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)

		SOL	MG	LG
Twitch peak magnitude	Experimental	N.A	0.04 – 2.00 N	0.04 – 2.00 N
	Model	0.03 – 3 N	0.015 – 2.15 N	0.015 – 2.15 N
Twitch contraction time	Experimental	N.A	50 – 110ms	50 – 110ms
	Model	84-170ms	25 – 110ms	25 – 110ms

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

	Contraction-time	½ relaxation-time
TS (Dalton et al., 2009)	122 ms	217 ms
Model	98 ms	207 ms

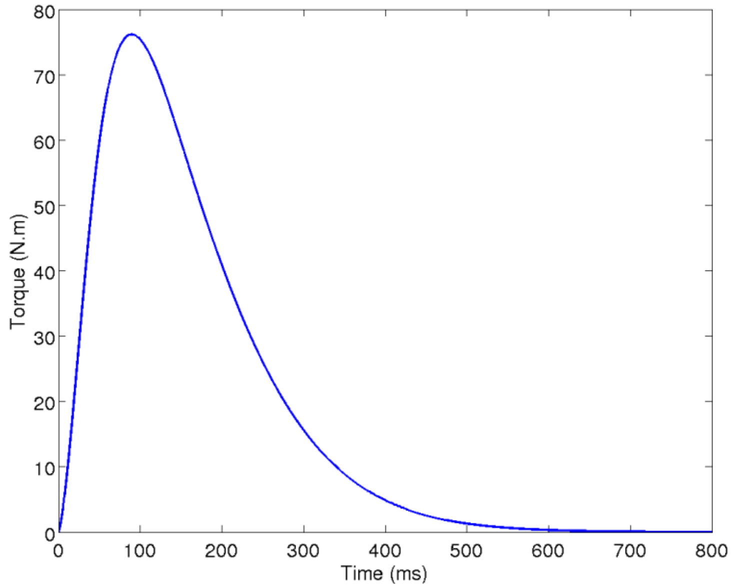

Figure 1 Model TS contraction-time 100 ms and ½ relaxation-time 207ms. Obtained simulating a stimulus that recruited all MUs from the three motoneuron pools

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

	Experimental (Oliveira and Menegaldo, 2010)	Obtained with the model
SOL	63.2%	68.7%
MG	23.8%	21.8%
LG	13.0%	9.4%

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

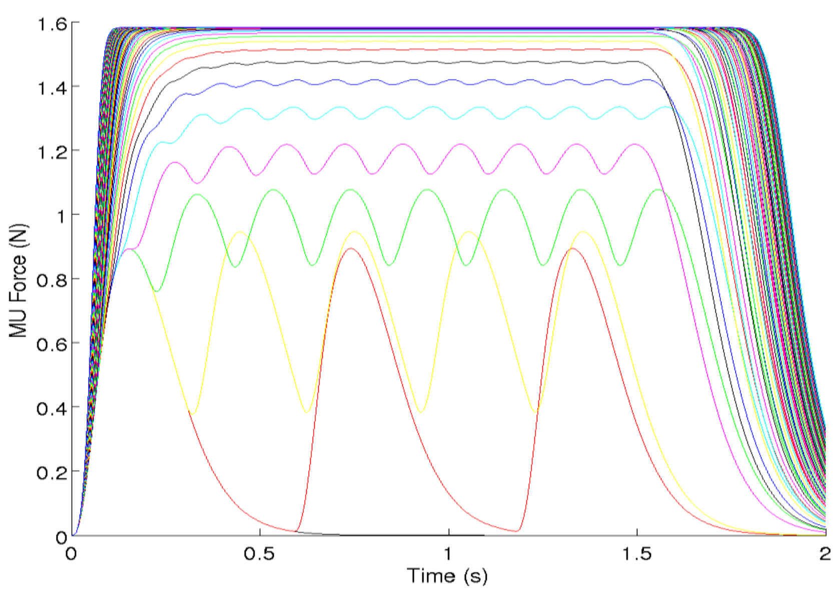

Figure 2 Type S MU force. Stimulus frequency varied from 0.1 Hz to 110.5 Hz (step of 1.6 Hz).

MU isometric force as a function of stimulus frequency, for the three types of MUs

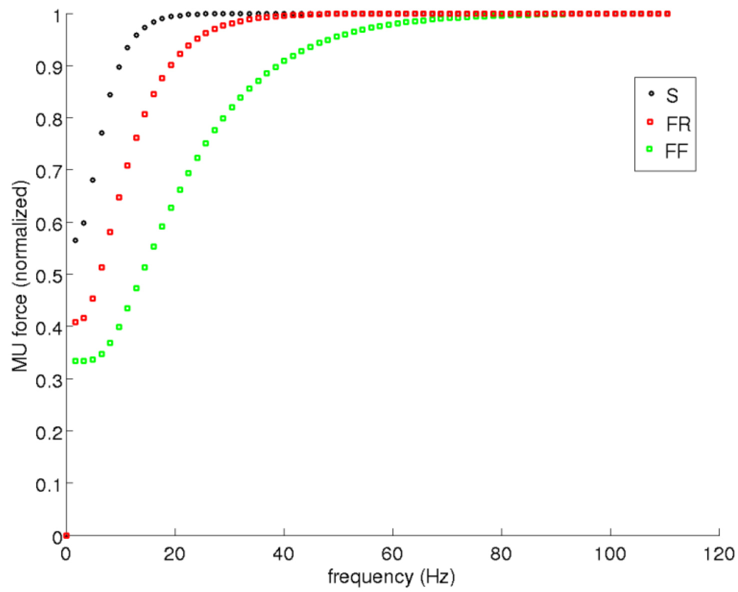

Figure 3 MU mean force levels for different stimulus frequency for the three types of MUs. Frequencies of saturation were based on Enoka and Fuglevand (2001) **and were used to define the parameter *c* in formula (5) of the main text.**

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).

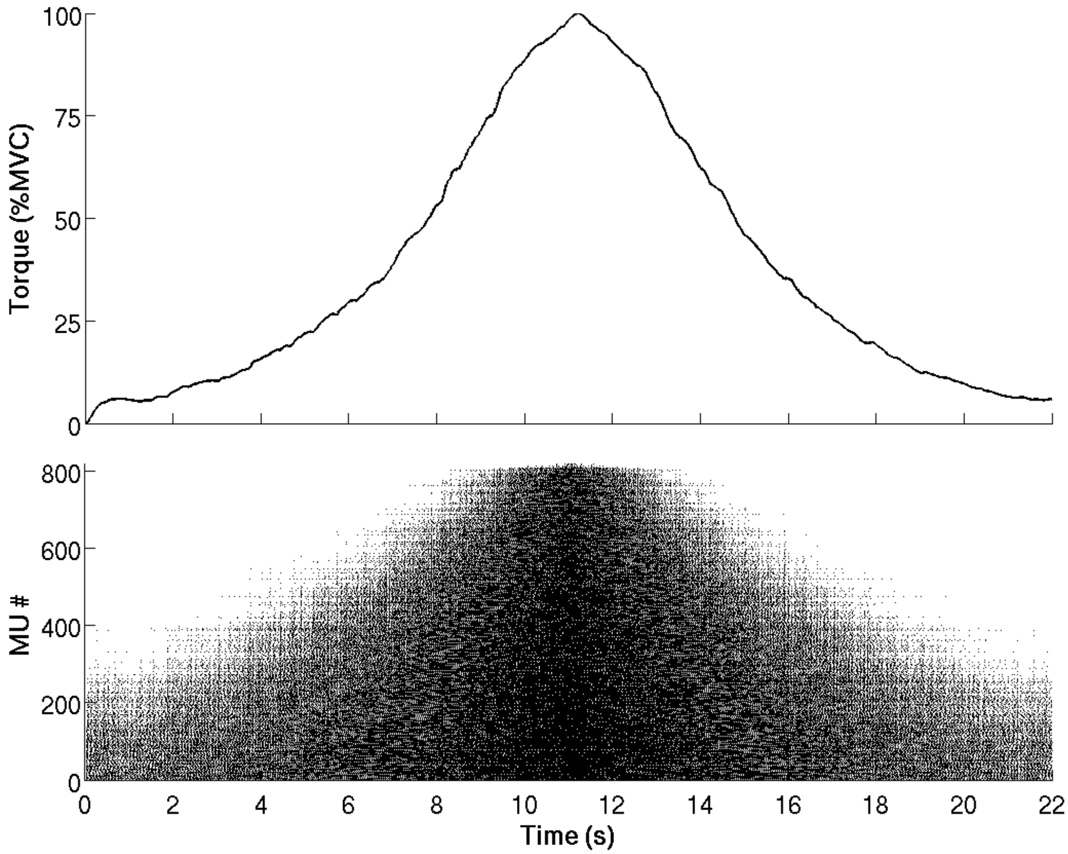

Figure 4 Plantarflexion torque as a percentage of MVC (upper panel) for a triangular activation of the MN pools. Lower panel shows the corresponding SOL spikes. MUs are recruited until 100 % MVC is reached, as reported by Oya et al., (2009)**.**

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.

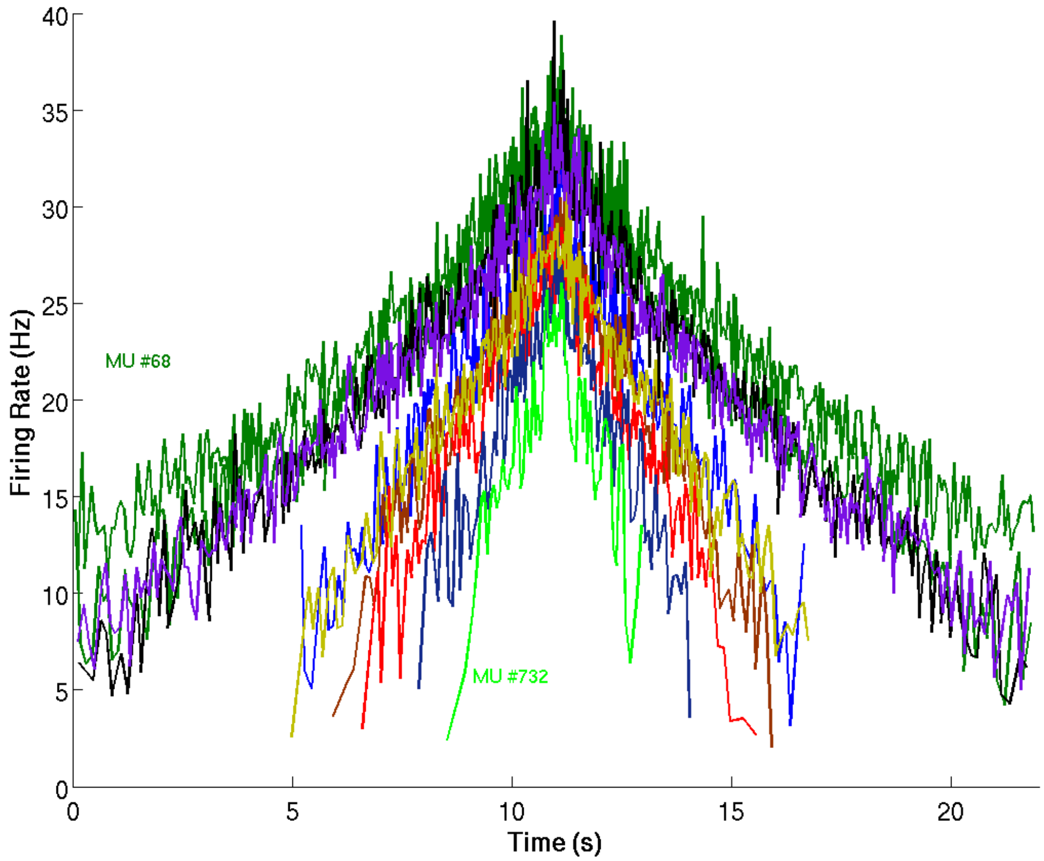

Figure 5 Discharge behavior of 10 randomly selected MUs. The onion skin phenomenon is observed in the simulated data as reported in experimental studies (De Luca and Hostage, 2010)

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

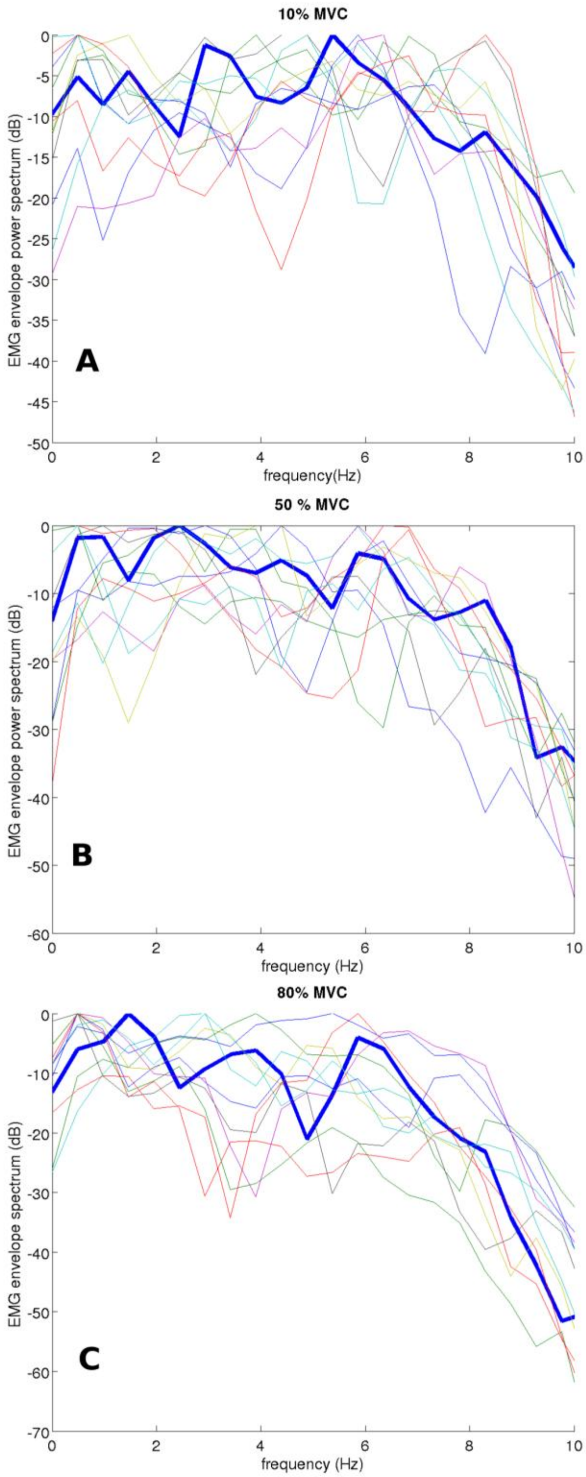

Figure 6 EMG envelope spectra computed from simulated data (thick lines) and experimental data from subjects (thin lines) at three torque levels (A) 10% MVC, B) 50% MVC and C) 80% MVC).

References

Dalton BH, Harwood B, Davidson AW, Rice CL. Triceps surae contractile properties and firing rates in the soleus of young and old men. *Journal of Applied Physiology* 107: 1781–1788, 2009.

Enoka RM, Fuglevand AJ. Motor unit physiology: Some unresolved issues. *Muscle & Nerve* 24: 4–17, 2001.

Friederich JA, Brand RA. Muscle-Fiber Architecture in the Human Lower-Limb [Online]. *Journal of Biomechanics* 23: 91–95, 1990. <Go to ISI>://A1990CQ50200011.

Garnett RAF, Odonovan MJ, Stephens JA, Taylor A. Motor Unit Organization of Human Medial Gastrocnemius. *Journal of Physiology-London* 287: 33–43, 1979.

De Luca CJ, Hostage EC. Relationship between firing rate and recruitment threshold of motoneurons in voluntary isometric contractions. *Journal of Neurophysiology* 104: 1034–1046, 2010.

Oliveira LF de, Menegaldo LL. Individual-specific muscle maximum force estimation using ultrasound for ankle joint torque prediction using an EMG-driven Hill-type model [Online]. *Journal of Biomechanics* 43: 2816–2821, 2010. <Go to ISI>://000284343700024.

Oya T, Riek S, Cresswell AG. Recruitment and rate coding organisation for soleus motor units across entire range of voluntary isometric plantar flexions. *The Journal of Physiology* 587: 4737–48, 2009.

Wickiewicz TL, Roy RR, Powell PL, Edgerton VR. Muscle architecture of the human lower-limb [Online]. *Clinical Orthopaedics and Related Research* : 275–283, 1983. <Go.

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