Identification of Individual Muscle Length Parameters from Measurements of Passive Joint Moment Around the Ankle Joint*

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Abstract

In this study, we proposed a method for estimating muscle length parameters on an individual basis from measured data based on a musculo-skeletal structure with a Hill-type muscle model. Passive joint moments of the ankle were measured for 4 healthy subjects in two different knee positions, i.e., in knee flexion and extension, using manual measurement apparatus. Estimation of muscle length parameters based on measurement data from each subject was performed using a two-dimensional musculo-skeletal model of the lower limb with a Hill-type muscle model. Predicted passive joint moment properties using the estimated parameters were consistent with measured data. The estimated length parameters of muscles differed between subjects depending on their passive joint moment properties. These observations suggest that the proposed estimation method is available to identify muscle length parameters required for a quantification of ankle joint function and the musculo-skeletal model analyses on an individual basis.

Key words: Ankle Joint, Passive Joint Moment, Muscle Model, Musculo-Skeletal Model

1. Introduction

There have been many attempts to quantify lower limb joint function in human subjects to clarify human musculo-skeletal behaviors during movements, such as walking and running, or to establish indexes for the evaluation of physical abilities available for clinical rehabilitation medicine(12). The passive joint moment of the ankle is often used as a functional scale for individual ankle joints(39). Passive joint moments within the physiological range of movement are considered to be mainly generated by musculotendons complex elongation(1), although it is more or less affected by other soft tissues and bone structure surrounding the joint(4).

Many researches performed biomechanical analysis of various human motions using a typical musculo-skeletal model, in which Hill-type muscle model is commonly used for calculating muscle tension forces<sup>67</sup>. There are many parameters such as lengths, the ratio of muscle and tendon lengths, physiological cross-sectional area, pinnation angle, elastic coefficients and so on in Hill-type muscle model. Thus, to calculate muscle tension forces in each individual, these parameters must be specific to each individual. However, there have been only few works, in which individual specificity of muscle properties is considered.
Here, we propose a new method for estimating length parameters in a Hill-type muscle model, which are specific to each individual. This method consists of two steps. In the first step, experimental data on passive ankle joint moment versus ankle angle are obtained using a manual measurement apparatus. In the second step, the obtained ankle joint moment–angle relation is reproduced by a two-dimensional musculo-skeletal model of lower limb combined with Hill-type muscle model. The best reproduction of the experimental data could be achieved by setting the desired muscle length parameters.

2. Methods

Volunteers

Four healthy male subjects (age 30 ± 11.5 years, height 170.3 ± 5.2 cm, weight 61.5 ± 15.4 kg) were recruited for this study.

Measurement of Passive Joint Moment around the Ankle Joint

Applied moment against foot-shank relative angle was measured when foot was passively moved in the plantar/dorsal flexion direction around the ankle joint. Figure 1 shows the photos of the measurement apparatus, which is the same as that used in previously. The foot plate rotates against the base around the axis via movement of the handle. A torque meter (TD-050, Kubota, Osaka, Japan) mounted on the axis between handle and foot plate is used to measure the applied torque. A potentiometer (#6187, BI Technologies, Fullerton, USA) measures the foot plate angle against the base. Applied torque and the angle of the ankle joint were then simultaneously recorded on PC at 1200 Hz.

![Ankle joint assessment device](image)

(a) Top view  (b) General view

Figure 1  Ankle joint assessment device.

![Schematic representations of the two postures](image)

(a) Knee flexion  (b) Knee extension

Figure 2  Schematic representations of the two postures in which measurements were performed. (a) Knee flexion. (b) Knee extension.
To confirm that muscles around the ankle joint were not activated during the measurement, electromyograms (EMG) of the gastrocnemius (GA), soleus (SO) and tibialis anterior (TA) were measured simultaneously using surface EMG sensors (#6480731, DelSys, Boston, MA). The subject laid or sat down on the bed with the knee in two different positions, i.e., knee flexion and extension positions, as shown in Figs. 2(a) and (b), respectively. The foot was fixed on the foot plate of the apparatus by Velcro straps with adjusting foot plate height so that the ankle joint axis was aligned with rotational axis of the foot plate. Ranges of the ankle joint motion for the measurements were set depending on individual ankle joint stiffness, i.e., the standard range was set between 50˚ plantar flexion and 5˚ dorsal flexion and maximum and minimum angles for each subject were adjusted in each pretest so that the applied torque did not exceeded approximately 10 Nm. The foot plate was manually moved within the range defined in each subject by the increase or decrease of handle rotation angle at a range of angular velocity with the aid of a metronome. Here, tempo of the metronome was set for 20˚ increments or decrements per second, at which a velocity-dependent effect on passive joint moment was little in our previous work8). All subjects were tested for at least 10 cycles and 2 trials were performed.

The study protocol was approved by the ethics committee of Graduate School of Engineering Science, Osaka University and the Hyogo Institute of Assistive Technology. Also, all subjects gave written informed consent.

Musculo-skeletal Model

The musculo-skeletal model of the ankle joint consists of a two-dimensional skeletal structure and GA, SO and TA muscles, as illustrated in Fig. 3 (a). The ankle joint is comprised of two skeletal structures: the shank and the foot. They are regarded as rigid links and are connected at the ankle joint with one degree of freedom, in which plantar-dorsal motion is allowed. From the balance of momentum around the ankle joint, the equation of motion is described as

\[ I \ddot{\theta} = -(F_{GA} + F_{SO})d + F_{TA}d - Mgl \cos \theta + T \]  

(1)

where \( \theta \) is the ankle joint angle, \( F_{GA}, F_{SO} \) and \( F_{TA} \) are the muscle tension forces of GA, SO and TA, respectively, \( M, I, \) and \( l \) are the mass of the foot segment, the moment of inertia for the foot segment, and the distance between the center of gravity of the foot segment and the ankle joint for the foot part, respectively, \( g \) and \( d \) are the gravity acceleration and the lever arm length of muscles around the ankle joint, respectively, \( T \) is the moment applied externally.

![Musculo-skeletal model](image1)

(a) Musculo-skeletal model.  

![Muscle model](image2)

(b) Muscle model.

Figure 3  Schematic diagrams of (a) the two-dimensional lower limb musculo-skeletal model from the femoral part to the foot part and (b) the muscle model, which consists of muscle and tendon elements.
Each muscle model consists of three components: contractile, parallel elastic and tendon elements, as illustrated in Fig. 3 (b). Here, it can be assumed that the tension force generated by the contractile element is equal to zero. Therefore, the muscle tension force is equal to the tension force generated by the elastic element in the muscle element. As a result, the muscle tension force \( F_m \) of the \( m \)th muscle is modeled as

\[
F_m = F_{CE}^m = \left\{ \begin{array}{ll}
0.00159 \exp \left[ 5.40 \left( \frac{L_{CE}^m}{L_{CE}^0} - 1 \right) \right] - 1 & \quad \text{if } L_{CE}^m \geq L_{CE}^0 \\
0 & \quad \text{if } L_{CE}^m < L_{CE}^0 
\end{array} \right.
\]  

(2)

where \( L_{CE}^m \) and \( L_{CE}^0 \) are the length and natural length of the muscle element, respectively, and \( F_{CE}^m \) is the maximum contractile force of the contractile element. The model parameters used in this study are summarized in the Appendix, which were determined according to previous studies and anatomical charts.

**Parameter Identification for Muscle Natural Length**

We identified the "natural" angle of the ankle joint corresponding to each muscle natural length, defined as the angle at which the length of each muscle is equal to the respective natural length, i.e., there are three natural angles; that of GA, SO and TA. To estimate the natural angle for each muscle, we examined the reproducibility of passive joint moment using the musculo-skeletal model. Based on measurement data in the knee flexion position, the \( \theta_{m}^0 \) of SO or TA (\( m = \) SO or TA), which indicates the ankle joint angle when the length of the \( m \)th muscle (\( m = \) SO or TA) is equal to its natural length, was estimated using the least squares method. Similarly, \( \theta_{GA}^0 \) was calculated using the measured data in the knee extension position. Here, data within the range of the angle between maximum plantar flexion and 10° below maximum dorsal flexion were used to estimate \( \theta_{SO}^0 \) and \( \theta_{TA}^0 \), because GA may have the potential to affect passive joint moment when the dorsal angle becomes high, even in the knee flexion position.

**3. Results**

**Measurement**

Using the measured raw data of the last 5 cycles of the 2 trials in each subject, means and standard deviations are calculated in every one-degree. Figure 4 shows the measured data of passive moment versus angle of one subject’s ankle joint in the knee flexion and extension positions. Curves were drawn from the means. Plots are means and standard deviations in every 10°, and at maximum and minimum angles. Table 1 shows the neutral angle of ankle joint and the momentum gradients over the range between the neutral angle and 20° dorsal flexion from the neutral angle at each knee position for each subject. The neutral angle is defined as the angle at which the passive joint moment is equal to 0 Nm in the knee flexion position.

![Figure 4](image_url)  
Figure 4  An example of the ankle joint moment-angle relationship under passive moment (Subject 1).
Table 1  Neutral angle and gradients of angle to passive joint moment of each subject.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Neutral angle [˚]</th>
<th>Gradient in knee extension [Nm/˚]</th>
<th>Gradient in knee flexion [Nm/˚]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>–35</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>Subject 2</td>
<td>–24</td>
<td>0.15</td>
<td>0.06</td>
</tr>
<tr>
<td>Subject 3</td>
<td>–53</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Subject 4</td>
<td>–28</td>
<td>0.14</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The passive joint moment at every dorsal ankle positions was higher and the gradient was larger in the knee extension position as compared with the knee flexion position. The neutral angles differed between subjects. In subject 3, the neutral angle and the gradient in knee flexion position were much smaller than those of the other subjects.

Parameter Identification of Muscle Passive Elements

Figure 5 shows the measured (mean values of Fig. 4) and predicted data. The latter were calculated by using the set of estimated parameters, which fits the data plots of passive ankle joint moment versus joint angle of subject 1 in the knee flexion and extension positions. Tables 2 and 3 indicate the Pearson product-moment correlation coefficient $r$ between measured and estimated data for each subject, and the estimated natural angles of the ankle joint for each muscle and the estimated each muscle length, respectively.

The estimations showed good agreement with the measured data ($r > 0.969$). The estimated natural ankle angles $\theta_{GA}$ and $\theta_{TA}$ in subject 3 were much larger and smaller than those of the other subjects.

![Figure 5](image)

Table 2 Pearson's product-moment correlation coefficients $r$ between measured and predicted data of passive ankle joint moment versus joint angle for each subject.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$r$ in knee flexion</th>
<th>$r$ in knee extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>0.981</td>
<td>0.997</td>
</tr>
<tr>
<td>Subject 2</td>
<td>0.994</td>
<td>0.992</td>
</tr>
<tr>
<td>Subject 3</td>
<td>0.987</td>
<td>0.969</td>
</tr>
<tr>
<td>Subject 4</td>
<td>0.994</td>
<td>0.993</td>
</tr>
</tbody>
</table>
Table 3  Estimated natural ankle joint angles and muscle natural lengths for each subject.

<table>
<thead>
<tr>
<th>Subject</th>
<th>( \theta_{0,\text{GA}} [\degree] )</th>
<th>( \theta_{0,\text{SO}} [\degree] )</th>
<th>( \theta_{0,\text{TA}} [\degree] )</th>
<th>( F_{\text{GA}}^{\text{NL}} [\text{m}] )</th>
<th>( F_{\text{SO}}^{\text{NL}} [\text{m}] )</th>
<th>( F_{\text{TA}}^{\text{NL}} [\text{m}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>–56</td>
<td>–43</td>
<td>0</td>
<td>0.422</td>
<td>0.271</td>
<td>0.319</td>
</tr>
<tr>
<td>Subject 2</td>
<td>–65</td>
<td>–34</td>
<td>6</td>
<td>0.416</td>
<td>0.280</td>
<td>0.312</td>
</tr>
<tr>
<td>Subject 3</td>
<td>–7</td>
<td>–54</td>
<td>–25</td>
<td>0.472</td>
<td>0.261</td>
<td>0.345</td>
</tr>
<tr>
<td>Subject 4</td>
<td>–59</td>
<td>–34</td>
<td>1</td>
<td>0.420</td>
<td>0.280</td>
<td>0.318</td>
</tr>
</tbody>
</table>

4. Discussion

The passive joint moment was higher and the gradient was larger in the knee extension. These characteristics are qualitatively consistent with those in previous studies\(^3\)\(^12\). Elongation status of bi-articulation muscle over knee and ankle joints, \( i.e. \) GA, which is affected the status of knee position, may be responsible for these position-induced differences. From the musculo-skeletal parameters, it is estimated that GA is stretched when ankle angle is larger than \( \theta_{0,\text{GA}} \) at knee extension position and approx. \( \theta_{0,\text{GA}}+49 [\degree] \) at knee flexion position. Then, it is considered that differences for gradients between at two knee positions in subject 1, 2 and 4 shown in Table 1, which are 1.8-2.5 times, are caused by almost tensile force of GA. The difference for gradients in subject 3 is smaller, because the natural length of GA in subject 3 is larger than that of the others and GA of subject 3 was not stretched around neutral angle even at knee extension position. The neutral angle is considered as an angle at which moments generated by antagonist muscles are balanced. The difference of neutral angles means that the natural lengths of muscles will be different in each subject.

Passive joint moment has been often modeled as a double exponential function of joint angle\(^3\)\(^13\), which might be useful for quantification of joint stiffness in clinical case. However, such a model is not available for evaluating the joint properties that differ between individuals and the contribution of each factor to determine its individual specificity. A few works focused on identifying gastrocnemius length-tension properties by measuring ankle passive joint moment in several knee positions\(^2\)\(^12\)\(^14\) on an individual basis, showing that the muscle natural length is one of the major parameters for determining properties of passive joint moment. The mean and S.D. values of the estimated muscle natural lengths of all subject's GA is \( 0.433 \pm 0.026 \text{ m} \). The estimated value is similar with that calculated by Hoang\(^1\) (\( 0.423 \pm 0.015 \text{ m} \)) and it is considered the value is within reasonable range. We could not find out published data of the natural lengths of SO and TA. The estimated lengths of SO and TA should be also evaluated in future.

In this study, we assumed that the properties of ankle passive joint moment are dependent on the natural length of each muscle around the ankle joint. Actually, the neutral angle of the ankle joint and gradients of passive joint moment differed between individuals (Table 1), and furthermore, the model considering the individual difference in natural muscle lengths could predict well the passive joint moment (Fig. 5 and Table 2). The estimated natural ankle angles of GA and TA in subject 3 were larger and smaller, respectively, \( i.e. \) lengths of GA and TA of the subject are much larger than those of the other subjects (Table 3). These results suggest that the differences of individual passive joint moment properties in physiological range of movement can be expressed by the differences of muscles' lengths, \( i.e. \), its validate our assumption although the contribution of other parameters, which were treated as parameters common to all subjects, remained to be examined.

In vivo ultrasound measurements around the ankle joint during walking indicate that during human walking muscle-tendon elastic elements affect walking energetic efficiency\(^15\). However, there are few quantitative works based on a muscle model, which is
structurally and mechanically consistent with individual ankle joints. In order to investigate how much the muscle behaviors affect human walking motion, it is necessary to identify the elastic parameters of each muscle and develop a more appropriate and consistent muscle model. The estimation method proposed here, which combines the musculo-skeletal model with the in vivo measurements has potential to contribute to the better understanding of human walking motion.

The ankle joint stiffness of post stroke hemiplegia patients tends to become higher than that of normal subjects. In order to prevent the plantar flexion posture in the ankle joint during a swing phase of walking, ankle-foot orthoses (AFOs) are often prescribed and used as an assistive device in hemiplegia patients’ daily living. New AFOs with various functions have been developed in this decade. However, it is not clear what functions of AFOs are favorable for each individual hemiplegia corresponding to his/her own symptoms. The precise mechanisms underlying the higher ankle joint stiffness in hemiplegia are not clearly understood, although muscle and neuronal characteristic changes, such as shortening, stiffen, spasm etc. or mixture of them, are likely to be involved. At this moment it is difficult to apply the method proposed in this study to the evaluation of hemiplegic ankle joint function. In order to propose more effective rehabilitation training or functions of assistive device, quantitative validation on how and how much these muscle characteristic changes contribute to ankle joint function has to be done by multidiscipline approaches including not only musculo-skeletal mechanical and structural studies but also studies based on neuronal and anatomical observation and modeling.

5. Conclusion

The method for estimating individual muscle length parameters from measurement data was proposed. The static passive joint moment properties of ankle joint were measured using the manual measurement apparatus in 4 subjects in the knee flexion and extension positions. The measured data were basically consistent with those in previous works. By assuming that the properties of ankle passive joint moment differ between individuals owing to the individual differences of natural lengths of muscles around the ankle joint, muscle length parameters were estimated using the two-dimensional musculo-skeletal model of lower limb with Hill-type muscle model. It is shown that predicted passive joint moment properties using the estimated parameters were in good agreement with the measured data and the estimated lengths of muscles differed between subjects depending on their passive joint moment properties. These results suggest that the proposed method have the potential to be used to identify the individual natural lengths of muscles which are required for the quantification of passive joint moment properties of ankle joint as a function of ankle joint and musculo-skeletal analyses on an individual basis.

Acknowledgments

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References

Appendix

The parameters used in this study are summarized in the following equations and tables. Tension force in the tendon element of muscle model $F_{m}^{T}$ was given by:

$$F_{m}^{T} = \overline{A}_{m} \{ a \cdot \varepsilon_{m} + b \} \quad (A.1)$$

where the subscript $m$ indicates the $m$th muscle, $\varepsilon_{m}$ is the strain applied in the tendon element, $\overline{A}_{m}$ is the cross-sectional area of the tendon, and $a$ and $b$ are constants dependent on the ranges of $\varepsilon_{m}$, as described below.

- $a = 10, b = 0$ for $0 \leq \varepsilon_{m} < 0.005$,
- $a = 360, b = -1.75$ for $0.005 \leq \varepsilon_{m} < 0.010$,
- $a = 700, b = -5.10$ for $0.010 \leq \varepsilon_{m} < 0.015$,
- $a = 1200, b = -12.6$ for $0.015 \leq \varepsilon_{m} < 0.080$.

Mass $M$, momentum of inertia $I$, and distance between the ankle joint and the position of center of gravity of foot segment $l$ were calculated from the followings:

$$M[kg] = (-0.26784 + 2.61804L_{\text{shank}} + 0.00545W + 0.463)/2 \quad (A.2)$$

$$I[kg \cdot cm^2] = -38.9258 + 214.578L_{\text{shank}} + 0.01445W + 0.390 \quad (A.3)$$

$$l[m] = 0.405L_{\text{shank}} / 4 \quad (A.4)$$

where $L_{\text{shank}}$ [m] is the length of the shank segment and $W$ [kg] is the subject's weight.

Table A1  Parameters of musculo-skeletal structure.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of shank segment [m]</td>
<td>0.246 [m]</td>
</tr>
<tr>
<td>Distance between muscle attachment point and ankle joint [m]</td>
<td>0.312 [m]</td>
</tr>
<tr>
<td>Lever arm of knee joint [m]</td>
<td>0.036 [m]</td>
</tr>
<tr>
<td>Lever arm of ankle joint (d in eq.1) [m]</td>
<td>0.066 [m]</td>
</tr>
</tbody>
</table>

* $h$ [m] is the subject's height

Table A2  Parameters used in the present muscle model

<table>
<thead>
<tr>
<th>Muscle</th>
<th>$F_{m}^{CE}$ [N]</th>
<th>$\overline{A}_{m}^{T}$ [mm²]</th>
<th>$\overline{T}<em>{m}^{CE} / \overline{T}</em>{m}^{MT}$</th>
<th>$\overline{L}<em>{m} / \overline{L}</em>{m}^{T}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>1605</td>
<td>20</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>SO</td>
<td>2830</td>
<td>17</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>TA</td>
<td>1140</td>
<td>20</td>
<td>0.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>