PLASTICITY OF HUMAN TENDON'S MECHANICAL PROPERTIES: EFFECTS ON SPORT PERFORMANCE

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INTRODUCTION: In the literature it is often mentioned, that the tendon is very relevant for the work producing capability of the muscle fibers and for the motion and the performance of the human body. During a given movement, strain energy can be stored in the tendon and this way the whole energy delivery of the muscle can be enhanced. Further, the higher elongation capability of the tendon with respect to the muscle fiber, allows a bigger change in length of the muscle-tendon unit. Therefore, the muscle fibers may work on a lower shortening velocity and as a consequence of the force-velocity relationship their force producing potential will be higher. Generally, the main functions of the tendon during locomotion are: (a) to transfer muscle forces to the skeleton (b) to store mechanical energy coming from the human body or/and from muscular work as strain energy and (c) to create favorable conditions for the muscle fibers to produce force as a result of the force-length-velocity relationship. A higher force potential of the muscle fibers due to the force-length-velocity relationship during submaximal contractions would decrease the volume of active muscle at a given force or a given rate of force generation and consequently would decrease the cost of force production. In the same manner during maximal muscle contractions (maximal activation level) the higher force potential of the muscle fibers will allow the muscles to exert higher forces. The reports about the influence of the non rigidity of the tendon on the effectivity of muscle force production reveal the expectation that sport performance during submaximal as well as maximal running intensities may be affected by the mechanical and morphological properties of the tendon.

In a series of experiments we examined the mechanical properties of the lower extremities muscle-tendon units (MTU) from athletes displaying different running economy and sprint performance. The most economical runners showed a higher contractile strength and a higher tendon stiffness in the triceps surae MTU and a higher compliance of the quadriceps tendon and aponeurosis at low level tendon forces (Arampatzis et al., 2006). The faster sprinters exhibited a higher elongation of the vastus lateralis (VL) tendon and aponeurosis at a given tendon force and a higher maximal elongation of the VL tendon and aponeurosis during the MVC (Stafilidis and Arampatzis, 2007). Furthermore, the maximal elongation of the VL tendon and aponeurosis showed a significant correlation with the 100 m sprint times ($r = -0.567$, $P = 0.003$). It has been supposed that, the more compliant quadriceps tendon and aponeurosis will increase the energy storage and return as well as the force potential of the muscle due to the force-velocity relationship. These studies provide evidence that the mechanical properties of the tendons at the lower extremity at least partially explain the performance of the human musculoskeletal system during running activities. However, until now no study exist in reference to the potential for improving running performance by manipulating the tendon mechanical properties.

Mechanical load induced as cyclic strain on connective soft tissues such as tendons is an important regulator of fibroblast metabolic activity as well as for the maintenance of tendon matrix (Chiquet et al., 2003). An increased loading typically stimulates cells for remodelling and, therefore, for increasing the mechanical properties of the tissue (Arnoczky et al., 2002). Whereas, a decreased loading leads to tissue destruction and weak mechanical properties of the tissue (Arnoczky et al., 2004). These reports demonstrate the highly plastic nature of tendons within the muscle-tendon unit of mammals and give evidence that tendon strain is an important mechanical factor regulating tendon properties. Generally, from a mechanobiological point of view strain magnitude, strain frequency, strain rate and strain duration of cells influence the cellular biochemical responses and the mechanical properties of collagen fascicles. Although it is known that mechanical loading induced as cyclic strain affects the mechanical properties of human tendons in vivo, the effect of a controlled modulation in cyclic strain magnitude, frequency, rate or duration applied to the tendon on the plasticity of human tendons in vivo is not well established. Understanding the details of tendon plasticity in response to mechanical loading applied to the tendon *in vivo* may help to improve tendon adaptation, reduce tendon injury risks and increases the performance potential of the human system.

This paper aimed (a) to present the effects of a controlled modulation of strain magnitude and strain frequency applied to the Achilles tendon on the plasticity of tendon mechanical and morphological properties and (b) to investigate whether an exercise induced increase in tendon-aponeurosis stiffness and contractile strength at the triceps surae muscle-tendon unit affect running economy.

TENDON PLASTICITY TO CYCLING LOADING: In order to get relevant knowledge about the dependence of tendon mechanical loading induced as cyclic strain and the mechanical properties of tendon and aponeurosis we examined the effect of two different exercise interventions (14 weeks). In these two exercise interventions we modified the strain magnitude (low: 2.5-3.0 % strain vs. high: 4.5-5.0 % strain) and strain frequency (low: 0.17 Hz vs. high: 0.5 Hz) applied to the Achilles tendon. Thirty two adults (two experimental groups each with n=11 and a control group n=10) participated in the study after giving informed consent to the experimental procedure accomplishing with the rules of the local scientific board.

The participants of group 1 performed 5 sets, 4 times per week of repetitive (0.17 Hz, 3 s loading, 3 s relaxation), isometric plantar flexion contractions. Repetitive isometric plantar flexion contractions were used to induce cyclic strains on the triceps surae tendon and aponeurosis. One leg (randomly chosen) has been exercised at low magnitude tendon-aponeurosis strain (low strain magnitude exercise), and the other leg at high tendon-aponeurosis strain magnitude (high strain magnitude exercise, figure 1). Mechanical loading of the triceps surae tendon and aponeurosis at 55 % and 90 % of the MVC are supposed to cause a tendon aponeurosis strain of 2.5-3.0 % and 4.5-5.0 % respectively (Arampatzis et al. 2005). The participants of group 2 performed again 5 sets, 4 times per weeks of repetive isometric plantar flexion contraction but in the high strain frequency (0.5 Hz, 1 s loading, 1 s relaxation, figure 1). Similar to the first intervention one leg has been exercised at low magnitude tendon-aponeurosis strain (55 % MVC) and the other leg at high tendon-aponeurosis strain magnitude (90 % MVC). In both exercise interventions both legs were trained at the same exercise volume (integral of the plantar flexion moment over time).

After 14 weeks of loading in the low as well as in the high frequency interventions by equal exercise volume we found an increase in tendon-aponeurosis stiffness and tendon elastic modulus only in the leg exercised at high strain magnitude (~4.7 %). These findings suggest that tendon cells may have a threshold, or set point, regarding their deformation for triggering a homeostatic perturbation leading to anabolical responses. Low strain values (2.5 to 3.0%) may lead to a habitual loading of the Achilles tendon (i.e. similar loading as during daily activities). This habitual loading would result in a lack of cell stimulation for further extracellular matrix synthesis and of remodelling leading to constant mechanical and morphological properties over time. Furthermore in the low frequency and high strain magnitude training we found a region specific hypertrophy of the Achilles tendon. However, a threefold increase in the strain frequency (from 0.17 to 0.5 Hz) caused lower adaptational effects on the Achilles tendon mechanical and morphological properties (i.e. lower increase in tendon-aponeurosis stiffness and no effect on tendon CSA, figure 2). The maximum voluntary plantar flexion moment has been increased in both, the exercise protocol at 55% and 90% of the MVC indicating an improvement in muscular capacity of the triceps surae muscles. The consequence of the increased muscle strength was an increase in tendon stress during the MVC indicating a higher mechanical tendon loading after the intervention in both legs. On the other hand, the maximum tendon-aponeurosis strain during the MVCs has been increased only in the leg exercised at low strain magnitude (i.e. exercise at 55% MVC).

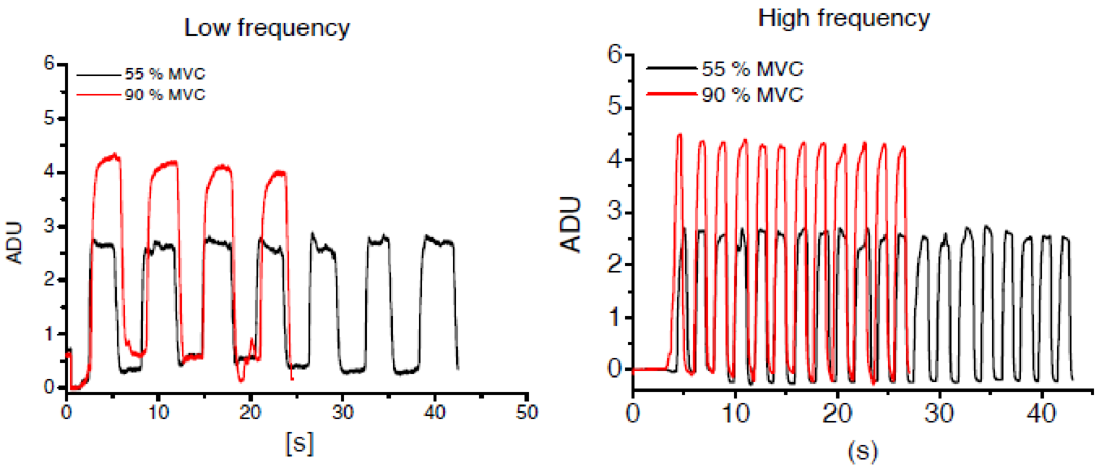

Figure 1: Each training day of the intervention protocol consisted of 5 sets of repetitive (3 s loading, 3 s relaxation, left and 1 s loading, 1 s relaxation, rigth) isometric plantar flexion contractions to induce cyclic strain on the triceps surae tendon and aponeurosis. One leg exercised at low magnitude tendon-aponeurosis strain (55 % of the MVC), whereas the other one exercised at high tendon-aponeurosis magnitude (90 % MVC). The total exercise volume (integral of the plantar flexion moment over time) was identical for both legs.

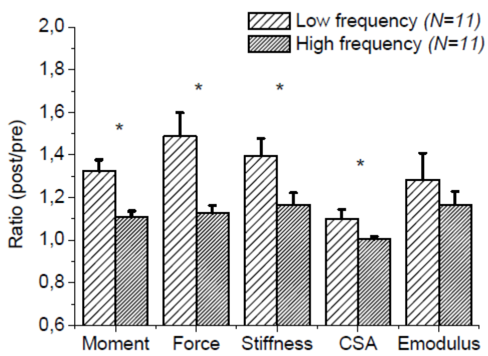

Figure 2: Ratio (post- to pre-exersice values) for the low frequency (0.17 Hz; 3 s loading, 3s relaxation) and high strain-frequency (0.5 Hz; 1 s loading, 1 s relaxation) exercise protocols. The ratios has been tested only for the high strain magnitude exercise.
***: Statistically significant differences between low- and high-frequency exercise protocols (P<0.05).**

Given that the ultimate failure strain of the tendons cannot be altered significantly (Abrahams, 1967) and the best predictor for tendon damage accumulation for both sustained and cyclic loading is the tendon strain (Wren et al., 2003) higher strain values during the MVC after the intervention for the low strain magnitude exercised leg would decrease the safety factor (ratio of tendon ultimate strain to functional tendon strain) and may increase the risk factors for tendon injury. The maximum strain during the MVC at the leg exercised with the high strain magnitude did not change despite an increase in muscle strength. Therefore, our results show that after the exercise intervention the safety factor against tendon loading has been updated only in the high strain exercised leg.
In conclusion our findings show that (a) there is not necessarily a coordinated adaptation between muscle and tendon by a given exercise loading, (b) the strain magnitude applied to the Achilles tendon should exceed the habitual value which occurs during daily activities to trigger adaptational effects on the tendon mechanical properties and finally (c) a higher tendon strain duration per contraction leads to superior adaptational responses on the mechanical and morphological properties of the tendon.

EFFECTS OF TENDON STIFFNESS AND CONTRACTILE STRENGTH ON RUNNING ECONOMY: In an additional experiment we examined the effects of an increased tendon stiffness and contractile strength at the triceps surae muscle-tendon unit on running economy. Twenty five recreational long-distance runners (experimental group, n = 12, control group, n = 13) participated in the study. The participants of the experimental group performed the 14 weeks exercise program similar to our high magnitude and low frequency protocol (3 s loading, 3 s relaxation, 95 % MVC) in both legs. Running economy (rate of oxygen consumption at a given running velocity), tendon stiffness, maximal voluntary ankle plantarflexion joint moment, and fascicle behavior during running were analyzed before and after the intervention. Running economy was determined by measuring the rate of oxygen consumption at steady state at two running velocities (3.0 m/s and 3.5 m/s) on a treadmill. After the 14 weeks intervention, the maximum voluntary ankle plantarflexion joint moment showed a statistically significant (p<0.05) increase of about 6%. The triceps surae tendon-aponeurosis stiffness showed a significant increase of ~15% (figure 3). During submaximal running the subjects showed a 5% reduction (p<0.01) and 3% reduction (p<0.05) in oxygen consumption for the low and high running velocity, respectively, while the control group showed no changes after 14 weeks (figure 4).

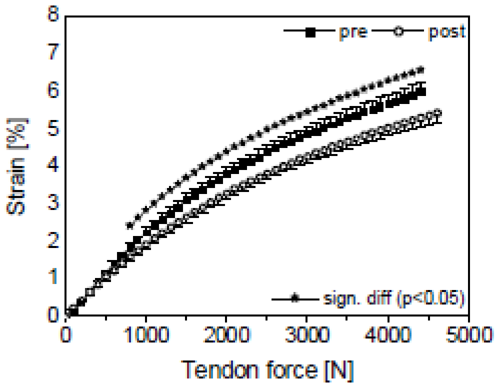

Figure 3: Strain values at every 100 N calculated tendon force (means ± sem)

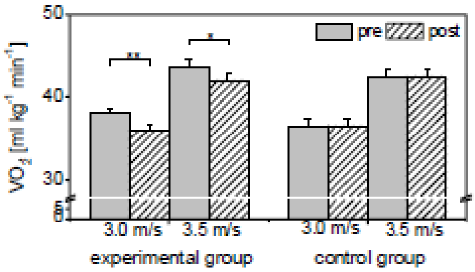

Figure 4: Rate of oxygen consumption (means ± sem)

elocity of the gastrocnemius medialis during the stance phase of running revealed no significant differences before and after the training intervention. Although, we could experimentally not confirm that fascicle behaviour of the gastrocnemius medialis muscle has been changed, the enhanced running economy found after increasing triceps surae tendon stiffness and contractile strength indicate that the force generation within the lower extremities has become more efficient while running.

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