IN VIVO MEASUREMENT OF STIFFNESS AND VISCOSITY OF SURAL TRICEPS

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The purpose of this study is the evaluation of the stiffness and viscosity of a particular muscle-tendon complex (MTC), the Surae Triceps (ST). The knowledge of these properties is essential for assessing and monitoring the physical condition of an athlete or sportman. A measurement procedure based on the free vibration technique, assuming that a part of the body behaves as a one degree of freedom system, has been developed to obtain the aforementioned properties. The apparent properties of MTC are obtained adjusting the experimental record of a force to a theoretical record assuming a one degree of freedom system. Assuming a Hill model for the behaviour of the muscle, the knowledge of these apparent properties leads, by a fitting procedure, to obtain the separate values of these properties for the soleus and the Achilles tendon.

KEY WORDS: Muscle-Tendon Complex, Viscous-elastic properties, In-vivo properties measurement.

INTRODUCTION: The high level of professional sport leads to coaches and technicians to control all variables that may affect the performance of players and sportmen. One way to control the level of subject's response is to examine a body part involved in most movements: the back of the lower leg, i.e. the ST.

Although there are five groups of muscles influencing the plantar flexion, the ST is primarily responsible for it, its contribution being estimated by some authors till a 88% approximately.

From the anatomical point of view, the ST is formed by the Gastrocnemius, oriented to generate movement, the Soleus, a postural muscle, and finally, the Achilles tendon, in series with both. To analyze the mechanical behavior of the ST, it will be represented by a simple mass-spring-damper system, whose behaviour is determined by two parameters: stiffness and viscosity.

The aim of the research carried out is to determine these two parameters to use them to monitoring and evaluating the fitness level of a subject.

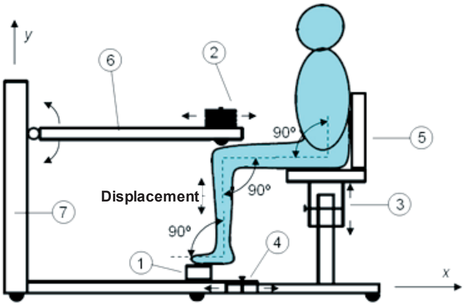
A brief review of the relevant proposals for the estimation of both variables indicates that basically there are two types of proposals: Methods on cadavers and on in vivo subjects. The present study is based on the second group, in the line of the procedures developed by Fukashiro et al, 2001, and by Babic & Lennarcic, 2004.

METHODS: The procedure developed is based on the assumption that the MTC under consideration, the ST, may behave, under adequate conditions, as a system of one degree of freedom (dof) with dumping. A detailed description of the whole procedure, foundations, results and discussion can be found in Paris-Garcia, 2010.

The way to allow the ST to behave as a system of one degree of freedom is described in Figure 1, which shows a scheme of the device developed based on the proposal of Fukashiro et al 2001.

As can be observed from Figure 1, the forefoot of the subject is simply supported on an area measuring device (1). The subject is required to maintain the equilibrium, after having placed a weight (2) on the knee. This weight helps in accentuating, increasing the mass of the leg involved in the movement, the behaviour of the system as a single degree of freedom one.

The subject adopts a position to maintain 90-degree angles at hip, knee and ankle, as shown in Figure 1, movements associated to devices (3) and (4) allowing these requirements for any morphological features of the subject. Rigid support (5) constitutes a limit to prevent front and back movements of the top of the body, in order to not alter the force recorded by the measurement device (1). Finally, (6) and (7) correspond respectively to the beam that allows the weight to be properly applied and to the frame that must be rigid enough to avoid non desired vibrations.



1. Load cell.
2. Impact device.
3. Height adjustment device.
4. Depth adjustment device.
5. Rigid back.
6. Simply supported beam.
7. Frame.

Figure 1: Scheme of the device developed to allow the ST to behave as a single dof system.

Having the knee joint in the neutral position (90º) shown in Figure 1, the gastrocnemius does not work because its origin is located in the heads of the femoral condyles.

Once all parameters of the machine have been adjusted, the subject maintains the position previously described. The application of an impulsive load on the weight unchains the vertical oscillation of the lower leg, which is assumed to behave as a single dof system.

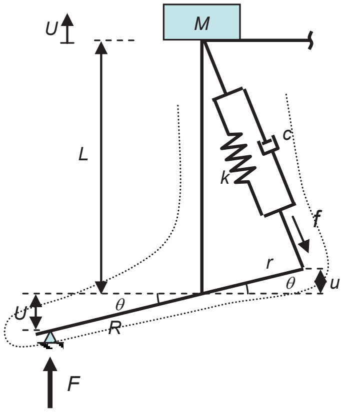


Figure 2: Simplified scheme of the system in a generic position during vibration.

Figure 2 shows the whole system at an arbitrary instant of the vibration once the impulsive load has been applied. The forefoot is resting on the measuring device where a reaction force *F*, recorded during the vibration, appears. The expression of this load, assuming a free vibration of the system after the impulsive load suffered, is:

$$F_m = F + Mg = e^{-\gamma t}(A_F sen\omega_D t + B_F \cos\omega_D t) + Mg \tag{1}$$

where F_m is the measured force that results from the addition of the vibration force *F* and the applied weight *M*.

The mass of the system, accentuated by the weight *M* applied on the knee, and the stiff character of the tibial segment, allow the rotation of the foot around the ankle articulation. The ST, represented in the figure by a spring of stiffness *k* and a damper of coefficient *c*, suffers a vertical displacement *u* that is related to the displacement *U* of the rotation point of the foot with respect the fixed point, by means of the equation:

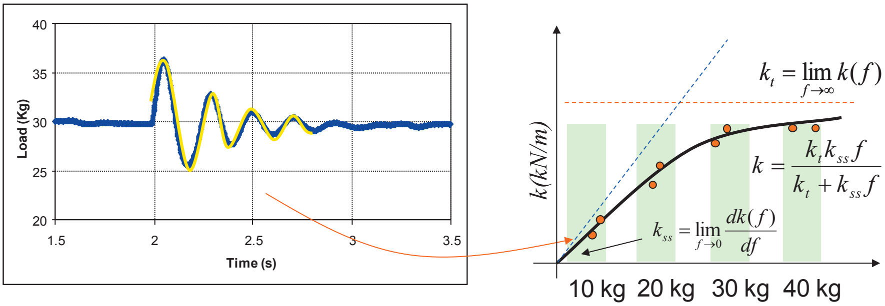
$$U = \frac{R}{r}u \tag{2}$$

where *R* and *r* are the lever arms of the foot. The force *F* registered by the load cell and the load *f* that passes along the ST, are related by:

$$F \cdot R = f \cdot r \tag{3}$$

This equation permits the value of *f* to be calculated from the value of *F* recorded.

The obtaining of the force during the test is carried out using a Labview program developed specifically for this purpose, a particular case being showed in figure 3a, where the experimental and adjusted curves are represented. The fitting is performed by means of a least square procedure, determining the values of the five parameters indicated in figure 3a. The values of these paremeters allow the values of the apparent stiffness and damping of the ST to be determined. This fitting represents the first phase of the total procedure.



$$F_m = F + Mg = e^{-\underline{\gamma} t}(\underline{A_F} sen\underline{\omega_D} t + \underline{B_F}\cos\omega_D t) + \underline{M}g$$

a)

γ= damping
A_F, B_F= constants associated with the amplitude
ω_d = vibration frequency
M = mass involved in the oscillation

$$k = \frac{k_t k_{ss} f}{k_t + k_{ss} f}$$

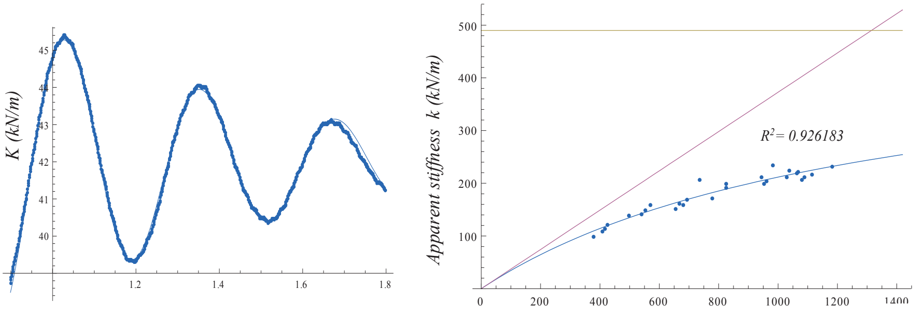
b)

kt= tendon stiffness.
kss = unitary stiffness of soleus.
f= applied force

Figure 3: Experimental signal processing: a) 1st phase: setting a damped 1dof system, b) 2nd phase: implementation of Hill model.

Once the value of the apparent stiffness has been obtained, a second phase to determine the stiffness of the Soleus and Achilles tendon is required. It is done based on Hill model. Due to the fact that stiffness of the Soleus is proportional to the mechanical stress, the developed protocol includes tests with different weights, tipically between 10 and 40 kgs.

The value of the apparent stiffness *k* is related to the values of the stiffness of the tendon k_t and the stiffness gradient of the Soleus k_{ss} as represented in figure 3b. Each test represents a point in the cloud appearing in figure 3b. Once the cloud of points obtained experimentally is fitted by a minimum square procedure, the slope at the origin gives de value of k_{ss} and the asymptote gives the value of k_t.



a)
b)

Figure 4: Results from both phases of adjustment, a) 1st phase: Obtaining apparent stiffness of ST for the right leg of one subject, experimental and fitted curve are shown, b) 2nd phase: Obtaining the stiffness values of Soleus and Achilles tendon for the right leg of a subject.

RESULTS: Figure 4 shows the results for the right leg of a subject. Figure 4a shows a typical curve of the first phase corresponding to a particular weight, including the experimental record and the curve numerically fitted. Figure 4b shows the result corresponding to the second phase having applied the full protocol of 8 weights (5, 10, 15, 20, 25, 30, 35 and 40 kg) to the subject.

DISCUSSION: Based on the inspection of the results, it seems on one hand, with reference to figure 4a, that the hypothesis done on the behaviour on the oscillating part of the human body as a single dof is correct. It is supported noticing the excellent agreement between the experimental record and the fitted curve.

On the other hand, the hypothesis of the muscle to behave in accordance with Hill model is not so clearly supported by the experiments. Although qualitatively the cloud of points can be approximated by a curve according to Hill model, the degree of dispersion found is negligible. It is obvious that it can be due to the variability of the human nature, but also to the relative simplicity of the model.

CONCLUSIONS: The equipment conceived and manufactured in conjunction with the developed protocol have proved to be adequate and coherent with the hypothesis of behaviour of the moving part of the body as a single degree of freedom system, the agreement between experimental record and fitted curve being almost unappreciable.

This excellent fitting supports the representativeness of the values obtained for the apparent stiffness of the ST.

With reference to the separate values of the stiffness of Soleus and tendon, although the values obtained can be used for comparison purposes, the results obtained open the possibility of considering more complex models of behaviour of the muscles.

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