PROPRIETÀ MECCANICHE DEL TENDINE IN VIVO

Fisiologia della prestazione sportiva

Università degli Studi di Verona
Scienze Motorie
aa 2014-2015

Stiffness

- **Stiffness** is the rigidity of an object — the extent to which it resists deformation in response to an applied force measured in units newton per of meter
- The inverse of stiffness is *compliance* (or *elastic modulus*), the more flexible an object is, the less stiff it is. measured in units of meter per newton

is defined as:

$$k = \frac{F}{\delta}$$

where,

F is the force applied on the body

δ is the displacement produced by the force

Elastic modulus is a property of the constituent material;
Stiffness is a property of a structure

Tension or compression axial stiffness

$$k = \frac{AE}{L}$$

where

A is the cross-sectional area,

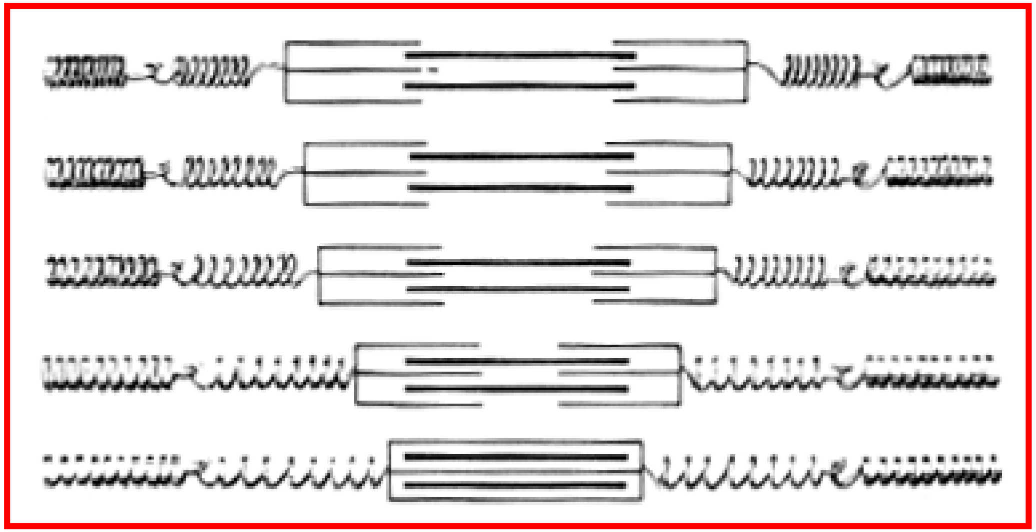
E is the (tensile) elastic modulus (or Young's modulus)

L is the length of the element.

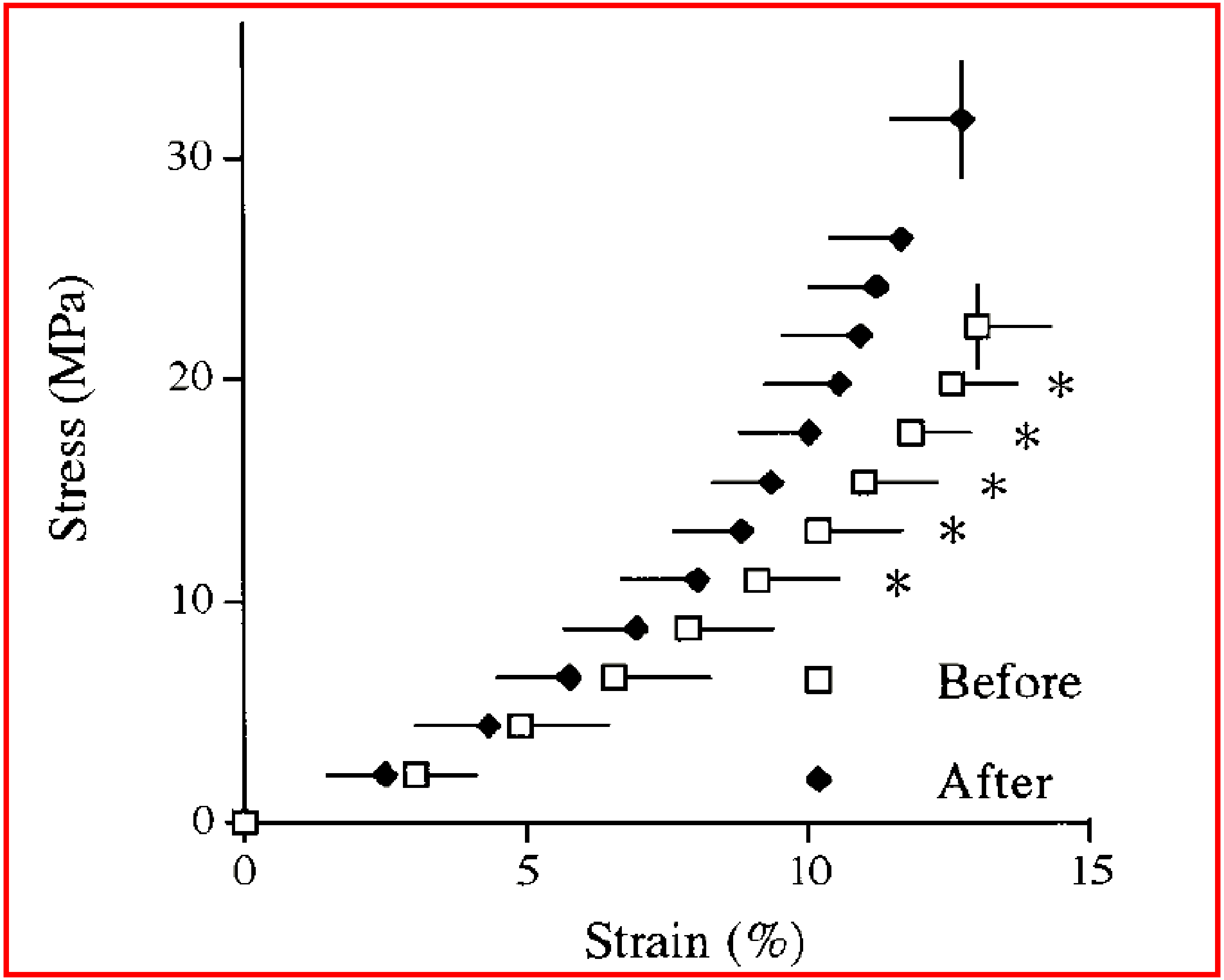
Young's modulus or **elastic modulus**

- is a measure of the **stiffness** of an **elastic material** and is a quantity used to characterize materials
- It is defined as the ratio of the stress (force per unit area) along an axis to the strain (ratio of deformation over initial length)
- A material whose Young's modulus is very high is rigid
- Units of measure Pa or N/m^2

Effect of strength training on the tendon



Changes in tendon stiffness as a result of 12-wk strength training



Myotendinous changes after 12-wk strength training

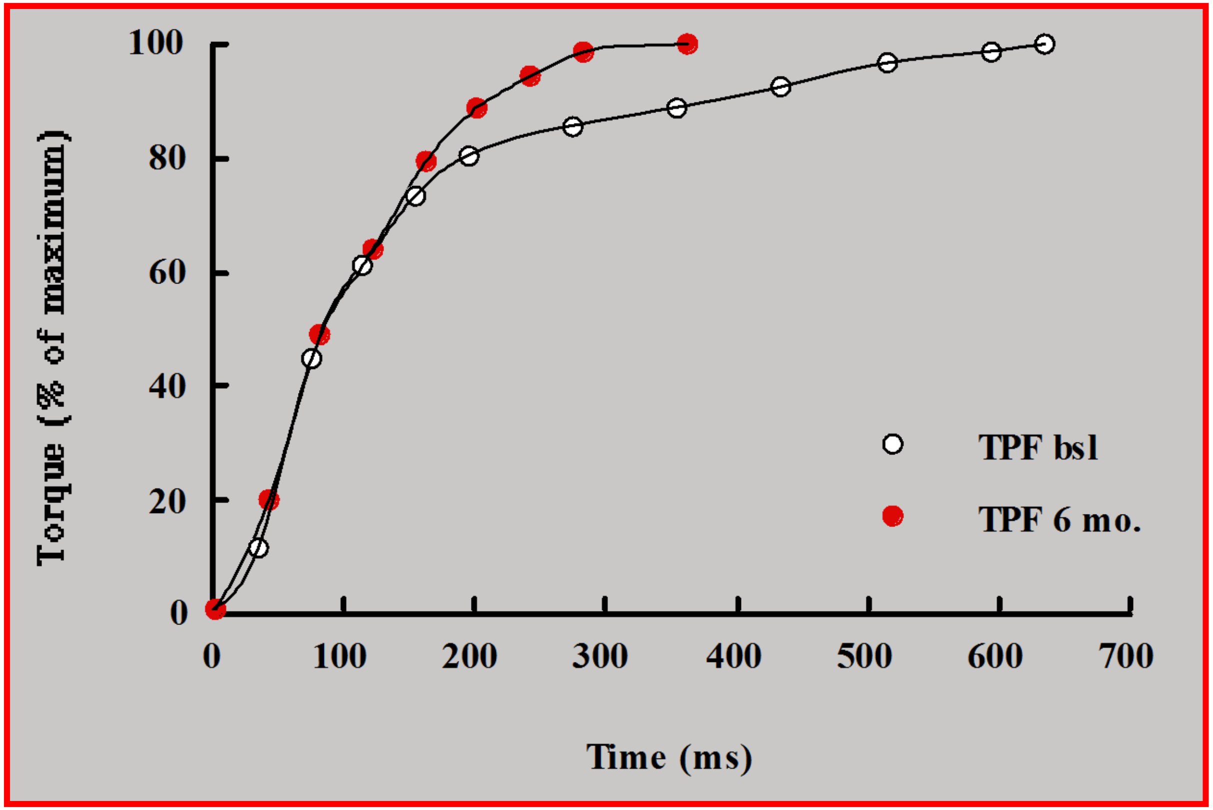
Table 1. *Measured parameters before and after training*

	Before	After
MVC, Nm	219 ± 37	310 ± 45*
Maximum *L*, mm	32.6 ± 3.7	31.9 ± 3.7
Tendon CSA, mm^2	212 ± 18	215 ± 21
Stiffness, N/mm	67.5 ± 21.3	106.2 ± 33.4*
Young's modulus, MPa	288 ± 26	433 ± 35*

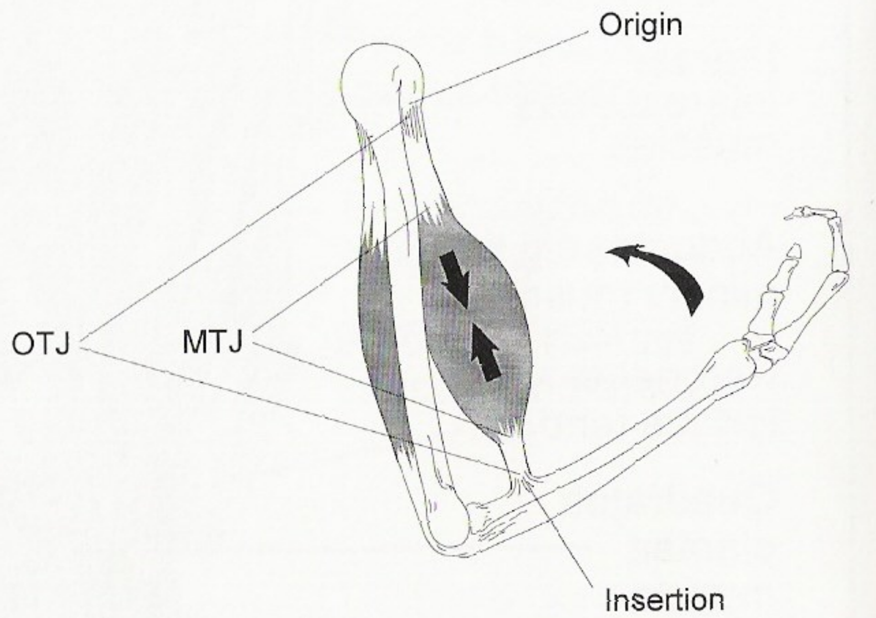
Values are means ± SD. MVC, maximal voluntary contraction; *L*, relationship between estimated muscle force and tendon elongation; CSA, cross-sectional area. *Significantly different from before, $P < 0.05$.

The hypothesis has been put forward that with strength training, the cross link pattern of the collagen or the structure and packing of the collagen fibers increases.

Rate of torque development before and after 6 mo. strength training



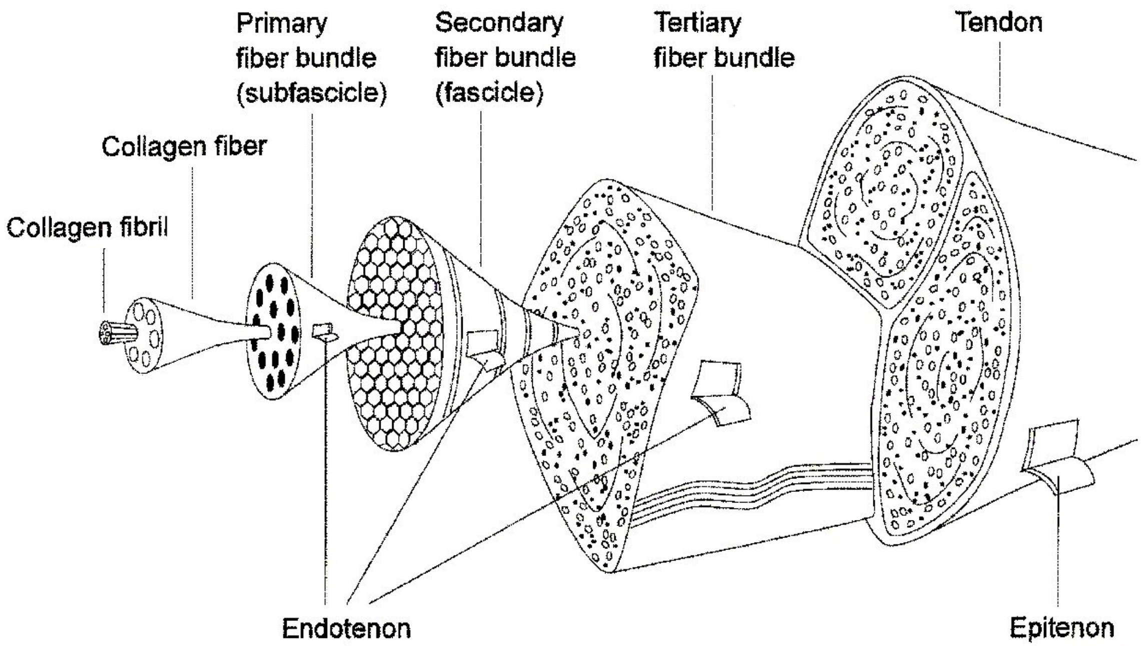
Anatomical location of tendons: Between muscles and bones



■ **Figure 2.1** The muscle-tendon unit. MTJ = Myotendinous junction. OTJ = Osteotendinous junction.

Main functional role of tendon: Force transmission

Structure

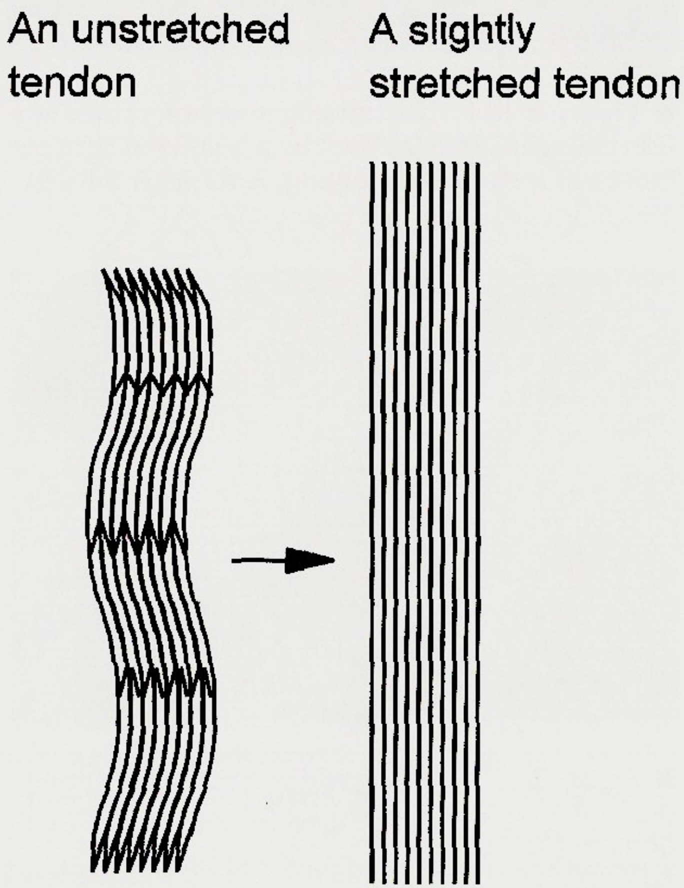


■ **Figure 2.6** The hierarchial organization of the tendon structure from collagen fibrils to the entire tendon.

Composition

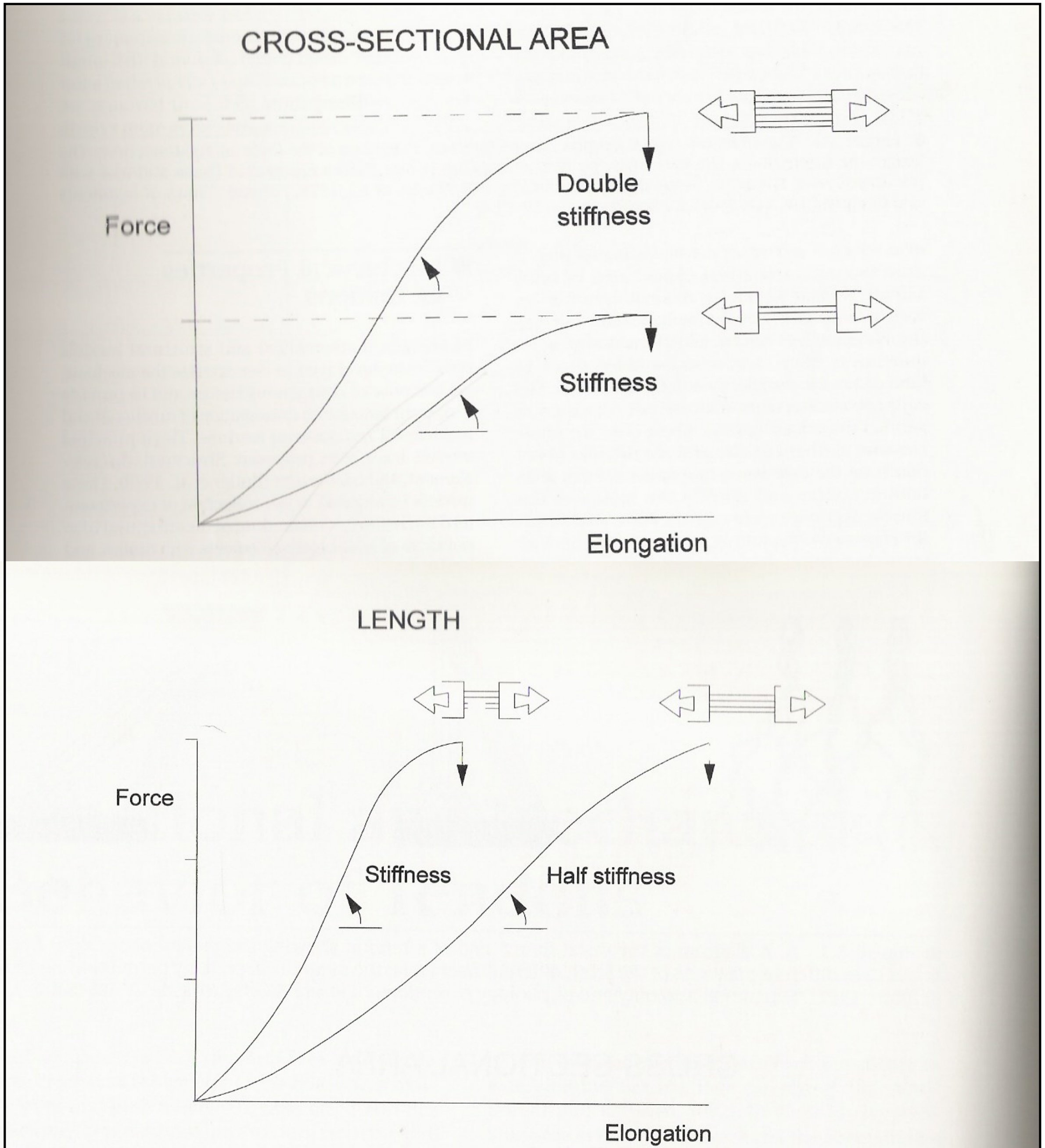
- Collagen (type I, II, III, IV and V): 70% of dry mass.
- Elastin: 2% of dry mass.
- Anorganic compunds (calcium, copper, zinc): 0.2% of dry mass.
- Water, Proteoglycans and Matrix Glycoproteins: 70% of the total mass.

Collagen fibre orientation

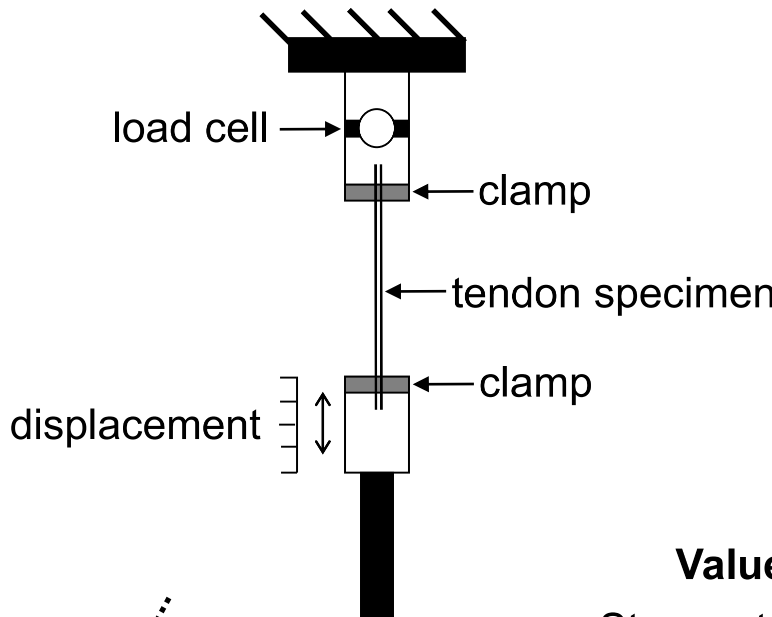


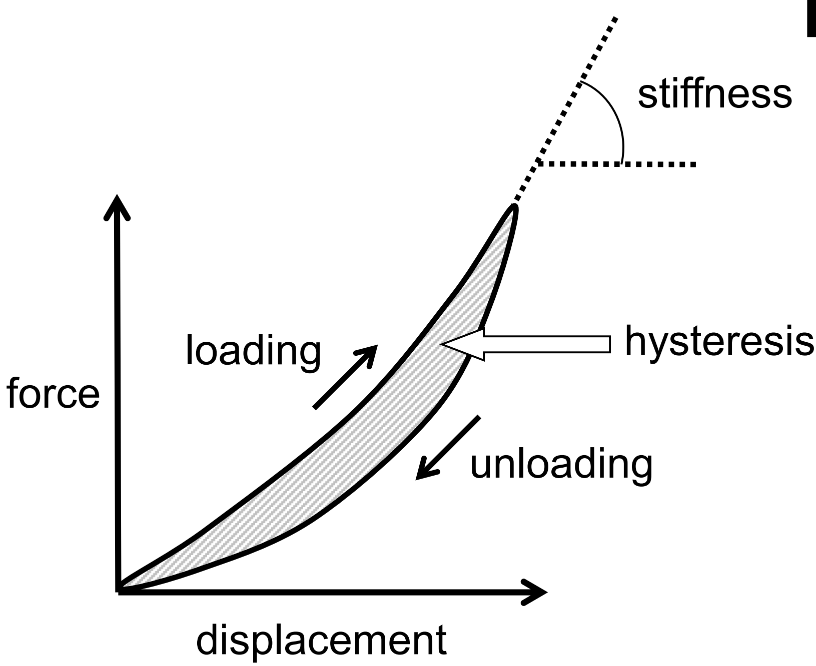
■ **Figure 2.17** The wavy configuration of the collagen fibers of an unstretched tendon disappears when the tendon is stretched slightly corresponding to straightening of the fibers.

Effect of tendon dimensions on tendon stiffness



Measurement of *in vitro* tendon mechanical properties





Values:

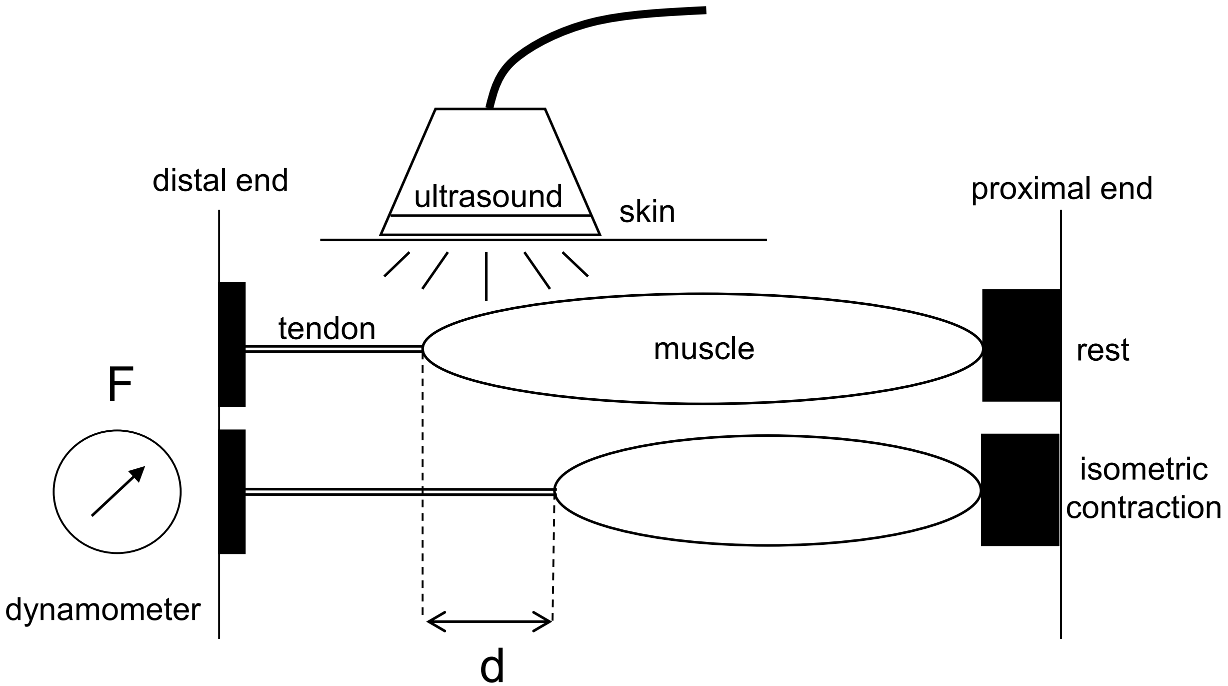
- Stress at F_{max} : ~25 MPa
- Strain at F_{max} : ~2%
- Young's modulus at F_{max}: ~1.2 GPa
- Hysteresis: ~10%

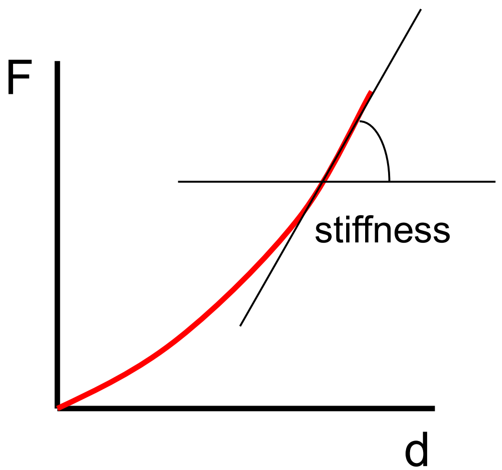
Problems:

- Specimen slippage
- Stress concentration
- Material changes from the *in vivo* to *in vitro* states

Principle of *in vivo* human tendon assessment:

An 'isometric' contraction is not truly isometric: the muscle shortens initially due to the elasticity of the in-series tendon





Young's modulus = stiffness · L/CSA

Question: Do the material properties of *in vivo* human tendon change in response to chronic loading alterations?

↓

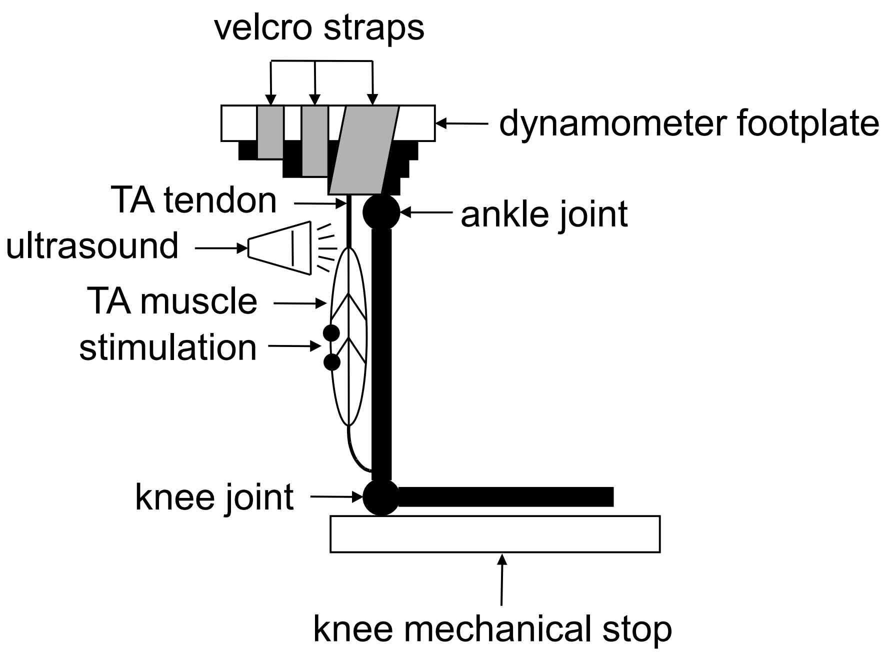
1) Comparisons between tendons subjected to different physiological loads in a given subject group

2) Examination of a given tendon in subject groups with different activity histories and ages

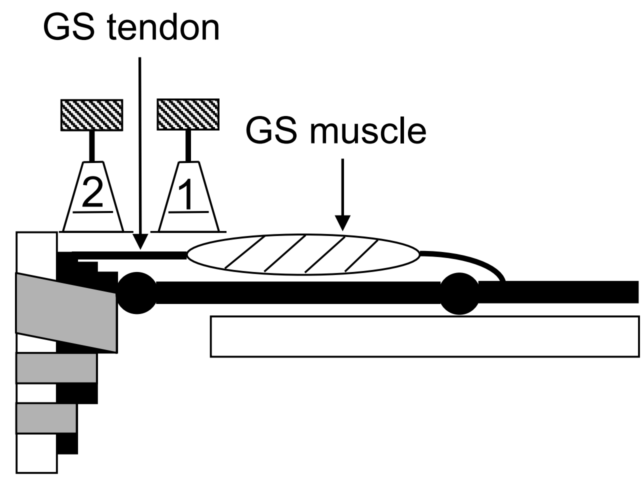
3) Investigation of the effects of interventions employing increased activity or disuse

1) Gastrocnemius (GS) tendon (high-stressed tendon) *vs.* Tibialis anterior (TA) tendon (low-stressed tendon)

TA tendon testing

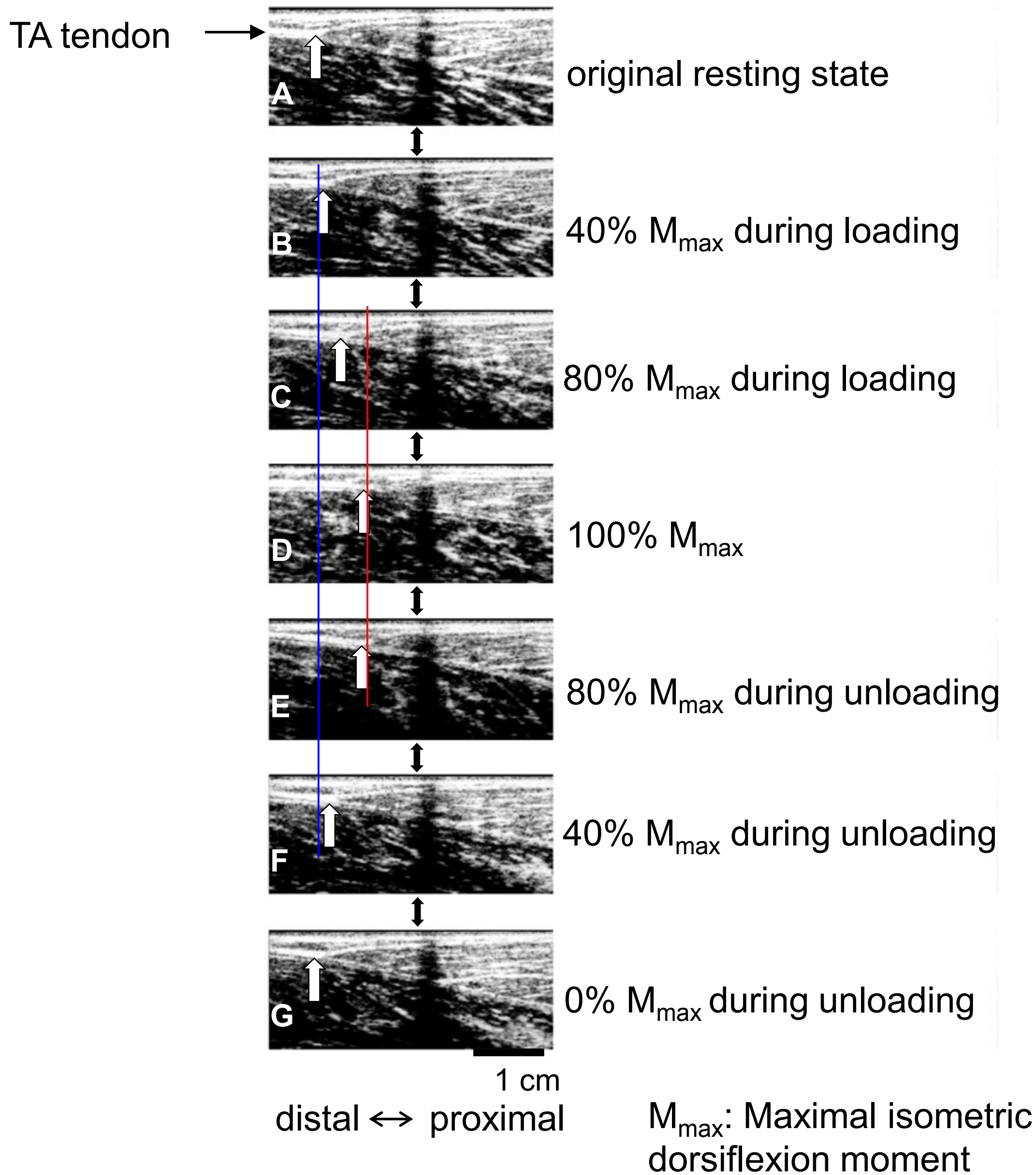


GS tendon testing



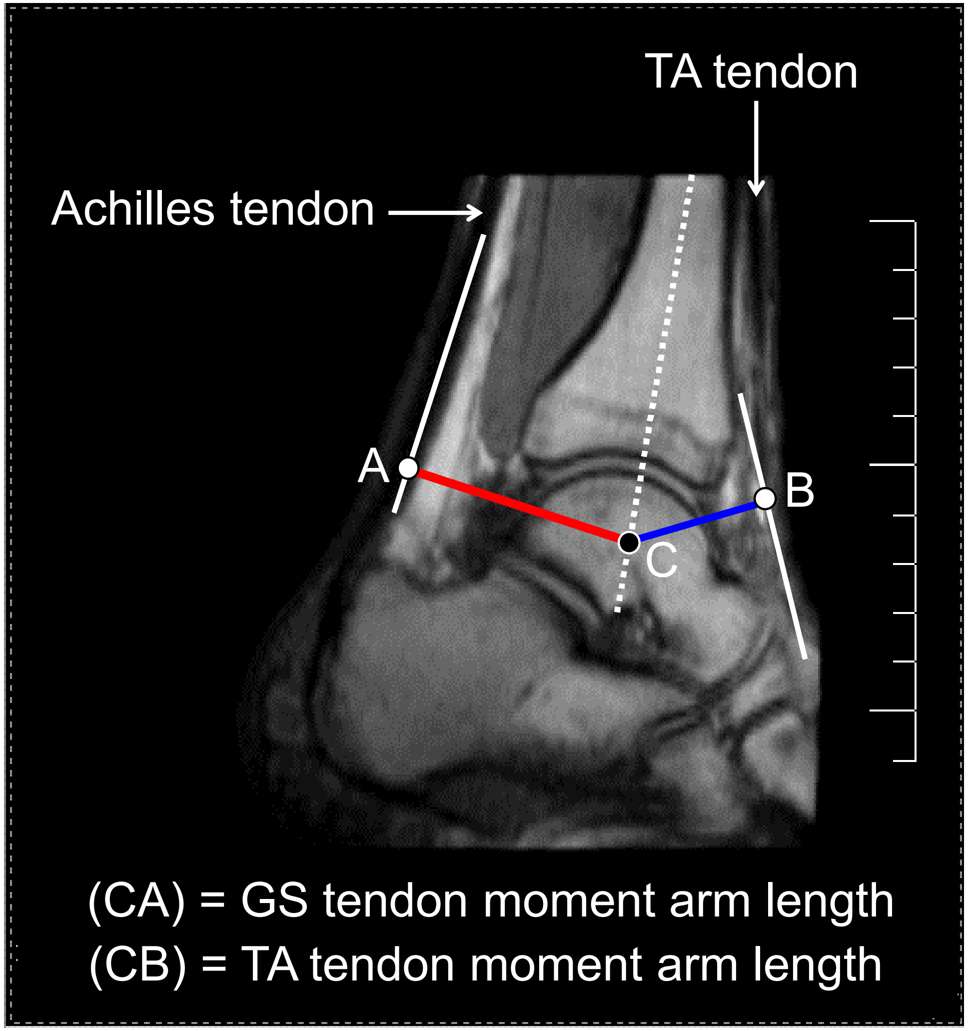
1 and 2: externally fixed
GS muscle moment: MVC@180^o -MVC@60^o

Tendon moment arms: MRI



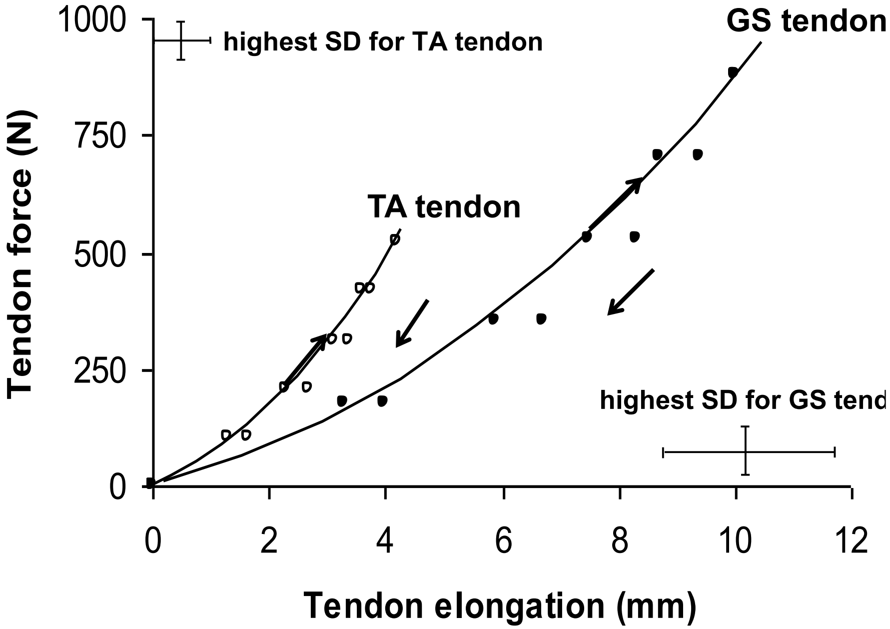
TA tendon
A
original resting state
B
40% Mmax during loading
C
80% Mmax during loading
D
100% Mmax
E
80% Mmax during unloading
F
40% Mmax during unloading
G
0% Mmax during unloading
1 cm
distal ↔ proximal
Mmax: Maximal isometric dorsiflexion moment

Tendon moment arms at the ankle

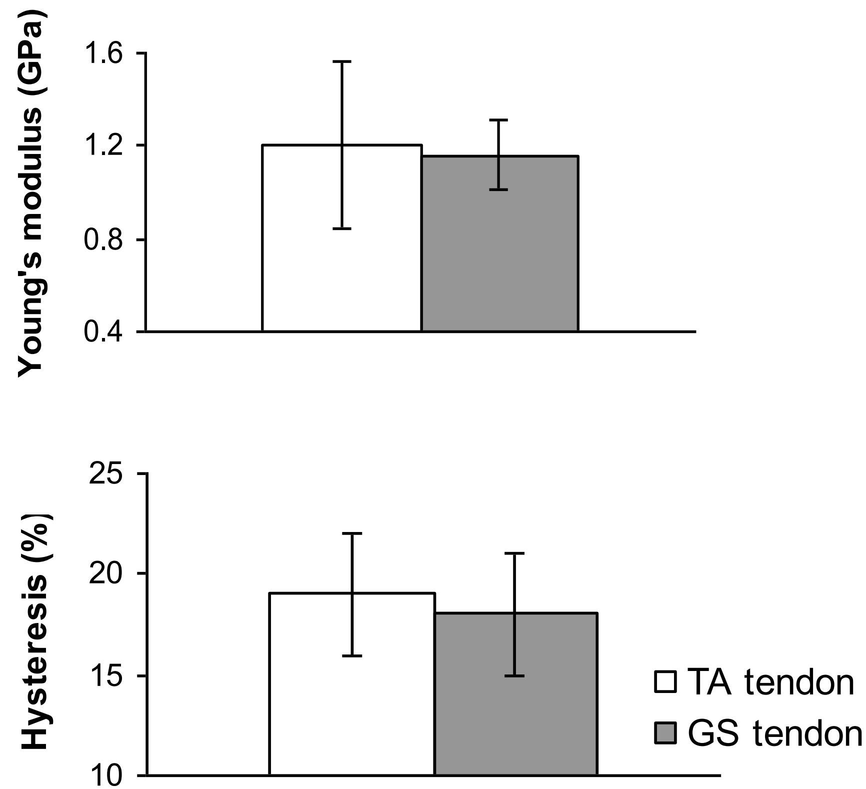


In vivo human tendon properties

(Maganaris, J Biomech 37: 1019-1027, 2002)



Mean±highest SD (n=6)



Mean±SD (n=6)

2) Examination of a given tendon in subject groups with a) different activity histories and b) different ages

↓

a) Patellar tendon properties in Spinal Cord Injured (SCI)
vs.
able-bodied (AB) individuals

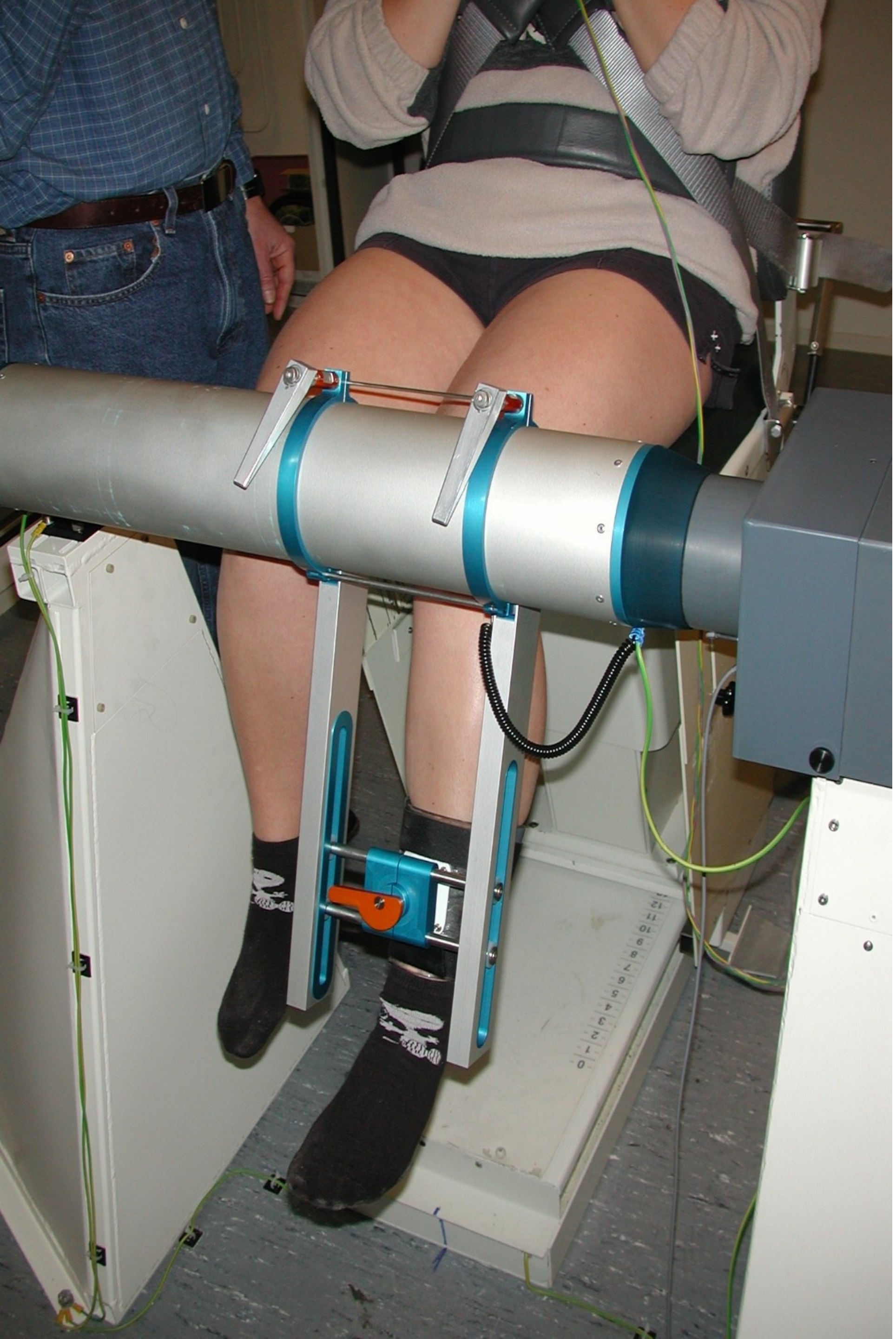
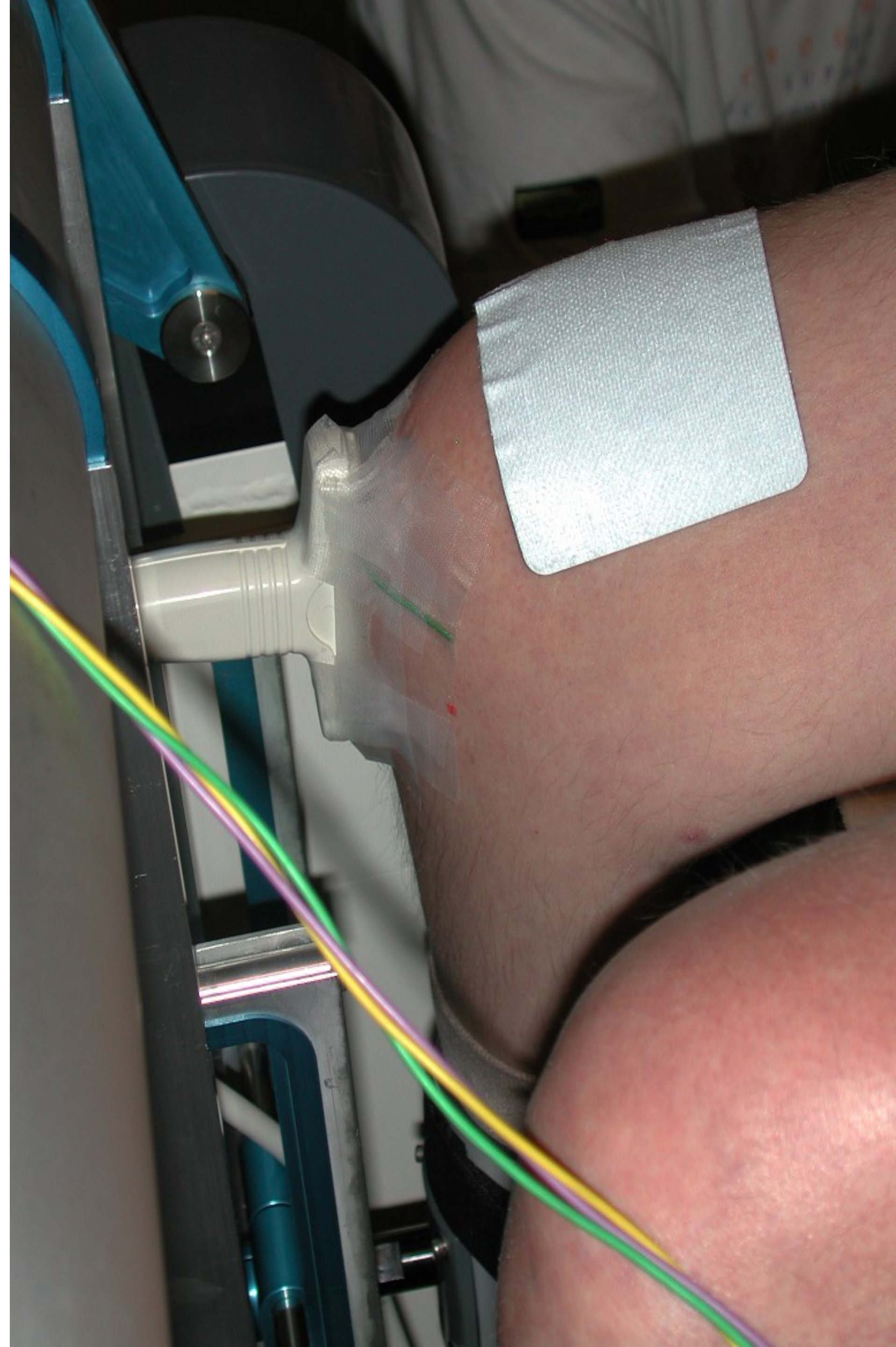
b) GS tendon properties in younger, middle-aged, and older individuals

a) SCI study

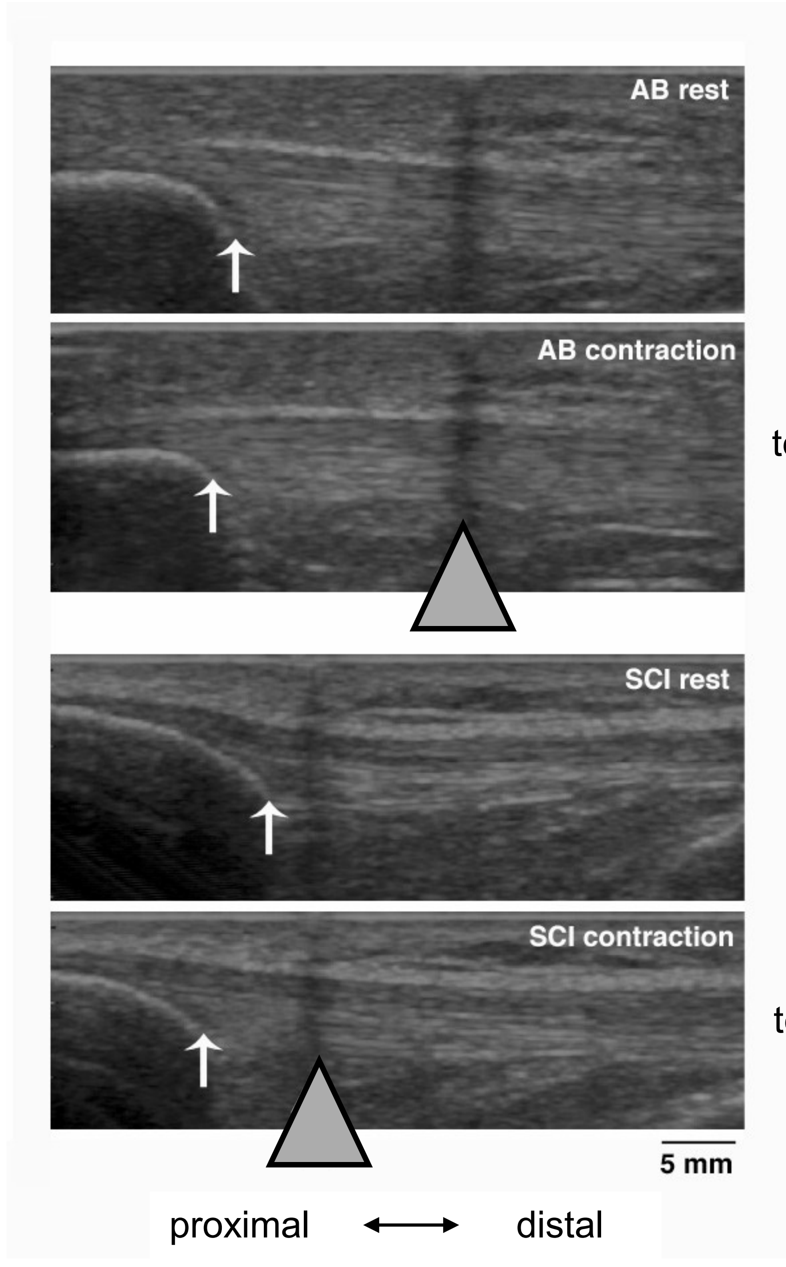
Lesion characteristics of the SCI subjects

Subject	Lesion level	Lesion duration (y)	Lesion completeness
1	C5-C6	1.5	A
2	T11	4	A
3	C5	24	A
4	C5-C6	5	B
5	L1	10	C
6	T7	4	A

Lesion completeness is classified according to the ASIA (American Spinal Injury Association) score (Maynard et al. 1997). A, sensory and motor complete; B, sensory incomplete but motor complete; C, sensory and motor incomplete, but no functional motor activity.

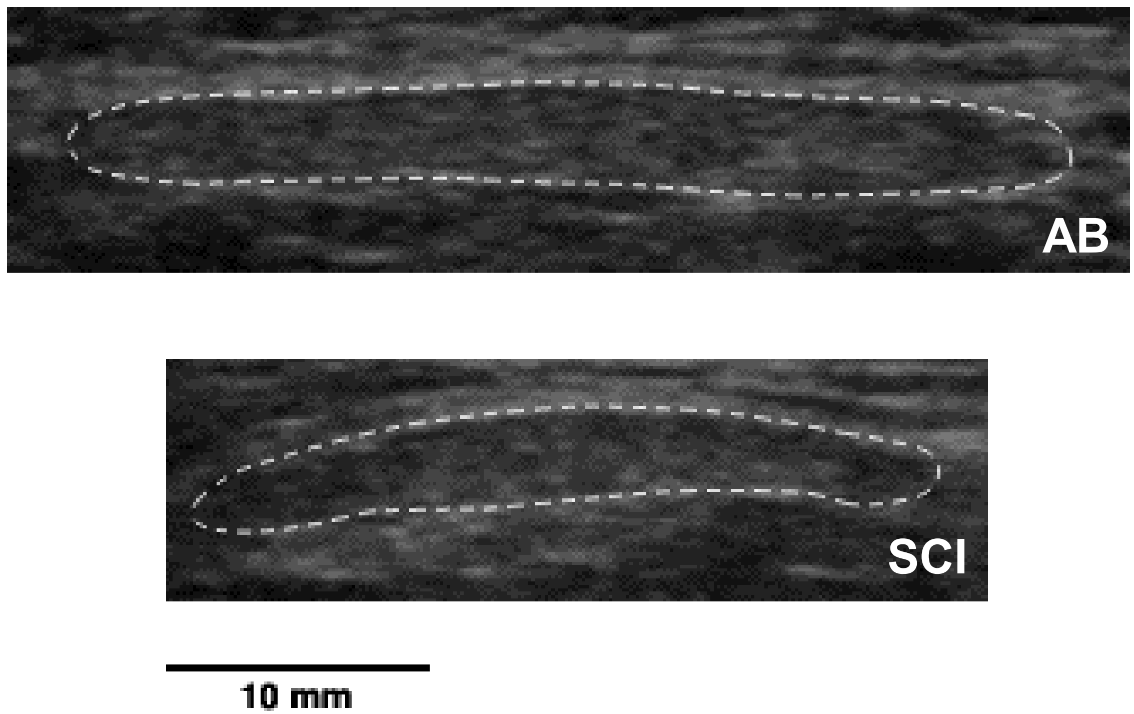
Patellar tendon elongations



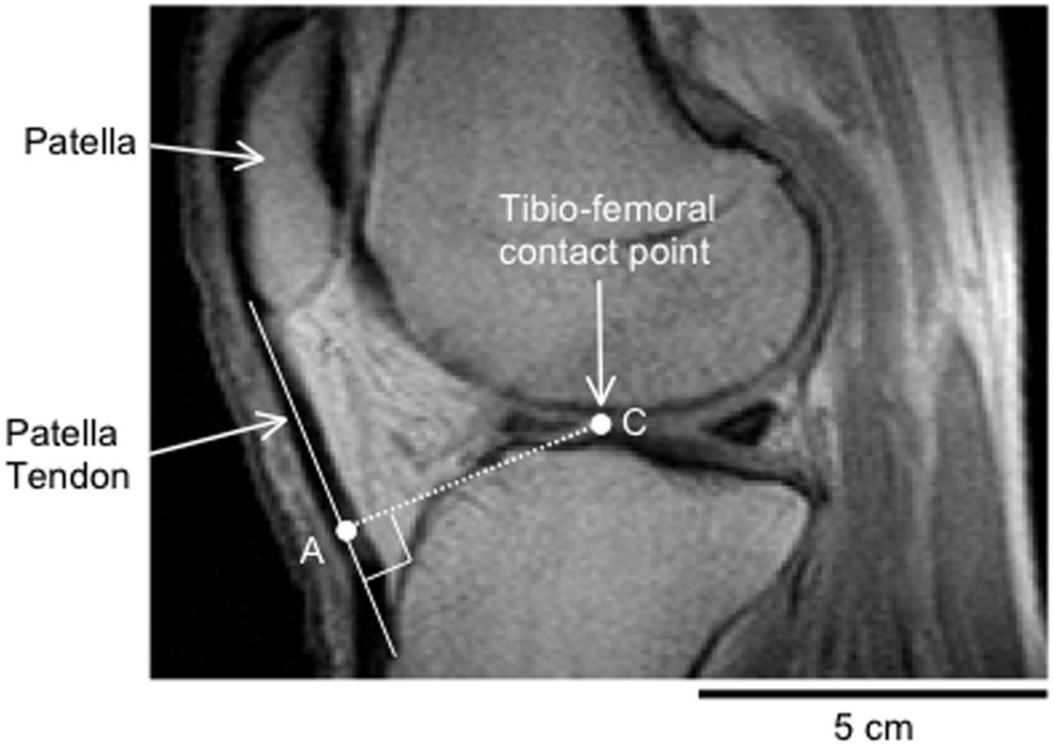
tendon force, 3702 N

tendon force, 846 N

Patellar tendon axial-plane sonographs

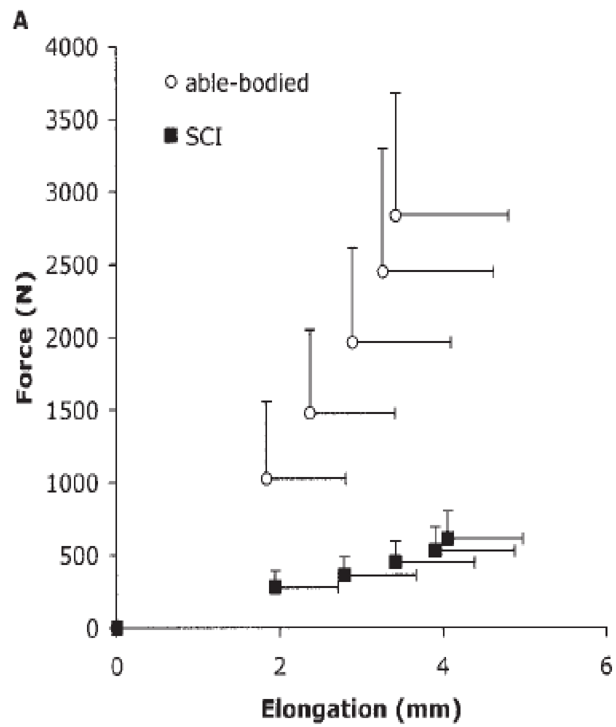


Knee MRI



Patellar tendon moment arm (CA)

SCI vs. AB tendon force-elongation and stress-strain curves



17% CSA reduction

64% stiffness reduction

55% Young’s modulus reduction

mean±SD (n= 6 SCI and 8 AB)

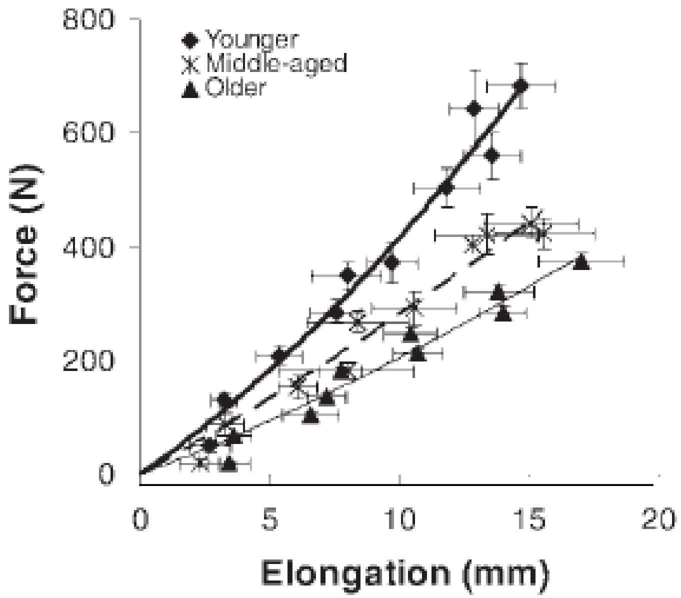
(Maganaris et al. Muscle Nerve 33: 85-92, 2006)

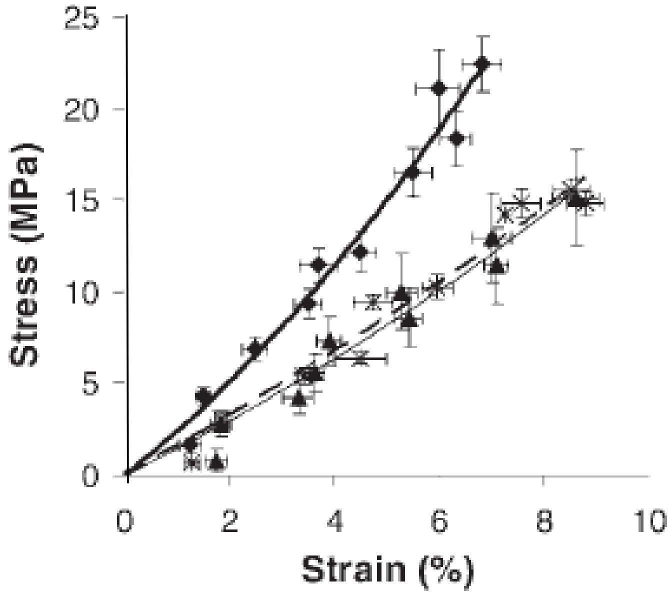
b) Ageing study: GS tendon properties

(Onambele et al. J Appl Physiol 100: 2048-2056, 2006)

36% stiffness reduction

48% Young's modulus reduction





Mean±SD (n=24 Younger, 10 middle-aged, and 36 Older)
Age: younger, 24±1 y; middle-aged, 46±1 y, older, 68±1 y

3) Investigation of the effects of interventions employing a) increased activity and b) disuse

a) Effect of resistance training on patellar tendon in old age

Training group n = 9

Age: 74±3 years

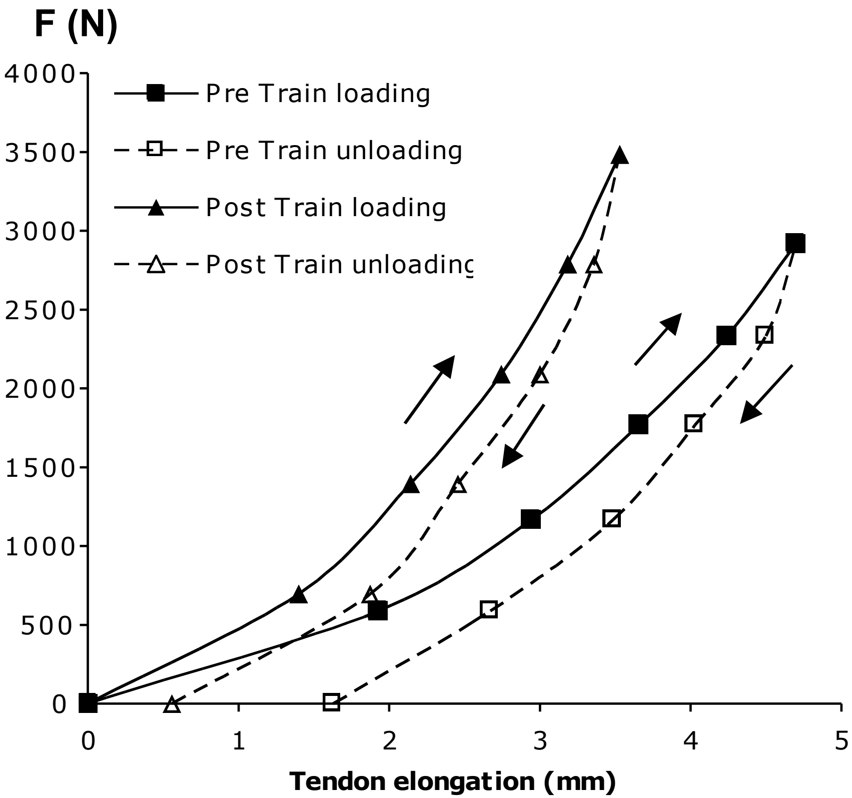
Control group n = 9

Age: 66±2 years

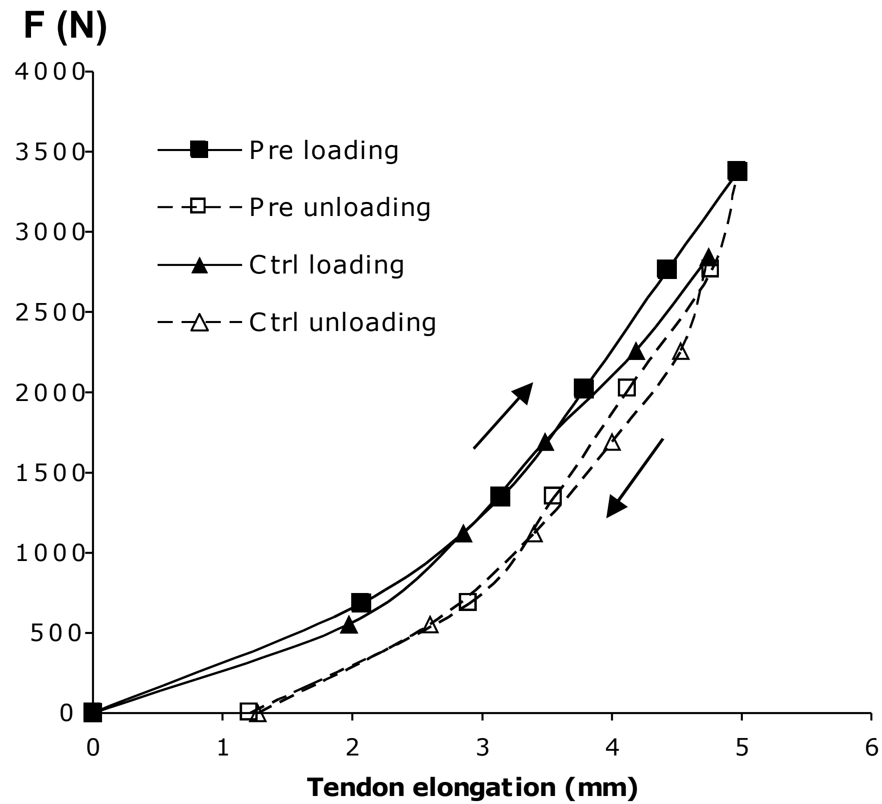
- Knee extension & leg press exercises
- 2 sets of ~10 repetitions
- 80% of 5-repetition maximum
- 3 times per week, for 14 weeks

Tendon adaptations to resistance training in old age

Training group



Control group



Stiffness increase by 69%
Young's modulus increase by 65%

Mean values are shown

(Reeves et al. Muscle Nerve 28: 74-81, 2003)

b) Disuse: Effect of bed-rest on GS tendon

90-Days Unloading (*Simulated Microgravity*)

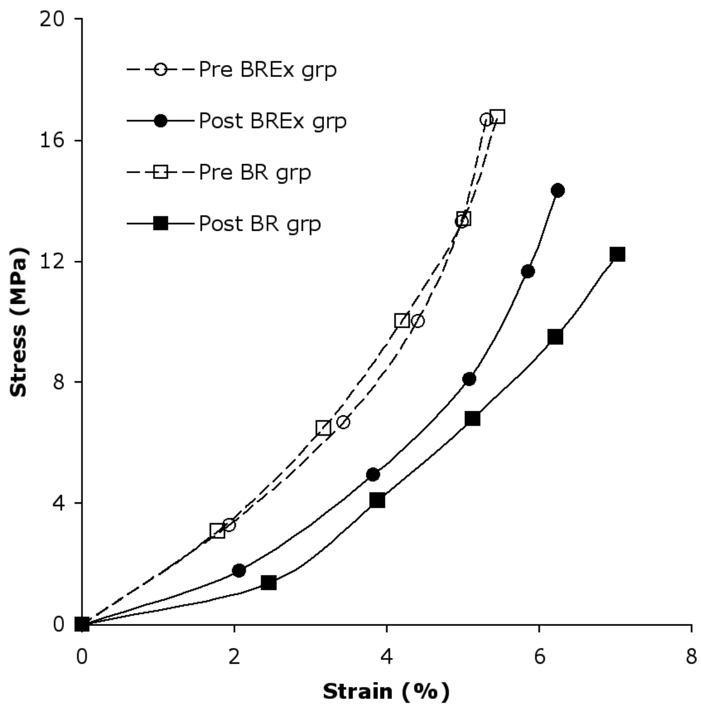
6 deg head-down tilt bed rest

Bed rest only group (n=9)

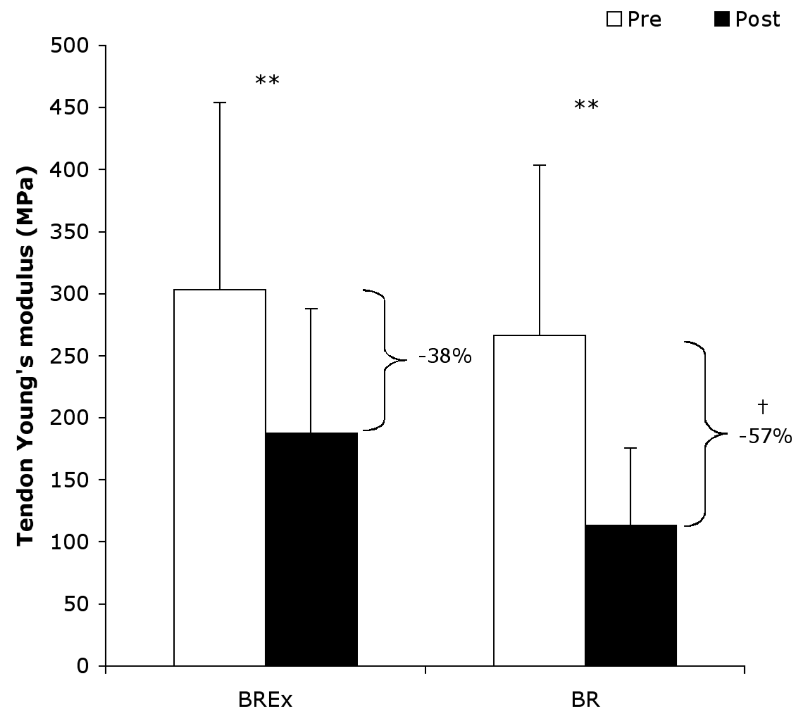
Exercise countermeasures

Bed rest + exercise group (n=9)

GS Tendon adaptations to 90 Days Unloading



Mean data are shown (n=9 in each group)



Mean±SD (n=9 in each group)

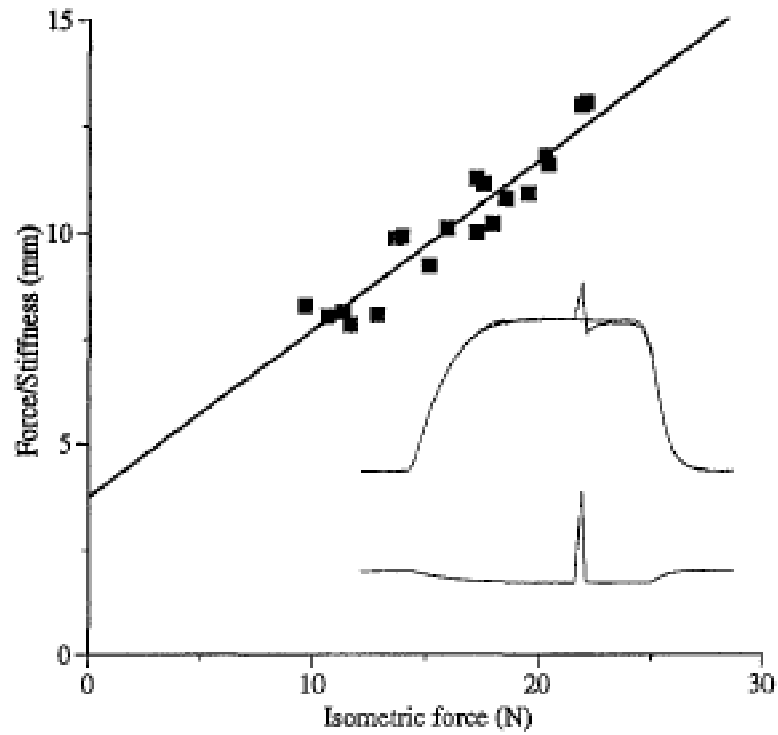
(Reeves et al. J Appl Physiol 98: 2278-2286, 2005)

Eur J Appl Physiol (1996) 72:380–382

SHORT COMMUNICATION

C. S. Cook · M. J. N. McDonagh

Measurement of muscle and tendon stiffness in man



Total compliance is the sum of the two individual compliances (compliance = 1/stiffness).

Tendon stiffness is defined as a constant k

Muscle stiffness (M) is defined as M=force/a where a is a constant.

1/Total complex stiffness = 1/Tendon stiffness + 1/Muscle stiffness

1/Total complex stiffness = 1/k + a/force

Y =mX + c is obtained: force/Total complex stiffness = (l/k)force + a

Eur J Appl Physiol (2010) 110:1037–1046
DOI 10.1007/s00421-010-1582-8

ORIGINAL ARTICLE

Changes in tendon stiffness and running economy in highly trained distance runners

Jared R. Fletcher · Shane P. Esau ·
Brian R. MacIntosh

Eur J Appl Physiol (2011) 111:539–548
DOI 10.1007/s00421-010-1667-4

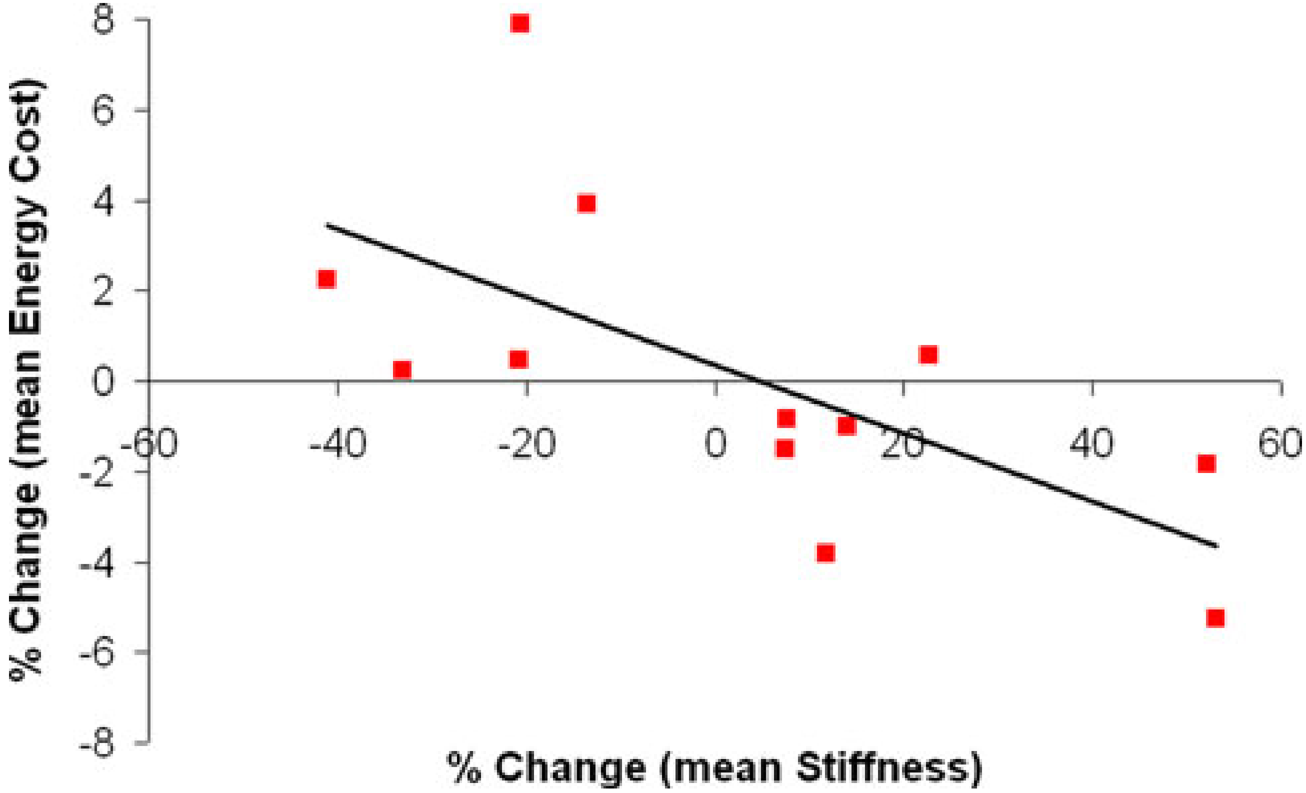
ORIGINAL ARTICLE

Effects of plyometric training on both active and passive parts of the plantarflexors series elastic component stiffness of muscle–tendon complex

Alexandre Fouré · Antoine Nordez ·
Peter McNair · Christophe Cornu

Accepted: 20 September 2010 / Published online: 8 October 2010

C and stiffness



Relationship between relative change in stiffness and change in economy. Data are expressed as an average % change from baseline across all measured velocities (75, 85 and 95% sLT) and force levels (25–45, 30–70 and 50–100% MVC) following the 8-week training protocol for all subjects. The relationship is significant ($r = -0.723$; $p = 0.005$)

Eur J Appl Physiol (2015) 115:651–673
DOI 10.1007/s00421-015-3115-y

INVITED REVIEW

Factors affecting the energy cost of level running at submaximal speed

Jean-René Lacour · Muriel Bourdin

Conclusions

- There are no differences in human tendon material properties between tendons subjected to different physiological loads
- Disuse and ageing deteriorate the tendon's material - Disuse seems to have a rapid effect
- Exercise training improves the tendon's material
- Physiological functioning is adequate to maintain the material properties of *in vivo* human tendons at a given 'base-line' level, deviation from which arise when the base-line loading is chronically affected
- Further studies are required to identify the mechanisms and determine the time course of the above adaptations