IN VIVO STIFFNESS EVALUATION OF HUMAN TENDONS

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The purpose of this study was to describe the use of *in vivo* ultrasonography to measure the tendon-aponeurosis linear stiffness of some muscles of the lower limb (*Gastrocnemius, Rectus femoris* and *Vastus medialis*) of long jump athletes.

KEY WORDS: stiffness, tendons, aponeurosis, muscle, ultrasonography.

INTRODUCTION: The behaviour of tendons was largely studied *in vitro* conditions, both in human and animal tissues (Abrahams, 1967; Benedict *et al.*, 1968; Woo *et al.* 1981), but information available in the literature about human tendons *in vivo* is scarce. Meanwhile, an advance in real-time ultrasonography enables the non-invasive determination of the displacement of the fascicles during muscle contraction, which made possible the study of deformation of the aponeurosis and the tendon (Fukashiro et al. 1995). Such techniques were used in the past for the study of vertical jumps. For instance, Kubo *et al.* (1999) showed that tendons have a parabolic like force-length relationship at low stress, and an almost linear relation at higher loads. To our knowledge, however, it was never used for the analysis of long jumpers.

METHODS: Six (n=6) adult male long jumpers were studied. The mean values and standard deviation (±sd) for the best long jump performance, height and body mass were, respectively, 7.12±0.30 m, 1.84±0.02 m, 79±5.75 kg. We recorded the tendon-aponeurosis displacement using an Aloka SSD-5500 ultrasonic apparatus, with a linear probe at 7.5 MHz. The probe was placed parallel to the aponeurosis and fixed with respect to the laboratory. The minimum frame rate was 26 Hz. Ultrasonographic records were afterward digitised using the *Peak-5* system (*Peak Performance Tech., USA*), with an uncertainty of 0.2 mm, to allow the quantification of displacements. The *Gastrocnemius* records from subject # 4, *Rectus femoris* from subject # 2, and *Vastus medialis* from subjects # 3 and # 4, were discarded due to errors in the recording phase. For the evaluation of the *Gastrocnemius* force, the subject performed an isometric plantar flexion of the take-off foot confined into a leg press machine instrumented with a load cell (*Ergo Tester*, sampling at 62.5 Hz, uncertainty below 1N). The knee was fully extended and the hip remained at 90°. The foot was kept forming a 90° angle with the lower-limb. A leg curl machine was used to estimate *Rectus femoris* and the *Vastus medialis* force of the take-off leg. The subject performed isometric knee extension contractions. The same load cell working at the same sampling rate was used. The knee was flexed at 90°. Stiffness was computed as a derivative of the force-displacement relation. Every effort was done to ensure that the exercises were isometric and free from collateral movements. Every subject performed 6 trials of each task with 3 min rest between trials. The 4 best performances of each task were used for analysis. Each exercise started with a slow isometric contraction, but subjects were encouraged to gradually increase force production over 10s. After this period, maximal isometric force should be reached and maintained for at least 2 to 3 seconds. For subsequent analysis, the strain gauge load records were stored into a computer and the echograms were recorded on a video recorder operating at 50 Hz. The moment arms for the lever of the foot was assessed by surface measurement of the distance from the basis of the 5th metatarsal bone to the vertical projection of the malleolus (d1, Δd1=±0.5cm) and from this point to the insertion of the *Achilles* tendon (d2, Δd2=±1cm). To estimate the knee moment arms, the distances were measured from the malleolus to the lateral condyle of the femur (d3, Δd3=±2cm) and from this point to the tuberosity of the tibia (d4, Δd4=±2cm). With this information and the external forces obtained from the strain gauge cell, forces in Achilles and patellar tendons were calculated.
Synchronisation of force and displacement records were obtained *a posteriori* considering the time course of both events, with a resolution of 0.02sec. To assess stiffness we

differentiated the force with respect to the displacement of the fascicle, using regression procedures at a 95% confidence level.

RESULTS: The results of our study showed that, in general, we didn't obtain the initial toe region of force-displacement relation of the tendon (Kubo et al., 1999). Contrarily, sometimes an inverse curvature, like in figure 1 have been observed. This may be explained through the possible effect of a pre-tension. However, in other cases the results were in agreement with the literature (fig 2)

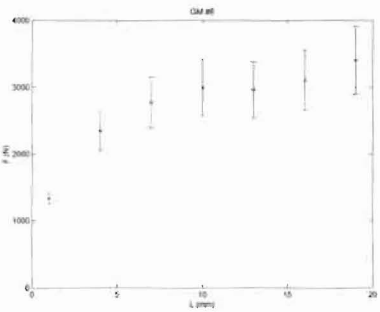

Figure1. Force (F) – tendon elongation (L) relationship for the *Gastrocnemius* muscle, subject 1.

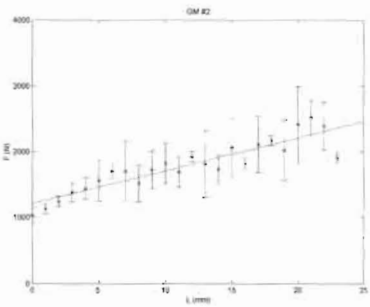

Figure 2. Relation between muscle force (F) and elongation (L) of *Gastrocnemius* muscle of subject # 2. The mean stiffness was 49.8 N/mm

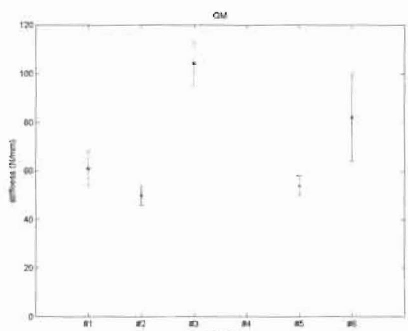

Figure 3. The mean stiffness (N/mm) of the *Gastrocnemius* muscle in all the subjects.

The *Gastrocnemius* stiffness of the subjects studied (Fig. 3) varied between 50 and 105 N/mm (Fig 3). For the *Rectus femoris* (RF) and *Vastus medialis* (VM) the values were in the range from 15 to 83 N/mm (Fig 4) and 32 to 69 N/mm (Fig 5), respectively.The maximal force exerted on the *Achilles* tendon varied between 2500N to 4000N, and for the patellar tendon the force was between 934N and 2900N when *Rectus femoris* was under test, and it was 971N to 3532N, when *Vastus medialis* was under test. The maximum displacement of the point of muscle-tendon junction of the *Gastrocnemius* muscle varied between 12 and 25 mm. For the *Rectus femoris* we obtained a maximum displacement from 13 to 23 mm, and for *Vastus medialis* from 11 to 17 mm.

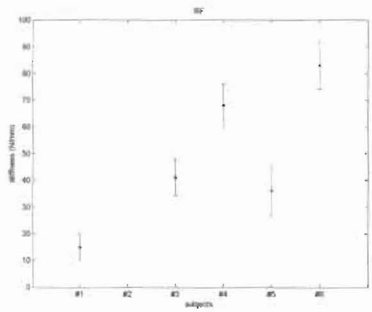

Figure 4. Representation of the mean stiffness (N/mm) of the *Rectus femoris* (RF) muscle of all the subjects.

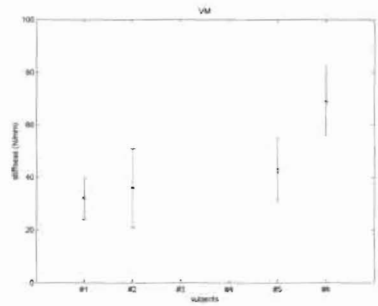

Figure 5. Representation of the mean stiffness (N/mm) of the *Vastus medialis* (VM) muscle of all the subjects.

DISCUSSION: With this study we quantified, *in vivo,* the elastic properties of the tendon structures of some muscles. For every muscle-tendon complex studied, large variability in the displacement of the aponeurosis and in the stiffness was observed. The stiffness values obtained for the *Gastrocnemius* muscle were 3 times higher than those obtained by Kubo et al (2000), and Fukashiro et al. (1995). We also observed that jumpers with better personal records have higher stiffness. The small number of subjects does not allow to perform a statistical testing of this assumption. We were also unable to obtain literature references about this. Nevertheless it is possible that, the high performance level of our athletes may contribute to the differences with previous reports. In the literature we found references to forces of 1430N in *Achilles* tendon, in a walking exercise, that were measured with an optic fibre technique (Fini et al., 1998). In jumping activities, Fukashiro et al. (1995b) obtained, with buckle transducer, tendon forces between 1895N and 3786N. Our subjects presented values in the same range, what suggests that isometric data is comparable to that obtained in real long jump. For the *Rectus femoris* and *Vastus medialis* muscles, we observed a high inter-subject variability in the stiffness and exerted forces. Kubo et al. (2000) found stiffness values between 118 and 167 N/mm for the *Vastus medialis,* which is about twice the values obtained in our subjects. The obtained data suggest that a more compliant *Vastus lateralis* might be advantageous in terms of performance. Our athletes were jumpers trained to produce and resist large impulsive forces, they also have a higher compliance in the aponeurosis, relatively to sprinters and untrained subjects. This higher compliance allows for developing large forces in mechanical advantageous positions. Perhaps the large differences between our data and that from Kubo et al. (2000) can be explained by the differences in their respective sports. A final remark should be made about the errors. They are large for the *Rectus femoris* and *Vastus medialis* muscles than *Gastrocnemius* muscle, mainly as a consequence of uncertainty in the geometric data.

CONCLUSIONS: Significant inter and intra-subject (muscle to muscle) variations in tendon stiffness values have been observed.

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