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Evaluation of the stiffnesses of the Achilles tendon and soleus from the apparent stiffness of the triceps surae

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Federico París-García[1], Alberto Barroso[2], Manuel Doblaré[3], José Cañas[2] and Federico París[2]

Abstract

The triceps surae plays an important role in the performance of many sports. Although the apparent average mechanical properties of the triceps surae may be a satisfactory parameter for estimating the training level of an athlete, a knowledge of the mechanical properties of the individual constituents of the triceps surae (in particular the Achilles tendon and soleus) permits a more detailed and in-depth control of the effects of training from more physically based parameters. The objective of this work is therefore the estimation of the individual viscoelastic properties (stiffness and viscosity) of soleus and Achilles tendon from the apparent properties of the triceps surae obtained by free vibration techniques. Different procedures have been developed and discussed, showing a high degree of robustness in the predictions. The results obtained for a non-oriented set of subjects present a high level of variability, depending on the training conditions and anthropometric features, although the corresponding average values compare well with data previously reported in the literature, particularly those associated with the tendon stiffness.

Keywords

Achilles tendon, soleus, triceps surae, stiffness, viscoelastic properties

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Introduction

Free vibration techniques have been widely used for the assessment of musculo-articular properties. An excellent comprehensive review has recently been presented by Ditroilo et al.[1] and Faria et al.[2]

With reference to the viscoelastic properties (stiffness and viscosity) of the triceps surae (TS in what follows), París-García et al.[3] have developed and studied two devices and the corresponding methodologies to measure, in vivo, the apparent stiffness and viscosity of the TS muscle–tendon complex (MTC). These two methods, based on the free vibration technique, followed earlier proposals from Fukashiro et al.[4] and Babic and Lenarcic,[5] respectively.

The main objective of the study in París-García et al.[3] was to clarify similarities and differences between the two methods and the reproducibility, consistency and physical interpretation of the results obtained with both when applied to the same set of persons, since each approach involves a different position of the subject and consequently analyses a different movement.

The study showed that the two methods led to similar trends in the results (e.g. the subject presenting higher values with one method also presented higher values with the other), although the actual values obtained were clearly different. Thus, it was concluded that both methods are consistent in themselves, and the values obtained are useful for comparison purposes, allowing, for instance, the effect of training on a control population to be assessed. However, a sufficiently accurate quantitative correlation between both methods was not found. The key point for these conclusions was having used the same set of subjects, and two similar equipments (in terms of devices for recording data) to apply the two methods.

Independently of the method used, only the apparent properties of the TS (the properties being represented by a single stiffness and a single viscosity) were

[1]Faculty of Sport Science, University Pablo de Olavide, Seville, Spain
[2]School of Engineering, University of Seville, Seville, Spain
[3]University of Zaragoza, Zaragoza, Spain

Corresponding author:
Alberto Barroso, School of Engineering, University of Seville, Seville 41092, Spain.
Email: abc@esi.us.es

obtained in París-García et al.[3] These properties, stiffness and viscosity, may be by themselves representative to estimate, in some cases, the evolution and performance of the TS, as for instance, to track the training level after a period of inactivity (e.g. after surgery). Nevertheless, knowing the actual mechanical properties of the individual constituents of the TS can provide more detailed information about the actual capacities of an athlete and his or her training level at a certain point in training or injury recovery protocol. In this work, of the three constituents of the TS, the gastrocnemius, the soleus and the Achilles tendon, attention will be focused on the mechanical properties of the latter two (soleus and Achilles tendon).

The measurements in París-García et al.[3] which are the starting point for this work, were performed using equipments in which the knee formed 90°. With such a position of the knee, it is assumed that the gastrocnemius is too short to contribute to the global stiffness, the load being borned by the structures that do not cross the knee. This assumption was made also in similar studies carried out.[2,5] Evidence of this assumption can be found in the literature, as for instance, in Fiebert et al.[6] using electromyography (EMG) and in Li et al.,[7] where little knee flexion moment was observed at knee angles of 90°. The role of the gastrocnemius in positions different of 90° can be found in many studies.[5–7] Additionally to the former hypothesis, we are not taking into consideration the role of the plantar flexors, as is also typically done in related works.[2–5]

Springs and dampers have been frequently used in the literature to develop biomechanical models of human body, for example, Nikooyan and Zadpoor[8] and Sousa et al.[9] Following Hill's model,[10] the contribution to the TS stiffness, in the configuration under consideration in this study, of the individual stiffnesses of the soleus and the Achilles tendon, can be modelled as two springs in series. This model will be detailed in section 'Relevant aspects of Hill's model and alternatives'. The objective of this work is the estimation of the individual viscoelastic properties (stiffness and viscosity) of soleus and Achilles tendon from the apparent properties of the TS obtained by free vibration techniques.

Five procedures have been carried out in this investigation to separate the mechanical properties of the soleus and Achilles tendon from the global properties of the TS. Two of them are based on the individual stiffness values of the two constituents under analysis. The remaining three procedures are based, following an idea explored for the first time in this article, on the compliance values of the individual constituents. This latter set of procedures, as will be seen later on, allows a linear regression to be used instead of the non-linear one necessarily associated with the procedures based on the stiffness values. In this investigation, it has been observed that there is a certain influence of the fitting procedure on the final results.

Although the authors have implemented procedures for the stiffness separation for both methods described in París-García et al.,[3] for the sake of conciseness they will be applied here to only one of the methods, that used in Fukashiro et al.[4] The conclusions obtained are in any case applicable to separate viscoelastic properties of the components from the apparent values of these properties, independently of the method used to measure the apparent properties, if the same muscular model is used (see section 'Relevant aspects of Hill's model and alternatives).

As pointed out by Ditroilo et al.,[1] there is a certain number of important aspects to consider in the separation of properties, some of them being addressed in the whole study carried out by París-García and colleagues.[3,11,12] Thus, with reference to the control of the amplitude of the perturbation, the energy of the impact (mass and height of the impactor) has been controlled.[12] With reference to an accurate measurement of the moment arms of the feet, a separated investigation, with an associated publication,[11] has been carried out by the authors. The number of cycles to be used in the fitting procedure, a fact that can play a relevant role in the results, was studied in París-García et al.[3]

In section 'Methods', a brief summary of the procedure developed in París-García et al.[3] to measure the global apparent values of the stiffness and viscosity of the TS is outlined. In section 'Relevant aspects of Hill's model and alternatives', the details of Hill's model of the TS will be introduced together with some more complex alternative models. In section 'Separation of soleus and Achilles tendon mechanical properties from those of the TS', two sets of procedures have been used. A first set, including three procedures based on the stiffness values, and a second set, including two procedures based on the compliance values, are introduced. Finally, the results obtained in the different tests are presented in section 'Results', while a complete discussion with previous existing results reported in the literature is featured in section 'Discussion'.

Methods

The apparent stiffness of the muscle articular system (MAS) is associated in this work, as in previous ones,[4,5] to the apparent TS stiffness. From this value, the results of separation procedure for obtaining the individual stiffnesses of the Achilles tendon and soleus depend only on the particular constitutive model assumed for the TS.

For the estimation of the apparent TS stiffness, the oscillating part is assumed to behave as a damped single degree of freedom (DOF) system. Under this assumption, the reaction force can be expressed by (1), being measured with a load cell

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

where t is the time, F_m is the measured force at the reaction point, A_F and B_F are constants related with the amplitude of the oscillation, γ is the damping

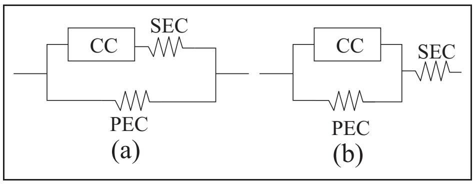

Figure 1. Schemes of two alternatives of Hill's model. CC: contractile component; PEC: parallel elastic component; SEC: serial elastic component.

coefficient, ω_D is the damped frequency and M is the mass involved in the oscillation (g is the gravity acceleration). Details about the oscillating and static masses involved in the vibration can be found in París-García et al.[3] These parameters were obtained in París-García et al.[3] by a least squares (LS) fitting procedure of the recorded data and allow the apparent stiffness k and viscosity c of the TS to be evaluated by means of the following relations[3,4]

$$c = \frac{2MR^2}{r^2}\gamma \tag{2}$$

$$k = \frac{MR^2}{r^2}(\omega_D^2 + \gamma^2) \tag{3}$$

where R and r are the forefoot and rearfoot distances, respectively. R is the distance between the second metatarsal head and the projection, on the transverse plane of the foot, of the ankle axis rotation. r is the distance between the projection of the Achilles tendon axis and the projection of the ankle axis rotation, both projections on the transverse plane of the foot. These distances have to be carefully measured due to their influence (to the power of two) in equations (2) and (3). A particular procedure for the determination of R and r, proposed in París-García et al.,[11] was used in París-García et al.[3]

Although, as mentioned, the separation process is independent of the procedure for evaluating the apparent stiffness of the TS, it was shown in París-García et al.[3] that the TS stiffnesses obtained for the same person using both equipments proposed in Fukashiro et al.[4] and Babic and Lenarcic[5] are not comparable with each other.

Thus, although the values obtained with each of these two methodologies are representative by themselves, and similar tendencies were observed in the measurements obtained with them, comparison between the values obtained with the two methodologies is not plausible. To clarify this question was one of the main objectives in París-García et al.,[3] since previous published results based on the two methodologies might be misleading on this question. The separation of the global properties of the TS in the individual constituents needs a previous understanding of the TS behaviour from a modelling point of view, which will be addressed in the following section devoted to the TS model by Hill.

Let us finally stress again that in this work the procedure suggested in Fukashiro et al.[4] has been used to get the TS apparent stiffness, although the procedure for separation of individual properties of the components of the TS is applicable to the values of the apparent stiffness of the TS obtained by any other procedure.

Relevant aspects of Hill's model and alternatives

Despite the multiple proposals to represent the dynamics of the muscles,[13] the phenomenological model based on the original ideas by Hill[10] has historically dominated the tendon–muscle complex analysis. In addition to the reasonably satisfactory results derived from its use, its simplicity and low computational cost are positive aspects of Hill's model.

There are, basically, two alternatives emerging from Hill's ideas, which are schematically represented in Figure 1. Both models have a parallel elastic component (PEC), a serial elastic component (SEC) and a contractile component (CC), the difference between the two models being the relative position of the elements inside the scheme. In the first model (Figure 1(a)), the PEC is parallel to both the CC and the SEC, whereas in the second one (Figure 1(b)) it is parallel only to the CC. The contribution of the PEC can be neglected in the oscillation movement of this study, as done in previous works (Van Ingen Schenau et al.[14] or Fukashiro et al.[4]), both alternatives in Figure 1 then leading to the same configuration.

Multiple proposals have tried to modify Hill's model, either altering the behaviour of some of the elements of the model or incorporating new elements to it. For example, Siebert et al.[15] analysed the incorporation of a non-linear behaviour in the elastic components of Hill's model, which makes the two alternatives shown in Figure 1 significantly different. Gunther et al.[16] investigated the incorporation of a dissipation element in the Achilles tendon, which appears in parallel with the elastic component, finding that its presence is crucial for suppressing the natural frequencies which typically appear in the resolution of Hill's model. A very interesting work by Winters and Stark[17] shows the benefits and drawbacks of varying the complexity of muscle–tendon models, including both Hill's and Huxley's models. Also of great interest, from a mathematical point of view, are the conclusions of the study by Scovil and Ronsky[18] in which they demonstrated that Hill's models are quite sensitive to parameter perturbations, obtaining for some constitutive parameters variations in the results much higher than those in the parameter. This is of crucial importance when performing statistical and stability analyses. In particular, the influence of at least 14 parameters in the sensitivity of different muscle systems based on Hill's models is analysed in Scovil and Ronsky.[18]

Of great importance therefore is the use of robust numerical procedures (quite insensitive to the presence of potential outliers) and techniques for fitting the experimental results to the model predicted response. The work by Ortiz et al.,[19] published in a different context, has been used in this study as a guide for defining robust regression techniques when fitting experimental data with model predictions.

Having a good idea of the range of values of the different parameters defining the individual constituents of the MTC helps to better fit the experimental data to the model results. Previous works, most of them based on in vitro studies, give, for instance, experimental values for tendons. Thus, Abrahams[20] analysed the influence of the strain rate in the tendon stiffness, Fukashiro et al.[21] used ultrasonography to obtain the stiffness of the human Achilles tendon in vivo and Sharkey et al.[22] made an interesting proposal for a testing machine allowing the measurement of the mechanical properties of the MTC. Wren et al.[23] presented an extensive experimental program of tensile testing in human Achilles tendons. Morgan[24] studied the separation of active and passive components. The range of values reported was used as a guide to start the fitting procedure, obtaining an efficient search for the optimum values of the parameters.

Separation of soleus and Achilles tendon mechanical properties from those of the TS

The separation of the soleus and Achilles tendon components from the global apparent value of the stiffness can be done, following Hill's model, by means of two different approaches: (1) using the stiffness values or (2) their inverse values, namely, the compliances. Both approaches will be explored in sections 'Procedures for separation using stiffness values' and 'Procedures for separation using compliance values', respectively.

Several procedures have been used for the two mentioned approaches, only some of them being included here for the sake of brevity. The results associated with the LS procedure have been included in both approaches to make the results obtained using it absolutely comparable. One additional procedure has been selected for each approach (trimmed least squares (TLS) for stiffness approach and minimum distance (MD) for compliance approach). Finally, a procedure (median–median line (MML)) specific for distributions that follow a straight line (the case of the approach based on compliances) has been applied.

Procedures for separation using stiffness values

The relationship between the global behaviour of the MTC and its individual constituents is schematically represented in Figure 2. Following Hill's model, with the previously mentioned assumption and neglecting the PEC contribution, the model has a spring in series with a damper. The spring includes the spring associated with the elastic behaviour of the Achilles tendon and a set of springs in parallel (in accordance with Hill's model[10]), in series with the Achilles tendon, representing the elastic behaviour of the muscle.

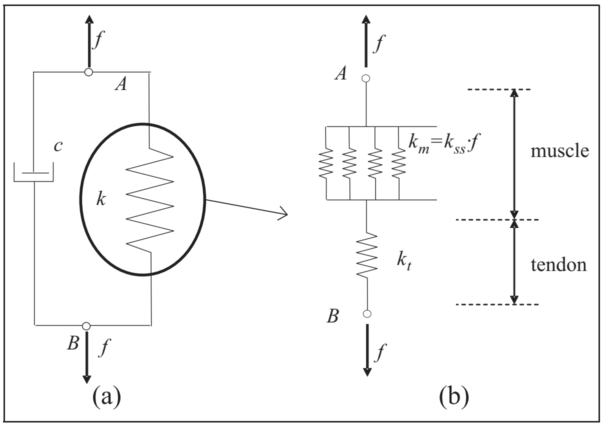

Figure 2. Triceps surae scheme: (a) apparent configuration and (b) individual constituents of the stiffness.

While the Achilles tendon is assumed to have a constant value of the stiffness (k_t), the soleus is assumed to have a stiffness (k_m) which is proportional to the load that is being transferred by the system. Thus, the total stiffness of the soleus (k_m) can be obtained from a unitary stiffness value (k_{ss}) multiplied by the total load (f), as described in passing through the MTC

$$k_m = k_{ss} \cdot f \tag{4}$$

The relationship between the apparent stiffness (k) and the individual stiffnesses (k_{ss} and k_t) can be easily obtained from Figure 2, with two springs in series. On one hand, for the apparent TS system, the elongation and the associated force are related by the apparent stiffness k by means of

$$u(k) = \frac{f}{k} \tag{5}$$

On the other hand, for the components in series, both with the same force (f), the following relation applies

$$u(k_t, k_m) = u(k_t) + u(k_m) = \frac{f}{k_t} + \frac{f}{k_m} \tag{6}$$

Identifying displacements in equations (5) and (6), in order to have an apparent behaviour, an expression of k in terms of its individual constituents (k_m and k_t) can be easily obtained, and using equation (4) in terms of (k_{ss} and k_t)

$$k = \frac{k_t k_m}{k_t + k_m} = \frac{k_t k_{ss} f}{k_t + k_{ss} f} \tag{7}$$

In equation (7), k and f are considered known (see París-García et al.[3] for example). The unknowns in equation (7) are the stiffness of the Achilles tendon and the unit stiffness of the soleus, k_t and k_{ss}, respectively. They will be evaluated by means of LS fitting between experimental data and equation (7).

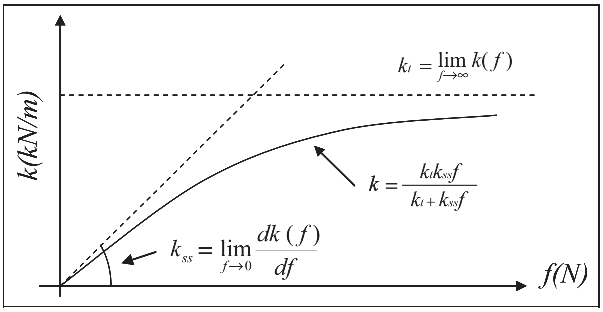

Figure 3. Graphical representation of equation (7) and meaning of k_{ss} and k_t.

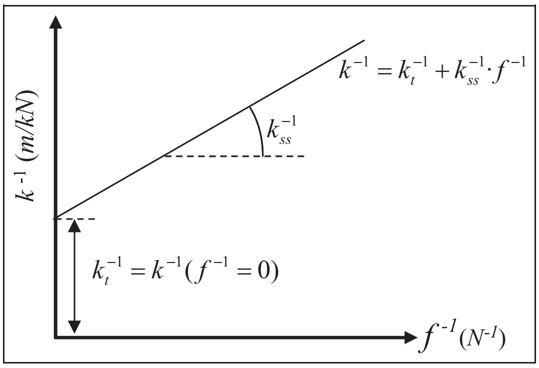

Figure 4. Graphical representation of equation (11) and meaning of k_{ss}^{-1} and k_t^{-1}.

It is important to stress that k_t and k_{ss} are unknowns of a different nature. While in the Achilles tendon k_t is a real stiffness value (measured in force/length, for example, kN/m), k_{ss} represents the stiffness per unit load in the soleus (e.g. (kN/m)/kN or simply m^{-1}). For a better physical understanding of the parameters k_t and k_{ss}, Figure 3 represents equation (7), showing the non-linear dependence of the total stiffness of the MTC (k) on the total load (f) and a saturation level for high values of f.

The stiffness per unit load in the soleus k_{ss} represents the slope of the curve at the origin

$$k_{ss} = \lim_{f\to 0} \frac{dk(f)}{df} \tag{8}$$

while the Achilles tendon stiffness k_t represents the horizontal asymptote of the curve for high values of the total force f

$$k_t = \lim_{f\to\infty} k(f) \tag{9}$$

With the two elastic elements (Achilles tendon and soleus) in series, the lower stiffness is the one that controls the apparent stiffness of the TS. With low values of the total transmitted force f, the stiffness of the soleus ($k_{ss} \cdot f$) is lower than the stiffness of the Achilles tendon k_t. Thus, the total stiffness k is controlled by the stiffness of the soleus. In contrast, at higher values of f, the stiffness of the soleus ($k_{ss} \cdot f$) is much higher than the constant value of the Achilles tendon k_t. Thus, in accordance with Hill's model, the total stiffness k is now controlled by the stiffness of the Achilles tendon k_t. Finding the experimental results close to the horizontal asymptote depends on the total stiffness that can be developed by the soleus. This fact is important as an accurate determination of both values (k_t and k_{ss}) should be carried out, having the experimental results for low and high values of f.

A difficulty inherent to the method now appears clearly defined, due to the need to perform tests close to the ideal conditions for determining k_{ss} (when f tends to 0) and k_t (when f tends to ∞). Basically, low-weight values (5 kg) do not produce a sufficiently good quality in the oscillation while high-weight values (above 35 or 40 kg) are physically difficult to maintain in the knee with the proposed configuration.

LS. In the LS method, the error function, *error* (k), to be minimized is written as

$$error(k) = \sum_{i=1}^{n} \left[k_{\exp}(f_{\exp}) - k(k_t, k_{ss})\right]^2 \tag{10}$$

TLS. A variation in the standard LS procedure is the so-called TLS, in which an iterative procedure is defined by means of an LS fitting excluding, at each iteration, the data with the worst residual (unlike in the case of the predicted analytical equation). A number of iterations around one half of the total number of data give this method a high robustness.[19]

After each iteration, a new regression line is obtained, and consequently a new list of residuals for each piece of data. The datum (only one) with the highest residual is then discarded for the next iteration.

Procedures for separation using compliance values

The inverse of equation (7) gives the relationship between the compliances of the TS (k^{-1}) and the compliances of the individual constituents, the soleus (k_{ss}^{-1}) and the Achilles tendon (k_t^{-1})

$$\frac{1}{k} = \frac{k_t + k_{ss}f}{k_t k_{ss} f} = \frac{1}{k_{ss}}\frac{1}{f} + \frac{1}{k_t} \Rightarrow k^{-1} = k_{ss}^{-1} f^{-1} + k_t^{-1} \tag{11}$$

The representation of equation (11) is a straight line (Figure 4) whose slope is the compliance of the soleus, per unit inverse load (f^{-1}) k_{ss}^{-1}, and the value at the origin ($f^{-1} = 0$) is the compliance of the Achilles tendon k_t^{-1}.

Although strictly speaking both procedures, using stiffnesses or compliances, are mathematically equivalent, the presence of a linear relation in the case of compliances allows more robust techniques to be used, specially developed for linear regression, which will be addressed in what follows. Three different fitting procedures have been analysed here: (1) one equivalent to that used (equation (10)) for stiffness values (section 'LS'); (2) one based on the minimization of distances (section 'MD') and (3) the MML approach (section 'MML').

LS. The quadratic error function, *error* (k^{-1}), to minimize is then

$$error(k^{-1}) = \sum_{i=1}^{n} \left[k_{\text{exp}}^{-1}(f_{\text{exp}}^{-1}) - k^{-1}(k_t^{-1}, k_{ss}^{-1}) \right]^2 \tag{12}$$

The results obtained using equation (12) will not necessarily coincide with those obtained using equation (10). The experimental results with the highest residuals have the highest weight in the LS fitting procedure and, if stiffness is replaced by compliance, all variables will have the inverse numerical value and thus the residuals will change.

MD. It is well known that in the presence of results which are numerically distant from the rest of the data, the use of an error function based on the minimum absolute residual, or MD, gives a better estimation than using the quadratic residual. In that case, an alternative to equation (12) is the error function $error2(k^{-1})$ expressed as

$$error2(k^{-1}) = \sum_{i=1}^{n} \left| k_{\text{exp}}^{-1}(f_{\text{exp}}^{-1}) - k^{-1}(k_t^{-1}, k_{ss}^{-1}) \right| \tag{13}$$

MML. The robustness of the median as an estimator in the presence of potential outliers, Beaton and Tukey,[25] has also led to an easier alternative, called MML, to linear regression. This proposal divides the set of data in the (k^{-1}, f^{-1}) space into nine regions, which result from the intersection of the three subsets, defined along each axis, containing the same number of data.

The medians of the subsets with the lowest and highest values of both axes define two points, respectively (f_1^{-1}, k_1^{-1}) and (f_2^{-1}, k_2^{-1}), and the following straight line in the (k^{-1}, f^{-1}) space

$$k^{-1}(f^{-1}) = \left(\frac{k_2^{-1} - k_1^{-1}}{f_2^{-1} - f_1^{-1}} \right) f^{-1} + \left(\frac{k_1^{-1} f_2^{-1} - k_2^{-1} f_1^{-1}}{f_2^{-1} - f_1^{-1}} \right) \tag{14}$$

The drawback of this procedure is that one-third of the values are not taken into account in the process. In the particular case under analysis, the excluded data may be those with the best quality, as mentioned in París-García et al.,[3] due to the fact that they have been obtained with intermediate values of the weight. Different problems were reported in París-García[12] (and also in section 'Procedures for separation using stiffness values') for tests with the highest and lowest weights.

Results

Following the previous paragraph, section 'Results using stiffness values' summarizes the results obtained using the stiffness values while section 'Results using compliance values' presents the results obtained using the alternative methods based on compliances. The LS fitting has been implemented in a program using *Mathematica*.[26]

For all approaches, using a set of data $\{(x_1, y_1), (x_2, y_2),..., (x_i, y_i),..., (x_N, y_N)\}$, to be fitted to a generic function $y^*(x)$, the basic statistical parameter used in this section is the regression coefficient R^2 $(0 < R^2 < 1)$.

Results using stiffness values

The starting point for the separation of Achilles tendon and soleus properties from those of the TS is a set of experimental list of data (f, k), where f is the force passing through the TS and k is the total apparent stiffness of the TS. These experimental results have been obtained using the methodology developed by the same authors in París-García et al.[3] in which the DOF corresponds to the vertical displacement of the lower leg. An example (for one subject) of the experimental data (f, k) which will be used in this article to apply the separation procedures is shown in Table 1, with a set of data

Table 1. Set of values (f, k) corresponding to a subject, used to apply the separation procedures.

f (N)	k (kN/m)	f (N)	k (kN/m)	f (N)	k (kN/m)
438.283	111.601	743.257	188.133	1063.99	220.050
442.067	141.105	745.767	206.140	1064.97	209.539
504.868	148.384	748.536	203.454	1054.45	216.375
502.694	147.936	849.429	193.141	1070.34	204.849
506.307	125.429	855.161	177.188	1210.85	203.584
500.163	154.790	852.990	195.085	1212.17	218.368
640.874	179.787	848.855	201.541	1214.16	226.406
641.870	195.869	965.603	218.838	1209.82	237.161
637.199	172.084	958.124	208.929	1314.83	247.453
639.068	175.483	950.517	211.187	1325.13	248.985
750.803	187.828	940.687	197.373	1322.24	251.336

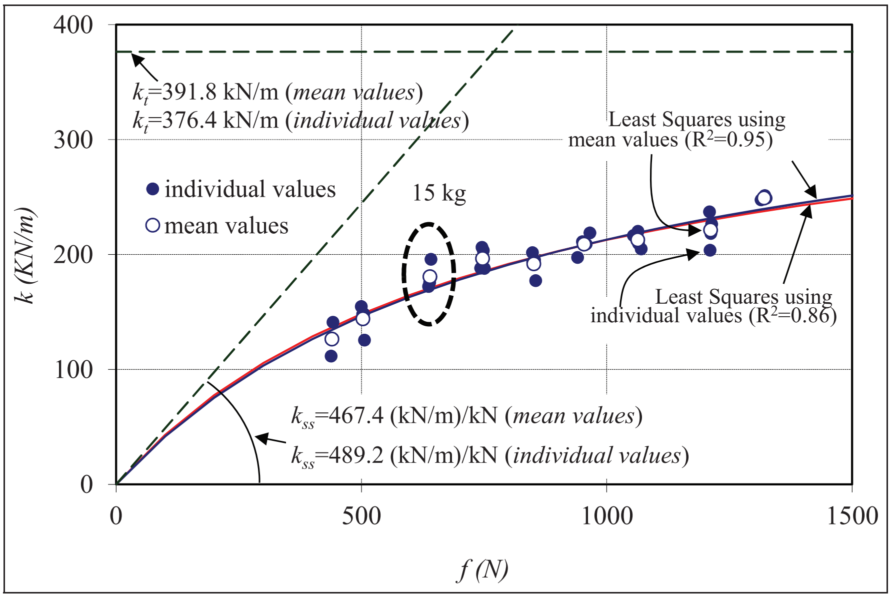

Figure 5. Stiffness (k) versus force (f) in the TS and results of least squares fitting of the Achilles tendon stiffness (k_t) and soleus stiffness per unit load (k_{ss}).

having the force f (N) and the apparent stiffness k (kN/m) values, respectively.

The Achilles tendon is assumed to behave as a single linear elastic spring. Then, considering that the gastrocnemius does not play any relevant role in the particular test under analysis (due to the 90° angle of the knee during the test), the only significant contribution to the total apparent viscosity of the TS comes from the soleus.

Figure 5 shows (for one subject) the experimental data from Table 1 together with the curve determined by equation (7) in which k_t and k_{ss} have been obtained by an LS fitting procedure, using equation (10).

The level of repeatability of the results obtained by a certain value of the weight applied was high, the coefficient of variation being lower than 9% in all cases. The values of f obtained in subsequent tests using the same load were very similar, the values of k corresponding to

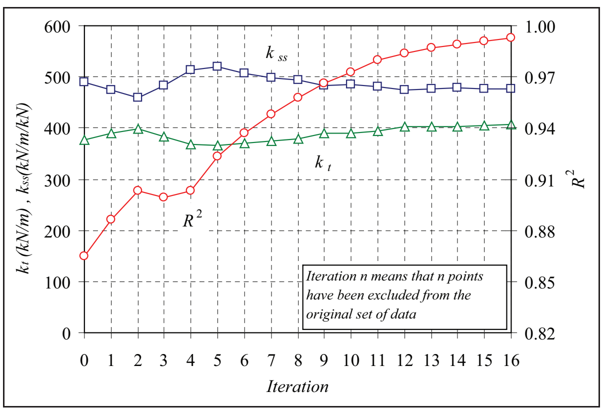

Figure 6. Results of k_t, k_{ss} and R^2 for the trimmed least squares procedure.

each weight appearing then almost in a vertical line (the results corresponding to a 15-kg weight have been circled, in Figure 5, as an indication of this fact).

Although it is normal to carry out the fitting procedure using the mean values of the results corresponding to all tests performed for each weight,[4,5] in this study the fitting will be performed both using these mean values and using all the individual values, as both approaches may lead to different regression coefficients R^2. To illustrate this fact, two fitting curves have been represented in Figure 5. As can be observed, both curves are almost coincident, but with a difference in the regression coefficient R^2, which is 0.86 for the curve fitted with all individual values and 0.95 for the curve using the mean values.

From the LS fitting procedure using all individual test data in Table 1, the following values of k_t and k_{ss} were obtained: $k_t = 376.4\,\text{kN/m}$ and $k_{ss} = 489.2$ (kN/m)/kN. When the mean values were used in the fitting process instead of individual values, the results changed slightly to $k_t = 391\,\text{kN/m}$ and $k_{ss} = 467$ (kN/m)/kN, with a 3.9% and 4.5% difference, respectively.

The TLS procedure previously defined was also applied to these stiffness values. Sixteen points were iteratively eliminated from the original data set, evaluating at each iteration a new fitting curve and a new list of residuals to eliminate the following point. Figure 6 shows the values of k_t and k_{ss} for each iteration, together with the value of R^2. After each iteration, the regression factor R^2 increases (with the exception of iteration 3), moving from an original value of $R^2 = 0.865$ with the complete set of data to $R^2 = 0.993$ for the last (16th) iteration. Figure 7 shows the first (Figure 7(a)) and 16th (Figure 7(b)) iteration results graphically. It is noteworthy that only in the first five

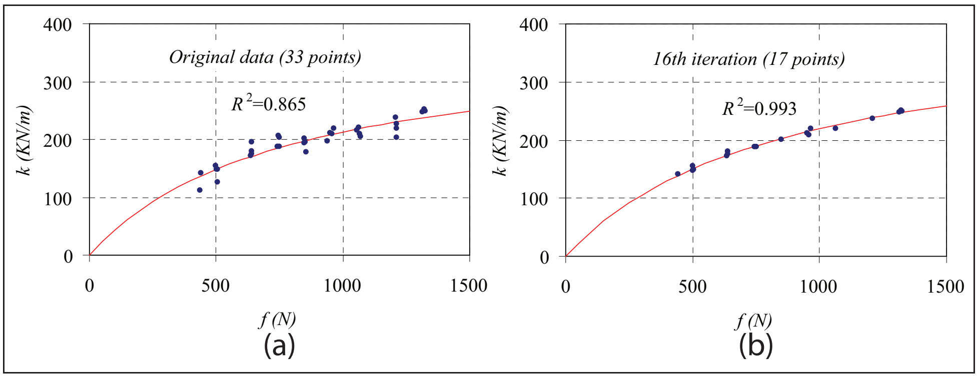

Figure 7. Fitting of experimental results in the (a) first and (b) 16th iterations of the TLS procedure.

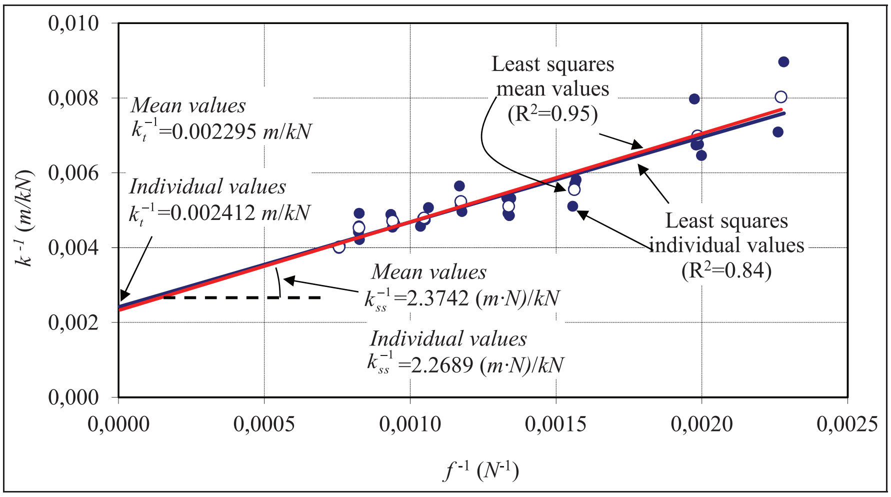

Figure 8. Least squares fitting of the Achilles tendon compliance (k_t^{-1}) and soleus compliance per unit load (k_{ss}^{-1}).

or six iterations, there are major changes in the values of k_t and k_{ss}, coinciding with the elimination of the data with larger differences to the model, after which the values remain reasonably constant.

Results using compliance values

The starting point for the separation of Achilles tendon and soleus properties from those of the TS is now the inverse values of the set of data shown in Table 1, f^{-1} (N^{-1}) and the compliance k^{-1} (m/kN).

As stated in section 'Procedures for separation using compliance values', the graphical representation of the inverse values of the set of data in Table 1 in the space (f^{-1}, k^{-1}) can now be fitted using linear regression. Figure 8 shows the data associated with compliance values (the inverse data of Table 1) together with the linear fitting. The regression coefficient obtained using all individual values was $R^2 = 0.84$, which is almost equal to that obtained in the case of fitting the individual stiffness data ($R^2 = 0.86$; see Figure 5). When the mean values were used for the linear regression, instead of individual values, the resulting regression coefficient was $R^2 = 0.95$.

From Figure 8, when using individual values for the linear regression, the compliance of the Achilles tendon can be evaluated as the value at the origin, which leads to $k_t^{-1} = 0.002412\,\text{m/kN}$. The value of the compliance of the soleus per unit inverse load can be estimated from the slope of the fitted line, which leads to $k_{ss}^{-1} = 2.2689\,(\text{m N})/\text{kN}$. The values obtained in the case where the mean values are used are, respectively, $k_t^{-1} = 0.002295\,\text{m/kN}$ and $k_{ss}^{-1} = 2.3742\,(\text{m N})/\text{kN}$, which are 4.8% and 5.9% different, respectively, from those obtained considering all points and not just the mean values.

The inverse of these values (k_t^{-1} and k_{ss}^{-1}) gives rise, respectively, to the stiffness of the Achilles tendon and the stiffness of the soleus per unit load, these values being, when the individual values are used, $k_t = 414.6\,\text{kN/m}$ and $k_{ss} = 0.4407\,\text{kN/(m N)} = 440.7\,\text{kN/(m kN)}$. When using the mean values, the results are $k_t = 435.7\,\text{kN/m}$ and $k_{ss} = 0.4212\,\text{kN/(m N)} = 421.2\,\text{kN/(m kN)}$.

Finally, Achilles tendon and soleus compliances were evaluated using the MML. Figure 9 shows the nine quadrants (red dashed lines) in which compliance data are equally divided. The medians of the two extreme

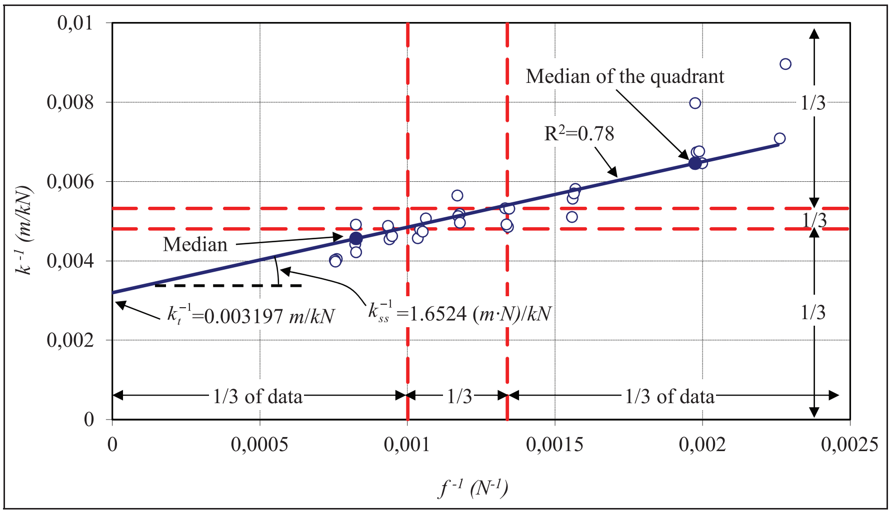

Figure 9. Achilles tendon compliance (k_t^{-1}) and soleus compliance per unit load (k_{ss}^{-1}) using the median–median line.

Table 2. Comparison of mean values (set of 10 subjects) of k_t and k_{ss} values with previous results.

Fitting procedure	Left leg		Right leg	
	k_t (kN/m)	k_{ss} (kN/m)/kN	k_t (kN/m)	k_{ss} (kN/m)/kN
Least squares – stiffness[a]	376	475	386	443
Least squares – compliance[b]	360	495	382	453
Trimmed least squares – compliances[c]	369	483	376	461
Minimum distance – compliances[d]	358	495	385	449
Median–median line – compliances[e]	424	443	408	427
Mean/standard deviation[a–e]	377/27.1	478/21.5	387/12.1	447/12.9
Mean/standard deviation[a–d]	366/8.1	487/9.6	382/4.4	452/7.4
Fukashiro et al.[4,f]	k_t = 364 kN/m, k_{ss} = 611 (kN/m)/kN (mean of both legs)			
Babic and Lenarcic[5,g]	410	669	408	665

[a]Mean value of 10 subjects using the least squares procedure with stiffness.
[b]Mean value of 10 subjects using the least squares procedure with compliances.
[c]Mean value of 10 subjects using the trimmed least squares procedure with compliances.
[d]Mean value of 10 subjects using the minimum distance procedure with compliances.
[e]Mean value of 10 subjects using the median–median line procedure with compliances.
[f]Mean value of six subjects and left/right legs.
[g]Mean value of the left leg for 10 trained male subjects.

quadrants define the line which gives the compliance values of the Achilles tendon $k_t^{-1} = 0.003197\,\text{m/kN}$ and soleus $k_{ss}^{-1} = 1.6524\,(\text{m N})/\text{kN}$. The corresponding stiffnesses are $k_t = 312.8\,\text{kN/m}$ and $k_{ss} = 605.2\,\text{kN/(m kN)}$.

Discussion

Table 2 summarizes the mean values of k_t and k_{ss} obtained by the means of all proposed fitting procedures for the right and left legs and for all tested subjects. It becomes clear, from data in Table 2, that the MML fitting procedure yields different results than the other proposed procedures. Let us remember that one drawback of this procedure is that one-third of the values is not taken into account in the process, the excluded data being those with the best quality, due to the fact that they have been obtained with the intermediate values of the weight. In Table 2, the global mean values and standard deviations of k_t and k_{ss} have been calculated both including this procedure (the row with superscripts 1–5) and not including it (the row with superscripts 1–4). The results show a significant decrement in the standard deviation, without a significant variation in the mean value, when excluding the MML procedure. Therefore, once the results obtained with the MML procedure are discarded, the rest of the results are quite similar, showing a satisfactory robustness and consistency.

It is important to note that each experimental data point (f, k), in Table 1, is the result of a previous fitting procedure between the experimentally recorded force versus time curve and the assumed oscillation model, see París-García et al.[3] for further information. This fact makes the actual fitting procedure to accumulate the uncertainties of the previous fitting step. Thus, the obtained regression coefficients R^2 in Figures 5 and 8 ($R^2 = 0.95$ for the mean values and for both the figures) can be considered to be very satisfactory.

For more detailed information, Figures 10 and 11 show, respectively, the values of k_t and k_{ss} for both legs of all tested subjects. The bars (grey/red bars represent

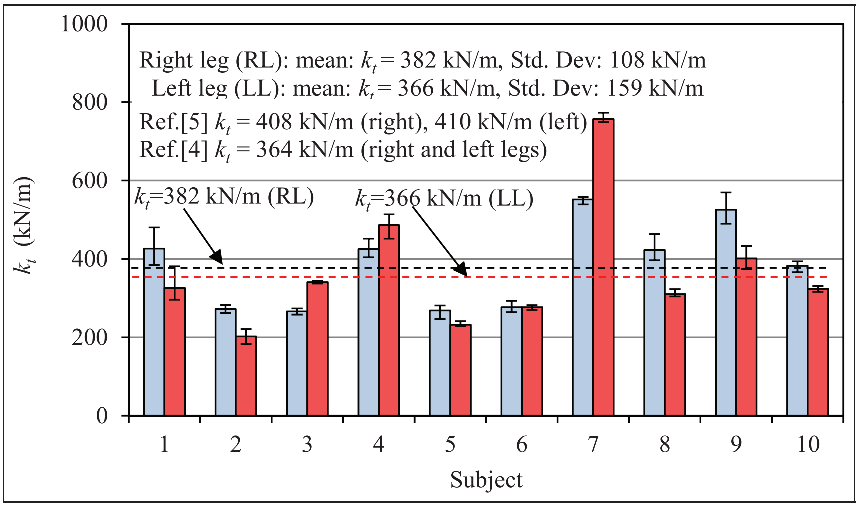

Figure 10. Stiffness of the tendon, k_t (kN/m) for all subjects (the range of values shown for each subject excludes the median–median line result) and both legs. Grey (red) bars represent results from left (right) legs.

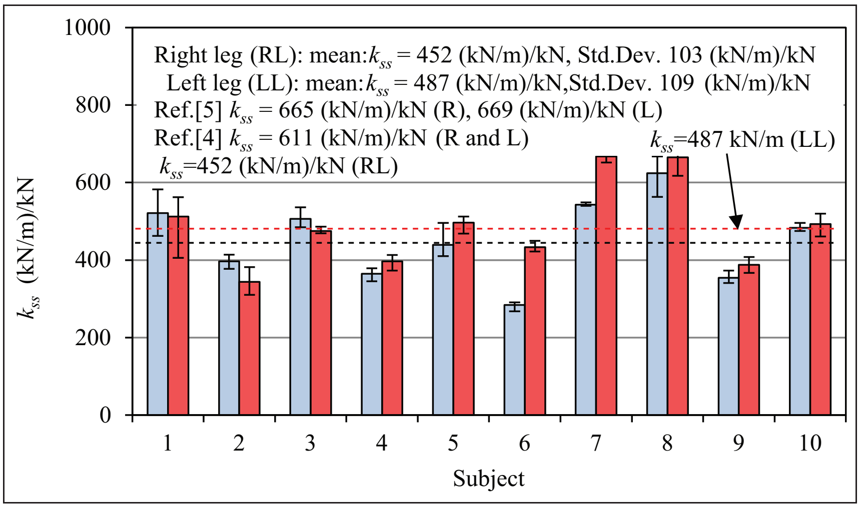

Figure 11. Stiffness per unit load of the soleus, k_{ss} (kN/m)/kN for all subjects (the range of values shown for each subject excludes the median–median line result) and both legs. Grey (red) bars represent results from left (right) legs.

the results from left/right legs) denote the mean values and the lines the ranges (min–max) obtained for each subject using all previously introduced fitting procedures (excluding the mean–mean line, for the reasons mentioned above).

The first observation for all plots in Figures 10 and 11 is that the definition of a mean value of k_t or k_{ss} for an unrelated set of people has a limited representativity, due to the high values of the standard deviation obtained (the values of the standard deviation included in the figures). It is clear, from Figures 10 and 11, that each subject has different values of k_t and k_{ss} due to their different sex, age, weight, height, training level and so on. It is also observable in Figures 10 and 11 that the ranges of variation, using any of the proposed fitting procedures, both for k_t and k_{ss}, are very low in comparison with their mean values. Subjects with different mean values do not share values in their range (min–max) of measured values.

Figures 10 and 11 also show two important facts. The first one is that the results for both legs are not equal (for the majority of subjects studied, the intervals of min–max values for both legs do not have a common range). This observation may be associated with the laterality of the subjects, which will be studied in a forthcoming article. The second one is that, although not equal, at least the trend is similar for both legs. Those subjects having the highest values of k_t or k_{ss} in one leg (in comparison with the rest of the subjects) have also the highest values of k_t or k_{ss} in the other leg (also in comparison with the other subjects).

In Table 2, the results reported in the literature for k_t and k_{ss}[4,5] have also been included for the sake of completeness. Although, as mentioned previously in this section, the determination of a mean value of an unrelated set of people might be a meaningless parameter, in the sense already explained, the lack of information on the individual values of the results reported in the literature leaves the comparison of the mean values as the only possibility. Even more, while Babic and Lenarcic[5] distinguishes between the values of k_t and k_{ss} for both legs, Fukashiro et al.[4] report one single value of k_t and k_{ss}. It is also remarkable, as pointed out in París-García et al.,[3] that the methodologies proposed in Fukashiro et al.[4] and Babic and Lenarcic[5] should yield different results for the same parameter (k_t or k_{ss}) if they are applied to the same subject, as done in París-García et al.[3] As the data used in this work are based on the measurements obtained using a methodology equal to that proposed in Fukashiro et al.,[4] more confident comparisons should be made with the results obtained in Fukashiro et al.[4]

With all these previous comments in mind, limiting the representativity of mean values, Table 2 shows for the set of 10 subjects used in this work a global mean value of k_t = 382 kN/m (right leg) and k_t = 366 kN/m (left leg), while the result reported in Fukashiro et al.[4] for both legs is k_t = 364 kN/m, which is quite similar. In contrast, values for k_{ss} obtained in this work are k_{ss} = 452 (kN/m)/kN (right leg) and k_{ss} = 487 (kN/m)/kN (left leg) which are different from the k_{ss} = 611 (kN/m)/kN reported in Fukashiro et al.[4]

The results in Babic and Lenarcic[5] using a different methodology from that used in this work (and in Fukashiro et al.[4]), and obviously applied to a different set of people, are very similar for k_t or k_{ss} to those reported in Fukashiro et al.[4] (see Table 2). Thus, to summarize, the results in terms of the mean values obtained in this work are of the same order in the values of k_t and clearly differ in the values of k_{ss}.

Although an explanation for this difference would need a deeper analysis, which is outside of the scope of this work, possible reasons justifying this difference could be associated with some observations derived from the different training levels and anthropometrical characteristics of the subjects. Of the 10 tested subjects in this study, subjects 7 and 8 had the best training level of all. Subjects 7 and 8 gave the highest values of k_{ss} for both legs, around 600 (kN/m)/kN, the other subjects being much more sedentary and giving lower values. Babic and Lenarcic[5] report a mean k_{ss} value of 665 and 669 (kN/m)/kN for the right and left legs, respectively, and these results are associated with a set of 10 trained male subjects. This observation is connected to the known fact that the stiffness of the soleus is more sensitive to the training status of the person than the stiffness of the Achilles tendon.

Conclusion

Several procedures have been developed for the evaluation of the stiffness of the Achilles tendon and the stiffness per unit load of the soleus. The evaluation of these stiffness values is based on the previous knowledge of the apparent stiffness properties of the TS MTC.[3]

Knowledge of the stiffness properties of these two individual constituents of the TS (the gastrocnemius not being involved in the oscillation due to the 90° position of the knee in the test) allows many questions, such as tracking the training level after a period of inactivity (after surgery or injury), the efficiency of a particular strategy of training in the improvement of the TS properties, and so on, to be clarified.

The values of stiffness of the Achilles tendon and the soleus have been evaluated by means of different fitting procedures for the apparent data (stiffnesses or compliances) of the TS. The fitting procedures have proved to be very robust in the determination of the initial slope k_{ss} (the stiffness per unit load of the soleus) and the horizontal asymptote k_t (the stiffness of the Achilles tendon). Only one procedure, the MML, was shown to be inaccurate, due to the nature of the procedure which discards, in this particular case, the best quality data. Comprehensive data have been reported for individual subjects, each leg and different fitting procedures, which might help researchers to use them as benchmark data.

The results obtained in this work have been compared with others in the literature (mean values only), and details about the representativity and comparability of these results have been discussed. The large intervals found for the stiffnesses of the Achilles tendon and the soleus give only a limited representativity to these mean values. In any case, the mean value found for the Achilles tendon stiffness turned out to be very similar to others presented in the literature. On the other hand, the soleus stiffness is very much affected by the training level, so that only people with similar training status should be compared.

With this and previous works of the authors, it has been shown that the results for the individual constituents of the TS are influenced by several different aspects which have to be taken into account, such as the methodology for obtaining the apparent mechanical properties of the TS[3] or the measurement of the lever arms of the foot and the fitting procedure itself.[11]

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Declaration of conflicting interest

The authors declare that there is no conflict of interest.

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