Supplemental material for the validation of the neuromuscular model developed for the triceps surae

The purpose of this supplemental material is to provide additional data regarding the validation of the neuromuscular model developed for the triceps surae. Previous papers from our group provide comparisons between experimental data and a series of model parameter values and results from simulations with the purpose of model validation. Here, additional comparisons are given between model-based parameters or simulation-based quantifiers and the corresponding experimental data (either from the literature or from our experimental measurements). The data cover motor unit (MU) twitch parameters, relations between MU force and MU firing rate, MU recruitment behaviors, and EMG envelope power spectra, with a specific focus on the triceps surae (TS) muscle group.

Motor unit twitch parameters

MU twitch peak amplitudes and twitch contraction times (see Table 1) were based on the study by Garnett et al. (1979) for the Gastrocnemius muscle. For the SOL muscle, twitch peak magnitudes were adjusted so that the contribution of the SOL muscle to the maximum voluntary plantar flexion torque was compatible with the available data (see Table 2). In addition, twitch contraction times for SOL MUs were estimated so that the simulated twitch contraction time for the whole TS muscle was compatible with the experimental data (see Table 3 and Figure 1).
Table 1 Motor unit twitch properties. Experimental are based on the work by Garnett et al. (1979)

<table>
<thead>
<tr>
<th>Twitch peak magnitude</th>
<th>SOL</th>
<th>MG</th>
<th>LG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>N.A</td>
<td>0.04 – 2.00 N</td>
<td>0.04 – 2.00 N</td>
</tr>
<tr>
<td>Model</td>
<td>0.03 – 3 N</td>
<td>0.015 – 2.15 N</td>
<td>0.015 – 2.15 N</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Twitch contraction time</th>
<th>Experimental</th>
<th>SOL</th>
<th>MG</th>
<th>LG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>N.A</td>
<td>50 – 110ms</td>
<td>50 – 110ms</td>
<td>50 – 110ms</td>
</tr>
<tr>
<td>Model</td>
<td>84-170ms</td>
<td>25 – 110ms</td>
<td>25 – 110ms</td>
<td>25 – 110ms</td>
</tr>
</tbody>
</table>

*TS muscle twitch contraction time*

The values of TS twitch contraction time and ½ relaxation-time obtained experimentally (Dalton et al., 2009) and from the model are in Table 2. An example of the model TS twitch is shown in Figure 1.

**Table 2** TS muscle twitch contraction time

<table>
<thead>
<tr>
<th></th>
<th>Contraction-time</th>
<th>½ relaxation-time</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS (Dalton et al., 2009)</td>
<td>122 ms</td>
<td>217 ms</td>
</tr>
<tr>
<td>Model</td>
<td>98 ms</td>
<td>207 ms</td>
</tr>
</tbody>
</table>
Figure 1 Model TS contraction-time 100 ms and ½ relaxation-time 207ms. Obtained simulating a stimulus that recruited all MUs from the three motoneuron pools.

*Percentage of contribution of each muscle to the maximum isometric maintained plantarflexion Torque*

Experimental results based on the literature were obtained by Oliveira and Menegaldo, (2010) by estimating the physiological cross-sectional area from ultrasound imaging, multiplied by the muscle specific tension (from Wickiewicz et al., 1983) and (Friederich and Brand, 1990). Simulated results were obtained by using 400 homogeneous independent Poisson point processes with 4 ms mean ISIs to drive the MN pools.
Table 3 Percentage of contribution of each muscle to maximum plantarflexion torque

<table>
<thead>
<tr>
<th></th>
<th>Experimental (Oliveira and Menegaldo, 2010)</th>
<th>Obtained with the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOL</td>
<td>63.2%</td>
<td>68.7%</td>
</tr>
<tr>
<td>MG</td>
<td>23.8%</td>
<td>21.8%</td>
</tr>
<tr>
<td>LG</td>
<td>13.0%</td>
<td>9.4%</td>
</tr>
</tbody>
</table>

**MU force vs. MU firing rate relations**

MU force responses to different trains of stimuli for a single type S MU are presented in Figure 2. For a stimulus frequency of 20 Hz the type S MU force was already saturated. This can also be seen in Figure 3. In this Figure the MU isometric force is plotted as a function of stimulus frequency. The saturation frequency is different for each MU type (20 Hz for type S, 45 Hz for type FR and 80 Hz for type FF).

Superimposed responses to trains of stimuli at different frequencies for a single type S MU

![Figure 2](image2.png)

Figure 2 Type S MU force. Stimulus frequency varied from 0.1 Hz to 110.5 Hz (step of 1.6 Hz).
**MU isometric force as a function of stimulus frequency, for the three types of MUs**

![Graph showing MU isometric force as a function of stimulus frequency for three types of MUs: S, FR, and FF.](image)

**Figure 3** MU mean force levels for different stimulus frequency for the three types of MUs. Frequencies of saturation were based on Enoka and Fuglevand (2001) and were used to define the parameter \( c \) in formula (5) of the main text.

**MU recruitment behaviors**

Figure 4 shows total plantar flexion torque (upper panel) and raster plots for the MUs of the SOL muscle (lower panel) during a triangular activation (10 s up and 10 s down) of the MN pools of the TS muscle. MUs are recruited up to \(~100\%\) of MVC for the three muscles (i.e. SOL, MG and LG), which is compatible with experimental data reported elsewhere (Oya et al., 2009).
Figure 4 Plantarflexion torque as a percentage of MVC (upper panel) for a triangular activation of the MN pools. Lower panel shows the corresponding SOL spikes. MUs are recruited until 100 % MVC is reached, as reported by Oya et al., (2009).

Figure 5 shows the firing rates of 10 randomly selected MUs of the SOL muscle. It is noteworthy that the “onion skin” phenomenon (De Luca and Hostage, 2010) is reproduced in the neuromuscular model.
Figure 5 Discharge behavior of 10 randomly selected MUs. The onion skin phenomenon is observed in the simulated data as reported in experimental studies (De Luca and Hostage, 2010)

**EMG envelope power spectra**

Figure 6 shows the EMG envelope power spectrum at three different contraction levels. The power spectra computed from the simulated data (thick lines) are in accord with the experimental power spectra (thin lines) computed from the data obtained in our experiments at three different torque levels.
Figure 6 EMG envelope spectra computed from simulated data (thick lines) and experimental data from subjects (thin lines) at three torque levels (A) 10% MVC, B) 50% MVC and C) 80% MVC).
References


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