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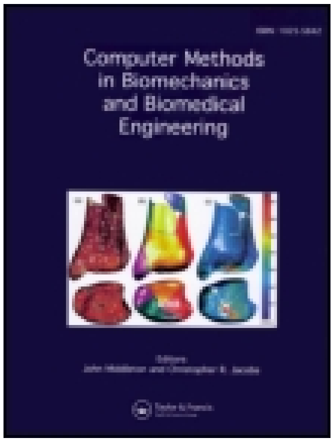

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Biomechanical model of the ankle to estimate the musculotendinous forces during an isometric plantar flexion

S. Bennour [a] , N. Zarrouk [b] , M. Dogui [b] , L. Romdhane [a] & J.-P. Merlet [c]

[a] Laboratoire de Mécanique de Sousse, École Nationale d'Ingénieurs de Sousse , 4054 , Sousse , Tunisia

[b] Unité de Recherche Neurophysiologie de la Vigilance, de l'Attention et des Performances, Service d'Explorations Fonctionnelles du Système Nerveux, CHU Sahloul , Sousse , 4051 , Tunisia

[c] Equipe de Recherche COPRIN, INRIA , Sophia Antipolis , 06902 , France

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Keywords: biomechanical ankle model; plantar flexion; musculotendinous forces; electromyography; optimisation

1. Introduction

The determination of musculotendinous forces generated in the joints during a person's daily activity has been investigated by several researchers (Cholewicki and Mcgill 1994). This biomechanical study has several applications in many fields such as medicine, ergonomics and rehabilitation.

Modelling the human joint musculotendinous apparatus can help prevent the onset of diseases, improving the ergonomics of work tools, or preventing the risk of injury associated with movements or sports techniques. To determine these forces, it is possible to make a direct measurement (*in vivo*) of muscle forces. These techniques were tested on animals (Jinha et al. 2006); however, they are not widespread in humans (Kursa et al. 2005). These experiments are indeed heavy and they require surgery. Most of the research in this field relies on models based on Hill's model presented in 1938 (Hill 1938). These models usually involve three parameters: muscle fibre length, velocity of contraction and muscle activation. The muscle activation may be correlated with the electromyography (EMG) recording.

In this work, we will be interested in presenting an improved model of the human ankle. This joint is of a primary importance in daily activity. Due to the complexity of the muscular system of the ankle, several models were proposed in the literature (Nigg and Herzog 1999), but these models took into account only a limited number of muscles. Indeed, the experimental validation of these models uses EMG measurements, which are usually performed on a very limited number of accessible surface muscles. Moreover, some authors presented a simplified geometry of the ankle and they neglected the pennation angle (Scott and Winter 1991). The effect of the contraction speed is also neglected in the works of others (Maurel and Thalmann 1999).

In this work, we are interested in estimating the level of musculotendinous forces in the ankle using an optimisation technique with an experimental validation.

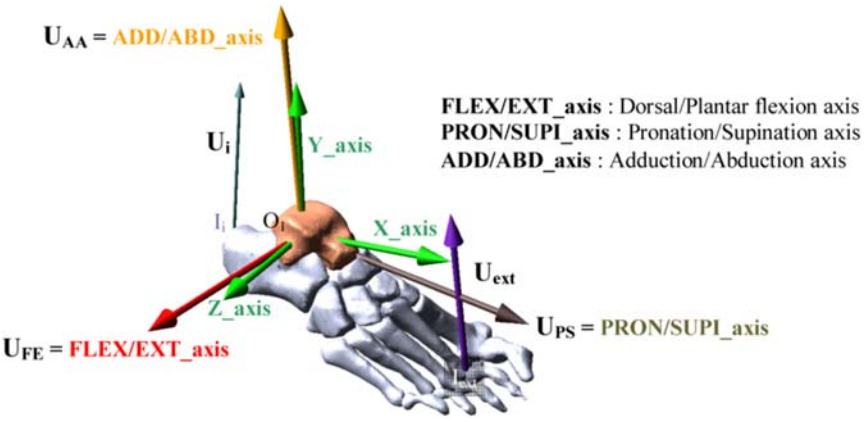

Figure 1. Musculotendinous forces, insertion points and ankle's centre.

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*Corresponding author. Email: sami.bennour@enim.rnu.tn

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2. Biomechanical model

To determine the musculotendinous forces for different muscles recruited during the plantar flexion, we constructed a biomechanical model of the ankle involving the skeletal structure and the different muscle groups performing the movements of this joint. The presented CAD model is built under ADAMS 12 (Figure 1). The equilibrium of the ankle joint under an external force applied at the tip of the foot can be written as:

$$\left(\sum_{i=1}^{8} 0_1 I_i \times F_i\right)_{\mathrm{PF}} = (0_1 I_{\mathrm{ext}} \times F_{\mathrm{ext}})_{\mathrm{PF}}, \tag{1}$$

where, I_i is the insertion point of muscle i. F_i is the force in muscle i. F_{ext} is the external force applied to the tip of the foot in point I_{ext}. The unknowns in these equations are the

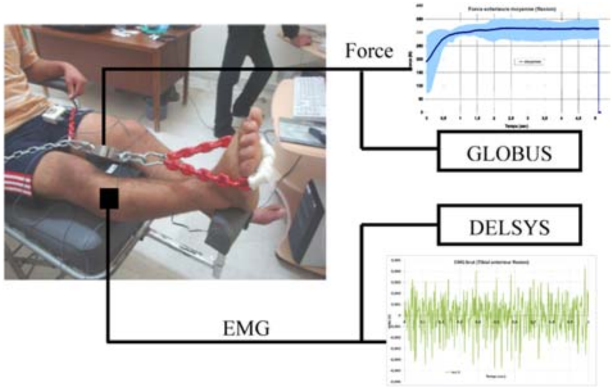

Figure 2. Experimental set-up. The recording of EMG MEDGAS, symbolised here by a black square, was made using the DVR station DELSYS. The recording of force signals was achieved using the acquisition system GLOBUS.

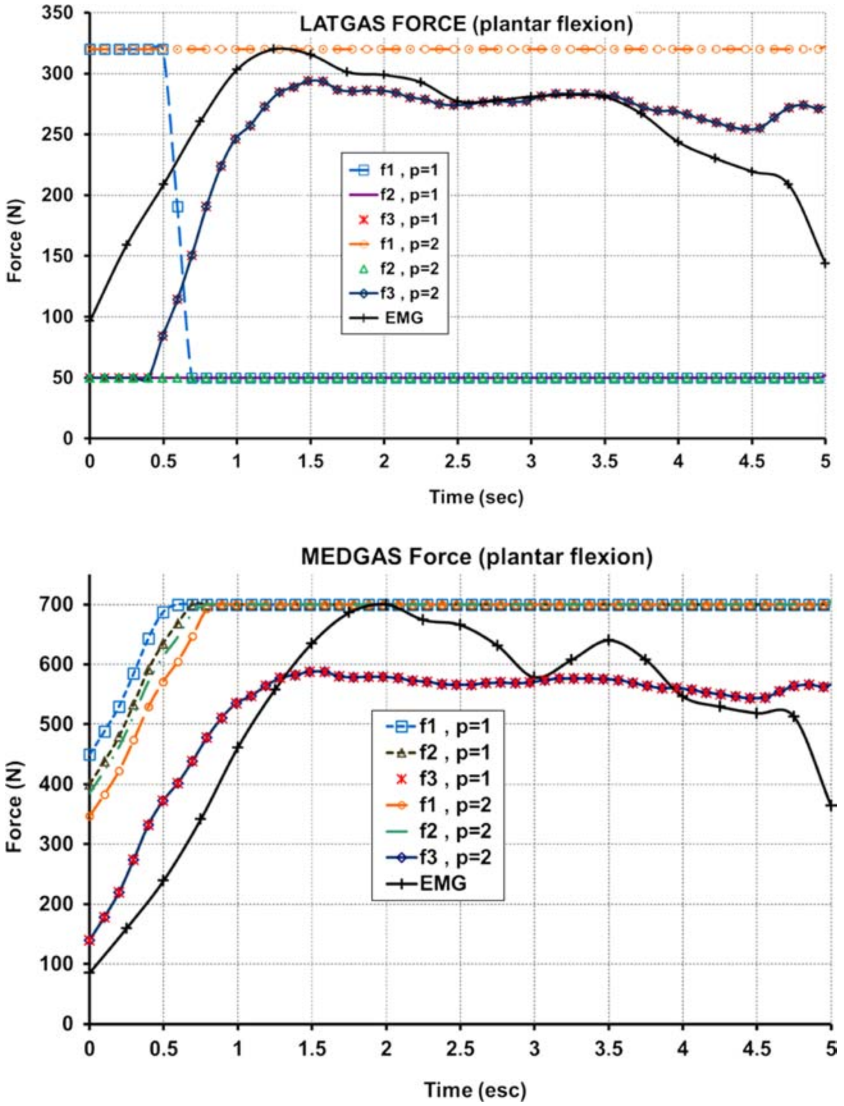

Figure 3. Muscle forces obtained through measured $\mathrm{EMG}_{\mathrm{RMS}}$ signal in comparison with those obtained by optimisation for LATGAS and MEDGAS muscles.

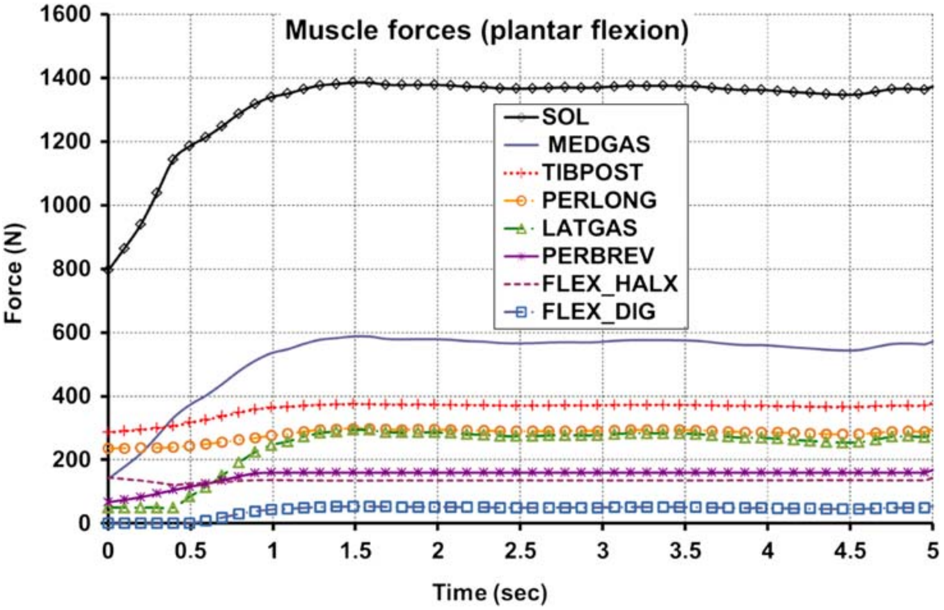

Figure 4. Muscle forces using f_3 as objective function.

muscle forces F_i. The insertion points, I_i, correspond to two muscle groups performing the motion plantar flexion of the foot relative to the leg. Each muscle produces an applied force at the tendon insertion point I_i, $i = 1, \ldots, 8$ if plantar flexion, and having a direction along the vectors $\mathbf{U}_i$ (Figure 1).

In this work, the musculoskeletal model of the ankle is made of eight flexor muscles for a single degree of freedom in rotation. Therefore, there are an infinite number of combinations of musculotendinous forces and moments to counterbalance the external force. Mathematically, one needs to solve three scalar equations with eight unknowns, which yield an infinite number of solutions. Therefore, we will apply an optimisation technique to find a solution that minimises a physiologically meaningful objective function to find an optimal solution to the problem. The objective function aims to identify the way human body recruits the muscle fibres to produce a given task. The most common ones are the sum of muscular forces, $f_1 = \sum_{i=1}^{8} (F_i)^p$, the sum of stresses in the muscles, $f_2 = \sum_{i=1}^{8} (F_i/A_i)^{\mathrm{p}}$, and the normalised sum of muscular forces, $f_3 = \sum_{i=1}^{8} (F_i/(F_i)_{\max})^p$, where '$p$' represents the exponent of the objective function: $p = 1$ linear, $p = 2$ quadratic, $p = 3$ cubic.

The optimisation problem can be stated as follows:

$$\text{Minimise} f(\mathbf{X}) = [F_1, F_2, \ldots, F_{N_{\text{var}}},] \tag{2}$$

$$\text{subject to} : h_j^*(F_i, F_{\text{ext}}) = 0, \quad j = 1, \ldots, 3 \quad \text{and} \\ (F_i)_{\min} \leq F_i \leq (F_i)_{\max}, \tag{3}$$

where, $f(\mathbf{X})$ is the objective function to be minimised. $\mathbf{X}$ is the vector containing all the musculotendinous forces. N_{var} has the value of eight in case of plantar flexion. $h_j^*(F_i, F_{\text{ext}}) = 0, \quad j = 1, \ldots, 3$ are the three constraint equalities given by Equation (1). They represent the equilibrium around the axes $\mathbf{U}_{\text{FE}}$; $\mathbf{U}_{\text{PS}}$ and $\mathbf{U}_{\text{FE}}$. $(F_i)_{\min}$ and $(F_i)_{\max}$ are, respectively, the lower and upper limits of the forces in the muscles.

3. Experimental set-up

The aim of this experiment is to load the ankle of a person and measure simultaneously the external force, using a load cell, and the activity of some muscles, using EMG measurements (Figure 2).

4. Results and discussion

Figure 3 illustrates the musculotendinous forces for the LATGAS and MEDAGAS muscles obtained experimentally by integrating the EMG^{RMS} signals and the forces given by solving the optimisation problem using different objective functions.

Comparing the results obtained by optimisation using the three functions tested (f_1, f_2, and f_3) to those calculated using the measured EMG^{RMS} signals, for the LATGAS and MEDAGAS muscles, shows clearly that f_1 and f_2 produce forces that are not comparable to those obtained experimentally (Figure 3). Using the f_3 objective function yields better results that are closer to the experimental results. (For linear ($p = 1$) and quadratic ($p = 2$) optimisation methods). The muscle forces obtained by the procedures of nonlinear optimisation ($p = 2$) under constraints are the closest to the force obtained through the measured EMG$^{\mathrm{RMS}}$ signal. Therefore, the objective function that will be used to find all the forces in all the muscles is $f_3 = \sum (F_i/(F_i)_{\max})^2$. Figure 4 shows the values of the musculotendinous forces of the FLEX-DIG, FLEX-HALX, LATGAS, MEDGAS PERPREV, PERLONG, SOL and TIBPOST in the case of plantar flexion of the ankle.

5. Conclusions

An improved biomechanical model of the ankle and the muscle groups involved to ensure the balance of the plantar flexion of the ankle under an external load was presented. Due to the high number of muscles involved in the ankle joint, the problem of solving for the muscle forces was presented as an optimisation problem. Several objective functions were tested, and an experimental procedure was required to identify the most adequate one. This experimental procedure was limited to the measurement of only two muscles, due to the problem of accessibility. The built biomechanical model, however, allowed us to quantify the forces in all eight muscles involved in the plantar flexion of the ankle. We showed that there are three to four muscles that are highly active while the rest have little contribution in this task.

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