xu, & Shi, 2008; Zajac, 1989).
Hill muscle model reflects the dynamic characteristics and physical properties, but also reflects the physiological properties of the muscles, so it plays an important role in the simulation of musculoskeletal model, and it can greatly improve the accuracy of the simulation. The different people have different height and weight, and muscle strength is different, there are a lot of individual differences in musculoskeletal model, but also it has some rule to follow. There is some relevant relationship between the musculoskeletal model and the specific part of body, for example: the forearm centroid is similar in proportion to the center of mass in the forearm. Thus, this article established the human body model referred to the human body parameters, it is shown in Table 1.

### 3. Research methods

#### 3.1. The simplified model of upper limb motion

According to the basic knowledge of the upper limb kinematics, it can be seen that not all upper limb muscles are involved in the movement, then based on the related research and the upper limb dynamics, this article selects the major muscles of the simplified musculoskeletal model, they are deltoid, the long head of biceps brachii, the short head biceps brachii, the long head of triceps and The lateral heads of triceps. During this motion, the movement of the hand and the wrist joint is not considered, so the structure of the upper limb can be simplified. As shown in Figure 3.

The shoulder is fixed, it can be regarded as a fixed end in the simplified musculoskeletal model, the shoulder joint can be regarded as spherical hinge structure, and it can do all the movement. The elbow can be regarded as a universal hinge structure, but because this article does not consider the internal and external rotation motion of the elbow joint, therefore it can reduce to around a single axis—the articulationes cochlearis of coronary axis rotation. The upper arm is equivalent to a rod structure, the forearm and the hand combine a rod structure, two rod are connected by the elbow.

In this article, the movement of upper limb is limited to the horizontal plane, and the rotational velocity and the angular acceleration of the elbow joint are a major focus of the motion signal analysis. The motion information captured is the 3D coordinates of Marker points. The analysis of three Marker point motion information can simplify the relationship between two straight lines, and then compute the angle every moment by mathematical deduction, establish the relationship graph.
between the time and the angle of the elbow motion, which is the movement of elbow joint. Using a first-harmonic, the change of the angular acceleration related to muscle force can be obtained.

As shown in Figure 3, the coordinate of Marker1 is \(A(x_1, y_1, z_1)\), the coordinate of Marker2 is \(B(x_2, y_2, z_2)\), the coordinate of Marker3 is \(C(x_3, y_3, z_3)\). The moving angle of elbow joint is the angle between the line \(BA\) and the line \(BC\), that is \(\theta_1 = \angle ABC\).

Firstly, compute the vector between the line \(BA\) and the line \(BC\).

\[
BA = (x_1 - x_2, y_1 - y_2, z_1 - z_2)
\]

\[
BC = (x_3 - x_2, y_3 - y_2, z_3 - z_2)
\]

Then, compute the angle cosine.

\[
\cos \theta_1 = \frac{(x_1 - x_2)(x_3 - x_2) + (y_1 - y_2)(y_3 - y_2) + (z_1 - z_2)(z_3 - z_2)}{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}(x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2}}
\]

\(\theta_1\), the angel of elbow joint is computed by the arccosine function, and perform the derivative of the angle-time function, the rotational speed is obtained, the second order derivative is the angular acceleration.

3.2. The simplified musculoskeletal model of upper limb

In the process of rehabilitation, the motion of upper limb is passive, and it is not like the normal movement, its driving point is just a few muscles. Towards the distribution and size of muscle force, there is a big difference between the patients and the normal human. Analyzing the rehabilitation treatment process based on the movement characteristics of the normal human, it causes a negative impact. In this article, the simplified musculoskeletal model is established, which only selects part of the muscles of human upper limb. As shown in Figure 4.

The muscles involved are the deltoid connected with scapula, the deltoid connected with clavicle, the long head of biceps brachii, the short head biceps brachii, the long head of triceps brachii and the short head of triceps brachii. The muscle attachment points are selected according to the
anatomical knowledge, and the quality and length parameters are consistent with the whole muscle model. The model is established by Anybody software. The establishment steps are as follows: (a) the establishment of reference coordinate system; (b) establish segmental structure connected by a joint; (c) determine the muscle attachment points (based on anatomical characteristics and corresponding adjustment), adding muscle; (d) determine the properties and elasticity coefficient of muscles; (e) add joint driving, it can connect with muscles, bones and joints according with dynamics characteristics.

3.3. The computing model of muscle force
The muscle force is generated by a muscle contraction in the muscle model. The mechanical behavior of the muscle contraction is based on the Hill muscle model. In this model, the muscle is considered as a viscoelastic and contractive material, the muscle force is mainly reflected in the active contraction unit (muscle fiber) and passive contraction unit (tendon) (Zhang & Wang, 2008), the expression is as formula (1):

\[ F = F_a + F_b = \sigma \cdot PCSA \left[ f_a(l)f_a(v)\alpha(t) + f_p(t) \right] \]  \hspace{1cm} (1)

where, \( F_a \) \( F_b \) express the active force and the passive force of muscle unit separately, \( \sigma \) expresses the maximum stress, which ranges from 30 to 100 N/cm². It is 33 N/cm² in this article. PCSA expresses the area of the muscle physiological cross section, \( f_a(l) \) means the relationship between the muscle force and the length with the active part of the muscle cell, \( f_a(v) \) expresses the relation between the muscle force and the velocity, \( \alpha(t) \) expresses muscle activation values, \( f_p(l) \) expresses the relationship between the muscle force and the length with the passive part of the muscle cell.

\[ f_a(l) = e^{\left[-40 \left(\frac{l}{l_o} - 0.95\right)^4 + \left(\frac{l}{l_o} - 0.95\right)^7\right]} \]  \hspace{1cm} (2)

\[ f_a(v) = 1.6 - 1.6e^{-1.1(\frac{v}{v_o} + 1)^2 + 0.1(\frac{v}{v_o} + 1)^5} \]  \hspace{1cm} (3)

\[ f_p(l) = 1.3 \cdot \arctan \left[ 0.1 \left(\frac{l}{l_o} - 0.22\right)^{10} \right] \]  \hspace{1cm} (4)

where, \( l \) means the total length between muscle and tendon in the process of muscle contraction, \( l_o \) means the total length between muscle and tendon in a resting state, \( v \) means muscle contraction speed.
The total length of the muscle and tendon in the process of muscle contraction is the total length of the muscle and tendon in the resting state.

This is the basic method of calculating muscle force, and also the method of calculating muscle force in musculoskeletal model, which not only includes some mechanical parameters and material parameters, but also a lot of physiological parameters. These parameters reflect the different characteristics in different muscles, which are based on the anatomical knowledge.

3.4. The wavelet decomposition and reconstruction of sEMG

At this stage, studies demonstrate that there is a certain relationship between the sEMG and muscle force (Camilleri, 2007; Lichtwark & Wilson, 2005; Thelen & Anderson, 2006). In order to find the relationship between sEMG and muscle force, the local feature analysis is very necessary. Wavelet transform has high time resolution and low frequency resolution in high frequency part and high frequency resolution and low time resolution in the low frequency part. With these characteristics, wavelet transform is more suitable for the processing of EMG signal.

The muscle also can discharge in resting condition, even if the muscle is not active, the sEMG is existing, and this sEMG is called sEMG of the resting state. The signal is usually kept in a fixed frequency range, and this is not a contribution to the muscle force. In order to analyze the change of sEMG clearly, this article uses the method of wavelet decompose and reconstruction. Firstly, the wavelet decomposition of the sEMG preprocessed is processed. This article selects the method of maximal overlap discrete wavelet transform, which can decompose the signal into different frequency bands. MODWT can extract the useful signal relate to nerve stimulation frequency, and avoid the non-related factors as least as possible. There are many factors that affect the frequency of sEMG, such as, the conduction velocity of nerve stimulation in muscle fibers, stimulation frequency, the length of muscle fiber, the shape of tendon and the electrochemical equilibrium (Hu, et al., 2010). In this article, the function of Daubechies-4 is used to decompose the sEMG into four layers.

The four layers wavelet decomposition is as formula (5) and Figure 5. Where, $V_j$ and $W_j$ respectively represent the $j$th low frequency subspace and the high frequency subspace after the $i$-layer decomposition.

$$V_0 = V_1 \bigoplus W_1$$
$$V_0 = V_{21} \bigoplus W_{21} \bigoplus V_{22} \bigoplus W_{22}$$
$$V_0 = V_{31} \bigoplus W_{31} \bigoplus V_{32} \bigoplus W_{32} \bigoplus V_{33} \bigoplus W_{33} \bigoplus V_{34} \bigoplus W_{34}$$

4. The experimental analysis

4.1. The design of experiments

In the process of the experiment, firstly determine the Marker point, as Figure 6; it designates the position of Marker point and the position of sEMG electrode. The position marked by a red circle is the position of motion marker: the position of two shoulder peak, the coracoid of elbow and the finger joint of hand. The positions of sEMG electrode are: deltoid muscle, biceps brachii muscle, triceps brachii muscle, infraspinatus muscle and pectoralis Major muscle. Each muscle was measured with 2 electrodes, two electrodes were 2 cm apart, and the center of two poles was the highest point in
the muscles measured, the poles are in line with the muscle fiber, the reference electrode attached to the forearm and far from the measuring electrode.

As the sEMG can reflect the active degree of muscle has been confirmed by many scholars, this article firstly acknowledge the theory, and no longer to demonstrate this theory, so the experiment does not need to measure subjects, only five subjects were selected, and each subject repeated the experiment with five times. As shown in Table 2, it is the information and related parameters of five subjects. Here, the arm length is from the finger joint to shoulder peak, the forearm length is from the finger joint to elbow joint.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Sex</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Arm length (cm)</th>
<th>Forearm length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>26</td>
<td>Male</td>
<td>170</td>
<td>70</td>
<td>66</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>Male</td>
<td>168</td>
<td>65</td>
<td>67</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>Male</td>
<td>167</td>
<td>62</td>
<td>65</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>28</td>
<td>Male</td>
<td>175</td>
<td>65</td>
<td>68</td>
<td>32</td>
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<tr>
<td>5</td>
<td>28</td>
<td>Male</td>
<td>170</td>
<td>68</td>
<td>68</td>
<td>33</td>
</tr>
</tbody>
</table>

The experiment is as follows: firstly, the shoulder of the subject is fixed; his back is closely attached to the chair back and cannot be separated in motion process, so as to ensure that the shoulder of subject is fixed in the experimental process. The initial position of the upper arm is tilted 10° relative to the horizontal plane. Blow the horizontal plane, spread out to the outside of the body, the humerus is about 105° relative to the chest plane in the initial state, the angle is 130° in the terminate state. The initial position of forearm is about 170 degrees relative to elbow, the angle is 90° in the terminate state, and the natural state of hand is 20° downward rotation.

In the course of the experiment, the subjects listened to the password and moved with a constant velocity according to the specified motion curve. The experiment was divided into two groups, each group measured three times; the subject accomplished the experiment in accordance with the specified curve and speed. In order to guarantee the integrity of the information acquisition, the time of acquisition is 7 s. The sampling frequency of Marker is 100 Hz, each Marker all has the position information of axis X, Y and Z, and the accuracy is 1 mm. According to the experimenter command, the
subjects did the motion, and the motion information and the sEMG were collected. The data was recorded in the Excel files. The information collected totally in 24 groups, each group is $12 \times 700$ points, and the sEMG is $5 \times 2,100$ points.

4.2. The motion sEMG analysis

After data processing with above theory, the motion information can be obtained, as shown in Figure 7, it is the data processing of the experimental object, it can be seen from the perspective of the subjects, the movement is still relatively stable, the subjects try to keep an even speed, but from the microscopic point of view, the angular velocity changes dramatically, it is convenient to establish the relationship between the motion and the sEMG, even though the velocity change is very small. It can also be seen that the acceleration changes with small range. Towards the angular velocity and angular acceleration, which is more closely related to the sEMG, it concludes after contrastive analysis.

As shown in Figure 8, it is the diagrams of the wavelet decomposition and each layers reconstruction of triceps sEMG. The blue line means the approximation coefficient signal. In subsequent four figures, they express respectively the reconstructed signal from the first to the fifth layer. Because the signal of the muscle activity is mainly concentrated in the high frequency part, the low frequency part is removed, and using the detail signal of 1–3 layers to reconstruct.

4.3. The comparative analysis between reconstructed sEMG and motion information

From a macro point of view, the muscles which drive the forearm to bend are biceps and triceps. As shown in Figure 8(a) and (b), the diagrams express the sEMG of the wavelet decomposition and reconstruction respectively for biceps brachii and triceps brachii. As shown in Figure 8(c–e), they respectively express angle, angular velocity and angular acceleration of the elbow joint motion.

In Figure 9, the triceps have little effect on the movement, its sEMG is very weak, it is not as expected to plays an important role in motion. However, even if the sEMG is so weak, it also can reflect certain motion information. Within 1 s, the motion has not yet to start; the sEMG amplitude is large, after the motion beginning, the sEMG amplitude decreases, but the change of amplitude increases obviously. In 2 s, the acceleration changes dramatically, the amplitude of the sEMG doesn’t change obviously before and after 2 s. The motion angle changed dramatically also can see the sEMG in response to this. In 2 and 3 s, the velocity diagram appears large fluctuation, at the same time, the sEMG has sharp fluctuations. When the angular velocity and angle acceleration fluctuate, the sEMG also changes dramatically in the corresponding moment, and the amplitude increases obviously. While the mutation of the velocity and acceleration, it is not evident on the sEMG. From these diagrams, this motion of elbow has certain influence to the triceps, but the amplitude of the sEMG is weak, and the motion information is not good expressed with sEMG. On both sides, the motion of flexion and extension has little impact on the triceps. In practical applications, when playing the similar the motion, the triceps can be considered to ignore.

Two driving muscle Involved elbow rotation can ignore the triceps, only left the biceps. Considering the physiology knowledge, the biceps play an important role to the motion of elbow joint. Indeed, as shown in Figures 4–7(b), the sEMG amplitude of biceps is bigger than triceps, nearly 20 times or so. The change of angular velocity and angular acceleration of elbow joint is consistent with the sEMG change of biceps, especially more obvious between angular acceleration and sEMG amplitude, they are almost consistent over time. Before 2 s, the acceleration changes little, the sEMG is weak. The angular acceleration changes dramatically around 2 s, at the same time, the sEMG has a sharp fluctuations, and it provides the power for motion. The angular acceleration reflects the size of joint torque, and reflects the muscle force directly. The wavelet decomposition and reconstruction of sEMG is consistent with the amplitude of angular acceleration. The results show that the EMG signal can directly reflect the muscle force. This is important to the analysis of human body dynamics such as rehabilitation therapy, and provides the theoretical basis for human body driving.
Figure 7. The information graph of elbow motion.

Figure 8. The wavelet decomposition of triceps sEMG.
Other several groups of experimental data all have similar characteristics. The sEMG reconstructed is a close relationship of the joint angular accelerations by a contrast between the sEMG wavelet analysis signal and motion information of two muscles. Even the sEMG of triceps is so weak, and still be able to reflect the change of angular acceleration in a certain extent. According to the direct relationship between angular acceleration and muscle force, it can be concluded that the reconstructed sEMG can reflect the change of muscle force. At the same time, as shown in Figures 4–7, the angular acceleration of the elbow is changed drastically at 2 s, and the sEMG is not synchronized with it, but the significant change occurs around 2 s. It can be seen that the sEMG does not reflects the motion signal in real time, but before and after the change of the motion. As you see, the change of sEMG is prior to the motion acceleration, namely muscle force. After the change of muscle force, there are corresponding changes.

5. Conclusion
This article mainly provides some theoretical analysis to the rehabilitation. With simplifying the upper limb, a reasonable and efficient mathematical model is established, and the Hill muscle model is used to establish musculoskeletal model. In order to confirm the relationship between sEMG and motion information and muscle force. The subjects have an experiment with the elbow joint flexion and extension, and use the electromyography collection device to collect the sEMG of biceps brachii and triceps brachii. And the motion information is processed to obtain the motion angle, angular velocity and angular acceleration. After preprocessing the sEMG, the wavelet decomposition and reconstruction is used to deal with the sEMG. The reconstructed signal is compared with the motion information, and finds the relationship between sEMG signals and elbow joint motion and muscle force. The experiment confirms the sEMG of biceps brachii can directly reflect the changes of muscle force. It is concluded that the sEMG of a single muscle can directly reflect the information of elbow joint flexion and extension.

Because of the limitation of the author’s level, there are, undoubtedly, many shortages, which need to deepen in further research.

(1) Although the simplified musculoskeletal model has a certain value, it also reflects some problems, such as: muscle force changes dramatically, each muscle has no detailed division, and roughly simplifies as a whole, it results in the forecast of muscle force has a larger deviations. With simplifying the detailed division of musculoskeletal model, it can make up for this defect.

(2) The simplified musculoskeletal model rarely considers the passive stress effect of the other muscles, which is one of the main factors of muscle force decrease, it should be considered.
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