XXIV CONGRESS OF THE INTERNATIONAL SOCIETY OF BIOMECHANICS
XV BRAZILIAN CONGRESS OF BIOMECHANICS

A Two Step Muscle/Tendon-Length Calibration in Musculoskeletal Models

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SUMMARY
It is very difficult or even impossible to obtain data from different muscle parameters in vivo. This is a problem when dealing with subject specific modeling. Therefore, a two-step calibration sequence was developed to adjust tendon and muscle lengths based on a given range of motion. An increase in muscle force production area was observed as well as a change in optimal fiber length and tendon slack length.

INTRODUCTION
In musculoskeletal models Hill-type muscle models are the most common [1]. These models consist of a contractile element (CE), parallel elastic element (PE) and a series elastic element (SE). The SE and PE are characterized by nonlinear relations. The CE is modeled by the force/velocity and force/length characteristics.
This type of muscle models have been shown to be very sensitive towards the tendon slack length (Lt_0) and optimal muscle fiber length (Lf_0) [2]. These muscle parameters are often based on data from morphologic studies, however this pose some issues when trying to analyze muscle forces from subjects that deviate from the specimen. Van den Bogert et al. 1998 suggested that a “hybrid” approach should be implemented in such a manner that some muscle properties are derived from morphological data while others by fitting the model to subject-specific data [1].
The AnyBody Modeling System (AMS) is a text-based inverse dynamic modeling system [3]. The AMS currently adjusts the Lt_0 by assuming optimal fiber length (full tensional force) at a given joint angle. By assuming this it is possible to adjust the length of the tendon to the specified position. However, by making this assumption the operating range on the force-length curve will change when scaling the model. This will be reflected in movements in the outer range of the range of motion.

A different approach was proposed by Garner and Pandy, where two parameters were estimated (Rmin, Rmax) the working ratios of the minimum and maximum fiber length normalized with respect to the optimal fiber length [4]. By estimating the joint angle and corresponding ratios the Lt_0 and Lf_0 could be calculated.

The aim of this study is therefore to develop and analyze the effects of a two-step calibration (based on the study of Garner and Pandy) that implements a given range of motion and corresponding Rmin and Rmax thereby adjusting optimal fiber and tendon slack lengths. Furthermore, the effects on the muscle force-length curve of the ankle dorsal/plantar flexor muscles will be analyzed.

METHODS
A musculoskeletal model consisting of 26 rigid segments and over a hundred muscles was implemented in the AMS (Anybody Technology A/S, Aalborg, Denmark).
One male subject (body mass: 62 kg, height: 1.73 m) was used.
A two-step calibration study was developed adjusting the Lf_0 and Lt_0 according to the given range of motion and anthropometrics which was scaled according to Damsgaard et al. 2006. A calibration was performed for each leg for all degrees of freedom resulting in twelve calibration sequences (Table 1). The range of motion was based on mean data from a study conducted by Roaas and Andersson 1982 [5].
The muscle working ratios were set to Rmin 0.5 and Rmax 1.2. This was based on the assumption that Rmax and Rmin represented the position in the range of motion where the muscle was respectively elongated and contracted the most voluntarily prior to passive resistance was experienced. Assuming that the range of motion used in the model corresponds with the Rmin/Rmax value it is then possible to adjust the Lf_0 and Lt_0.
The exact same gait trail was then calibrated with the original one-step calibration for comparison.
Furthermore, a series of isometric strength tests were performed for the larger muscles for both the one-step and two-step calibration muscles thereby illustrating the strength characteristics during a given range of motion.

RESULTS AND DISCUSSION
The two-step calibration resulted in longer Lf_0 and a shorter Lt_0 for all muscles except tibialis anterior (Table 2). Performing the two-step calibration increased the area in which the muscle was able to generate force in compare to the one-step (Figure 1 and 2).

In this study a range of 0.5-1.2 was used which agrees with the more physiological view stated by Zajac 1989. He stated a range of 05-1.5 as a more general physiological range [6]. However, it is not possible in vivo to determine the position corresponding to 1.5, since this would be just before rupture of the muscle-tendon unit.

Table 1: Calibration angles for the different muscle groups. [a] hip angle -10, [b] hip angle 90, [c] knee angle 90, [d] knee angle 0.

	Two-step calibration	
Muscles	**Rmin calibration angle**	**Rmax calibration angle**
Hip extensors	-10	120
Hip flexors	120	-10
Hip abductors	40	-30
Hip Adductors	-30	40
Hip interal rotation	-15	15
Hip External rotation	15	-15
Knee flexor	120[a]	0[b]
Knee extensor	0[a]	120[b]
Ankle plantar flexor	-30[c]	40[d]
Ankle dorsal flexor	40[d]	-30[c]
Subtalar eversion	30	-30
Subtalar inversion	-30	30

Changing these ratios has effects on the muscle force production during a certain joint angle as illustrated in figure 1 and 2. It can be argued whether 1.2 is an appropriate estimate or if a higher or lower value would be more suitable. However, in this study we find it reasonable to assume that 1.2 would be just prior passive resistance is felt. Furthermore, the plantar flexor muscles have lost most of their force generating capacity at full plantar flexion for the one-step calibration which does not seem realistic while toe-off in a gait trail is located in this range of motion. This method is not ideal while the normalized muscle length-tension ratios are not known for all the different muscles hence care should be taken when selecting appropriate ratios. However, van den Bogert et al. 1998 suggests that the muscle ratios and tendon slack length should be fitted to the subject rather than using an optimal fiber length from cadaver studies. The two-step calibration seems therefore to be a better estimate than the one-step.

Table 2: Selected i*nvolved muscles: Semitendinosus (SD), Biceps femoris (BF), Rectus femoris (RF), Vastus lateralis/medialis (VL) (VM), Soleus lateralis/medialis (SL) (SM), Gastrocnemius lateralis/medialis (GL) (GM), Tibialis anterior (TA), Extensor digitorum longus (EDL). Optimal fiber lengths and tendon slack lengths.*

	One-step calibration		Two-step calibration	
Muscles	**Tendon slack length (cm)**	**Optimum fiber length (cm)**	**Tendon slack length (cm)**	**Optimum fiber length (cm)**
SD	35.50	14.11	25.55	25.49
BF	31.01	8.50	23.32	24.81
RF	28.52	7.81	23.76	13.05
VL	27.99	9.08	26.91	12.11
VM	17.43	8.27	15.46	12.09
SL	29.91	4.41	28.37	7.75
SM	26.41	4.40	25.40	6.89
GL	43.29	5.69	38.66	11.33
GM	43.24	6.02	38.82	10.90
TA	30.31	6.84	31.19	5.27
EDL	45.22	6.01	44.30	6.75

The estimations made in this study were purely based on theoretical assumptions and should be kept in mind.

Compared to measurements reported in other literature the optimal muscle fiber lengths for GL and GM proposed in this study are longer [7].This could be due to the assumptions made in this study regarding the normalized fiber length ratios or the range of motion. However, it could also be due to the nature of the aponeurosis of the triceps surae that it is very difficult to measure Lf_0 correctly both in vivo and vitro.

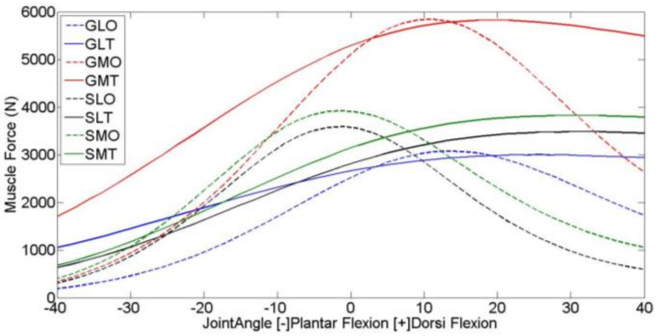

Figure 1: *Isometric muscle force of Gastrocnemius lateralis/medialis (GL, GM), Soleus lateralis/medialis (SL, SM) for the one and two-step calibrations respectively (O, T).*

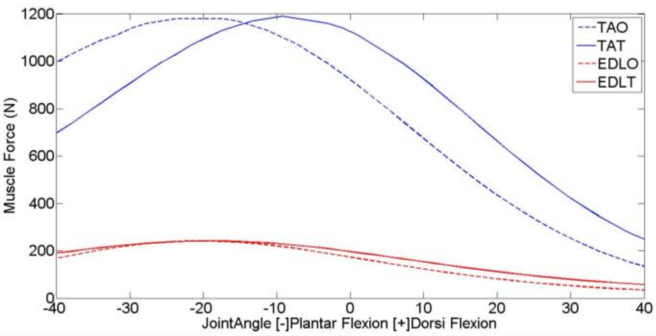

Figure 2: *Isometric muscle force of Tibialis anterior (TA) and Extensor digitorum longus (EDL) for the one and two-step calibrations respectively (O, T).*

CONCLUSIONS

It is possible to create a two-step calibration where the subjects' range of motion and the normalized length-tension relation is incorporated. This is however a preliminary study and further investigation and validation are needed in order to implement this method finally.

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