Plasticity of human tendon's mechanical properties and effects on running economy

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Tendon plasticity and sport performance

Tendons reduce the mechanical work done by their muscle fibres in each step (Biewener and Baudinette, 1995; Biewener et al., 1998; Biewener and Gillis, 1999) and reduce the metabolic cost of locomotion.

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tendons reduce the mechanical work done by their muscle fibres in each step and reduce the metabolic cost of locomotion.
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The compliance of the tendon

a. the energy storage and return from the tendon,
b. the rate of muscle force generation and transmission to the skeleton, and
c. the force and power producing capability of the muscle due to the force-length-velocity relationship
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- Proximal aponeurosis
- Origin (femur)
- Distal aponeurosis
- Cross-point at the aponeurosis ($P_a$)
- Calcaneus

Graph showing moment (Nm) vs. time (s):

- Moment (Nm) range from 0 to 150
- Time (s) range from 0 to 12

Images of ultrasound scans showing tissue movement and labeled points.
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\[ K = \frac{\Delta F}{\Delta L} \]
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Stress (MPa)

strain (ΔL/L₀)
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- Changes of the moment arm of the reaction force to the ankle/knee and dynamometer joints during the contraction

Arampatzis et al. 2005, J. Biomech. 38, 885-892
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![Image of tendon testing equipment]

Graph showing the relationship between moment and time with two curves labeled $M_{\text{meas.}}$ and $M_{\text{res}}$. The x-axis represents time in seconds ranging from 2 to 14, and the y-axis represents moment in Newton meters (Nm) ranging from 0 to 150.
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- During the maximal voluntary “isometric” contraction there was an angular displacement at the joint.
This joint angular displacement influences the actual elongation of the tendon and the aponeurosis
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Passive tendon displacement correction method

- The measured elongation of the tendon and aponeurosis without any correction overestimates the actual elongation about 58%.

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**Purpose**

The objective was to examine the relationship between the mechanical properties of the TS and QF tendon and aponeuroses and sport performance (e.g. running economy and sprint)
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- Twenty eight male long distance runners
- Three different velocities for 15 minutes on a treadmill

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Groups (cluster analysis / VO2)

- Three groups with different oxygen consumption
- The groups did not differ anthropometrically
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**Higher compliance at low level forces**

**ANTICIPATED EFFECTS**

- Increase the ability to store energy in the tendon
- Increase the force potential of the muscle
- Decrease the active muscle volume at a given force generation

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Higher tendon stiffness and contractile strength


Lichtwark et al., 2007, J. Biomech.
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- Participants: 28 sprinters
- Training: Minimum 5 times per week
- Running competition: Minimum 5 years

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- Greater elongation of the QF tendon and aponeurosis at a given tendon force
- Maximal elongation of the QF tendon and aponeurosis related to 100 m time

Conclusions:

- The mechanical properties of the tendon and aponeurosis affect the performance capacity of the human system during submaximal as well as maximal running intensities.

- The energy storage and recovery from the tendon as well as the influence of tendon compliance on the muscle force-length-velocity potential are the main reasons.
Question:
What kind of mechanical stimuli might affect the adaptation of the mechanical and morphological properties of tendons in vivo?
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HYPOTHESIS (Woo et al. 1982, Biorheol. 19, 397-408):

„Homeostatic responses of soft tissues subjected to stresses may be represented by a highly nonlinear curve“

- Immobilisation: rapid decline in the mechanical properties
- Long term exercise: slight increase in the mechanical properties
Recently it has been suggested, that the applied strain on the connective tissues may have a threshold to create a homeostatic perturbation in the collagenous matrix which regulates the catabolic and anabolic responses of the cells (Brown et al., 1998; Lavagnino and Arnoczky, 2005).

- mechanical loading > upper limit: anabolic cell responses
- mechanical loading < lower limit: catabolic cell responses
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**Mechanobiology**

- strain magnitude
- strain frequency
- strain rate
- strain duration
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Modification of strain magnitude

- Eleven healthy subjects performed repetitive (3s loading, 3s relaxation) isometric plantar flexion exercise.
- 14 weeks, 4 times/week, 5 sets/training day.
- One leg exercised at low magnitude tendon strain (55 % MVC), the other leg trained at high strain magnitude (90 % MVC).
- The control group consisted of ten additional subjects.
The total training volume (integral of the plantar flexion moment over time) was identical for both legs.
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Modification of strain frequency

- Eleven healthy subjects performed repetitive (1s loading, 1s relaxation) isometric plantar flexion exercise
- 14 weeks, 4 times/week, 5 sets/training day
- One leg exercised at low magnitude tendon strain (55 % MVC), the other leg trained at high strain magnitude (90 % MVC)
High strain-frequency exercise protocols

- The total training volume (integral of the plantar flexion moment over time) was identical for both legs
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- Similar volume
- Different frequency
- Different magnitude

Low frequency: 0.17 Hz
High frequency: 0.5 Hz

![Graphs showing ADU vs time for low and high frequencies.](image-url)
Measurement of the CSA of the Achilles tendon

1.5 Tesla, slice thickness 4 mm, spacing between slices 0.8 mm, pixel spacing 0.585 x 0.585 mm
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Low frequency: 0.17 Hz

- In both legs the maximal muscle strength increased
- The tendon stiffness changed only in the leg that was exercised at high strain magnitude

Arampatzis et al., 2007, J. Exp. Biol. 210: 2743-2753
The leg exercised at high strain magnitude showed region specific hypertrophy

Arampatzis et al., 2007, J. Exp. Biol. 210: 2743-2753
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High strain-frequency exercise protocols: 0.50 Hz

- Strengthening of the TS muscles in both protocols
- Tendon-aponeurosis stiffness increased only at the high strain exercised leg

*Arampatzis et al., 2010, J. Biomech. 43, 3073-3079*
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High strain-frequency exercise protocols: 0.50 Hz

The CSA of the Achilles tendon did not show any statistically significant (P>0.05) differences at every 10% interval of the tendon length compared to the pre exercise values in both legs.

Arampatzis et al., 2010, J. Biomech. 43, 3073-3079
The tendon elastic modulus showed a statistically significant increase after the intervention in the high-strain-exercised leg.
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**Ratios: post- to pre-exercise values**

- plantar flexion moment,
- calculated tendon force,
- tendon-aponeurosis stiffness and
- average CSA of the Achilles tendon

* a superior improvement at the low strain frequency (0.17 Hz) intervention

Only for the high strain magnitude exercise

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Arampatzis et al., 2010, J. Biomech. 43, 3073-3079
Conclusions:

- There is not necessarily a coordinated adaptation between muscle and tendon by given exercise loading.
- The strain magnitude applied to the Achilles tendon should exceed a threshold to trigger adaptational effects on the tendon mechanical properties.
- A higher tendon strain duration per contraction leads to superior adaptational responses on the mechanical and morphological properties of the tendon.
We found:

- The most economical runners showed a higher plantarflexor contractile strength and a higher stiffness of the triceps surae tendon and aponeurosis.

- Exercise protocol (3 s loading, 3 s relaxation, 90 % MVC, 14 weeks) increases both tendon stiffness and contractile strength.
Question:
Is it possible to improve running economy by increasing the tendon stiffness and contractile strength at the triceps surae muscle-tendon unit?
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Twenty six long-distance runners (experimental group, n= 13; control group, n=13)

**Experimental group:**

• performed repetitive (3s loading, 3s relaxation) isometric plantar flexion exercise in both legs, 90% MVC)
• 14 weeks, 4 times/week, 5 sets/training day
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Hypotheses

• reduce shortening velocity of the GM muscle fascicle during running
• decrease the metabolic cost of running

Lichtwark et al., 2007, J. Biomech.
Running economy was determined by measuring the rate of oxygen consumption at steady state at two running velocities (3.0 and 3.5 m/s)
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After the intervention

*increase*

- tendon-aponeurosis stiffness (~15%)
- contractile strength (~6%)
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After the intervention

decrease $\dot{V}O_2$
- 3.0 m/s (~5%)
- 3.5 m/s (~3%)
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After the intervention

No changes in MTU and GM-fascicle length behaviour

The same elongation of the SEE while running result to a 23% greater energy storage and give evidence for a higher force generation at the triceps surae MTU after the intervention.
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an anterior shift of the point of force application is probably the reason for the redistribution of muscle forces within the lower extremities
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Conclusions:

• Specific modification of the tendon aponeurosis stiffness and contractile strength at the triceps surae muscle-tendon unit has the potential to enhance running economy.

• 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.