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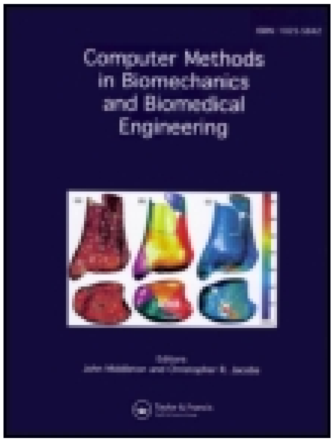

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Validation of optimisation model that estimates the musculotendinous forces during an isometric extension of knee

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Keywords: biomechanical knee 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 (Jinha et al. 2006). 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 (Herzog and Leonard 1991); however, they are not widespread in humans (Kursa et al. 2005). These experiments are indeed heavy and require surgery. Most of the research in this field relies on models based on Hill's model presented in 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 are interested in estimating the level of musculotendinous forces in the knee using an optimisation technique along with an experimental validation.

2. Methods

For extension, the isometric force recovered at the instep is the result of an eccentric contraction of four extrinsic flexors: Vastus intermedius (VASINT), Vastus lateralis (VASLAT), Vastus medialis (VASMED) and Rectus femoris (RECFEM). To determine the musculotendinous forces for different muscles recruited during the extension, we constructed a biomechanical model of the knee involving the skeletal structure and the different muscles performing the movements of this joint (Figure 1). In this work, an external force is applied at the tip of the tibia and its effect on the different muscles actuating the joint is studied. The equilibrium of the knee joint under an external force applied at the tip of the tibia yields three equations representing the equilibrium of the moments around the three axes x, y and z.

In our case, the musculoskeletal model of the knee is made of four flexor muscles for a single degree of freedom in rotation. Therefore, there are an infinite number of combinations of musculotendinous efforts to counterbalance the external force. Mathematically, one needs to solve three scalar equations with four unknowns in the case of extension, which yields an infinite number of solutions. Therefore, we apply an optimisation technique to find a solution that minimises a physiologically meaningful objective function. Several optimisation criteria have been devised for this problem. The most common criteria are:

$$f_1 = \sum_{i=1}^{4} (F_i)^p, \quad f_2 = \sum_{i=1}^{4} \left(\frac{F_i}{A_i}\right)^p, \quad f_3 = \sum_{i=1}^{4} \left(\frac{F_i}{(F_i)_{\max}}\right)^p$$

.

The objective functions to be minimised are f_1 (the sum of muscular effort; Sereig and Arvikar 1989), f_2 (the sum of stresses in the muscles; Crowninschield and Brand 1981) and f_3 (the normalised sum of muscular effort; Pedotti et al. 1978). F_i is the musculotendinous strength of the ith muscle. A_i and $(F_i)_{\max}$ are, respectively, the physiologic cross-sectional area and the maximum force of the ith muscle. p represents the exponent of the objective function.

3. Results and discussion

The objective of this experiment is to load the knee of a person and measure simultaneously the external force,

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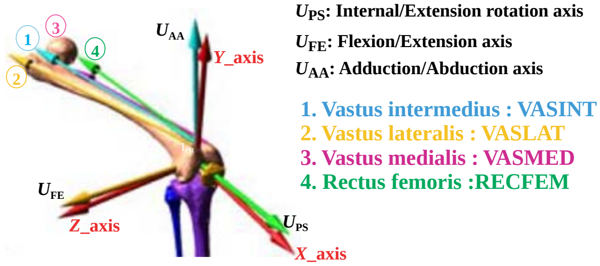

Figure 1. Different muscles for the extension motion from knee.

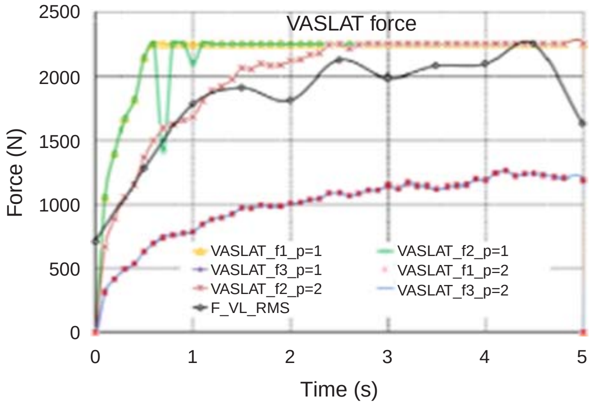

Figure 3. Muscle force of VASLAT obtained through measured EMG^{RMS} signal in comparison with those obtained by optimisation.

using a load cell, and the activity of some muscles, using EMG measurements (Figure 2).

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

Comparing the results obtained by simulation with those calculated using the measured EMG^{RMS} signals, for the VASLAT muscle, shows clearly that the linear optimisation methods ($p = 1$) produce forces that are not comparable to those obtained experimentally (Figure 3). Using the quadratic objective function ($p = 2$), however, yields better results that are closer to the experimental results. Still, among the three functions tested, only the function 'f_2' yields an acceptable value of the muscular effort of VASLAT, in the case of extension. In conclusion, the three objective functions were tested with linear ($p = 1$) and nonlinear ($p = 2$) exponents, yielding the following remarks: the use of linear criteria does not give satisfactory results because they favour muscle activity with the largest physiologic cross-sectional area or maximum force. The activation of another muscle is obtained only when the muscle reaches its physiological limit $\left((F_i)_{\max}\right)$. Therefore, the objective function that will be used to find all the forces in all the muscles is f_2. Figure 4 shows the values of the musculotendinous forces of the VASINT, VASLAT, VASMED and RECFUM in the case of extension of the knee. In this case also, there is one muscle that is the most active with forces around 2250 N, i.e. the VASLAT. A second muscle, VASMED, has forces around 900 N. The third is the VASINT, which develops a force of 500 N. The last muscle, i.e. RECFEM, develops a

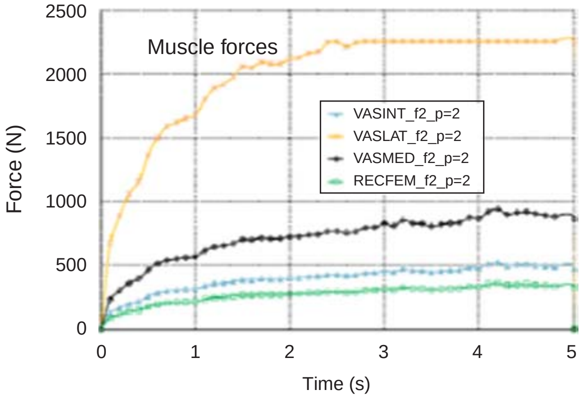

Figure 4. Musculotendinous forces obtained by simulation for extension test by f_2.

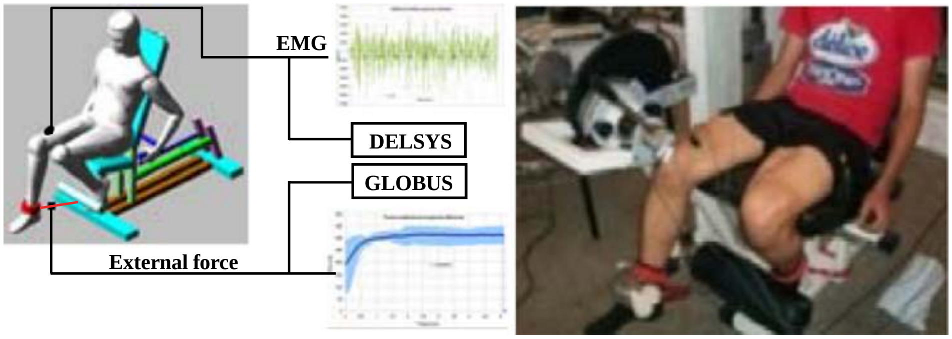

Figure 2. Experimental set-up. The recording of EMG signal, symbolised by a black square, was made using the DELSYS station. The recording of force signals was achieved using the acquisition system GLOBUS.

force of only 300 N. This analysis showed the role of each muscle in balancing an external force on the tibia.

4. Conclusions

An improved biomechanical model of the knee and the muscle groups involved to ensure the balancing of the extension of the knee joint under an external load. Due to the high number of muscles involved in the knee 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 best objective function. This experimental procedure was limited to the measurement of only one muscle, due to the problem of accessibility. The built biomechanical model, however, allowed us to quantify the forces in all the four muscles involved in the extension of the knee.

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