Training-induced changes in muscles: A cautionary tale

Your Prescription for Health
Exercise is Medicine®

Need to understand specific effects of different forms of training on different elements within muscle, and effects on whole muscle function…

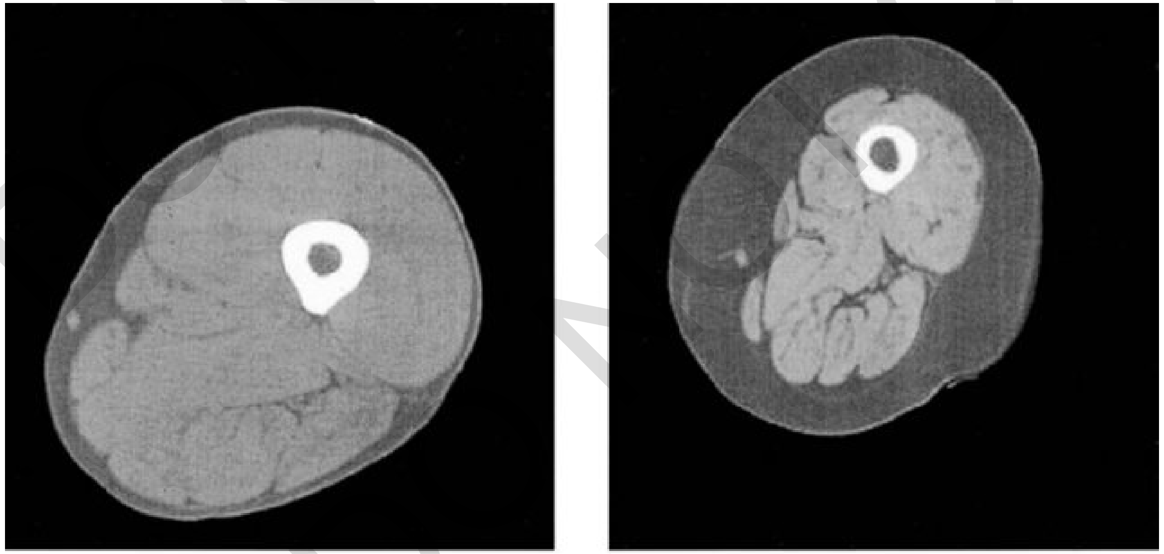
…then may get close to personalised training as part of personalised medicine.

Journal of Gerontology: MEDICAL SCIENCES
2003, Vol. 58A, No. 11, 1012–1017

Sarcopenia: Effects on Body Composition and Function

Ronenn Roubenoff

Clearly, significant changes in muscle size/mass will affect function…



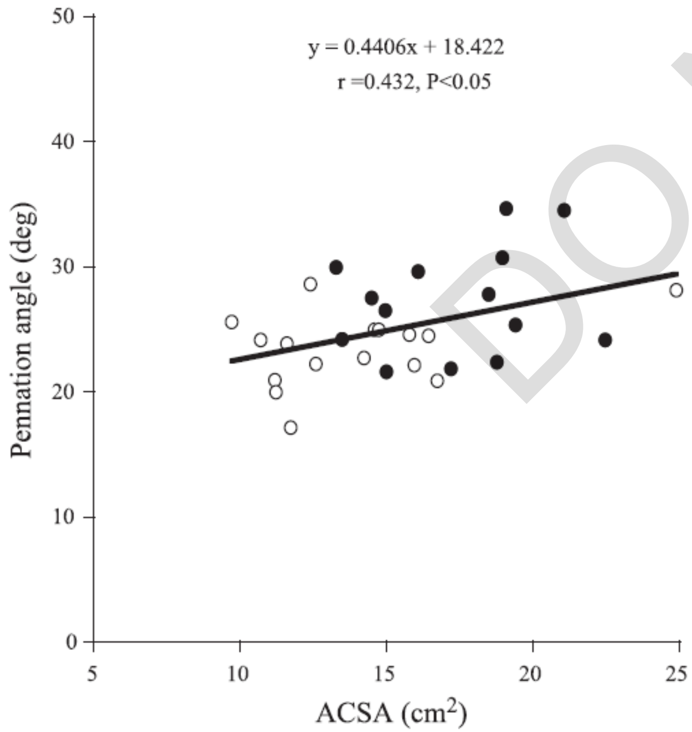
Young, active — Old, sedentary

J Appl Physiol 95: 2229–2234, 2003.

Effect of aging on human muscle architecture

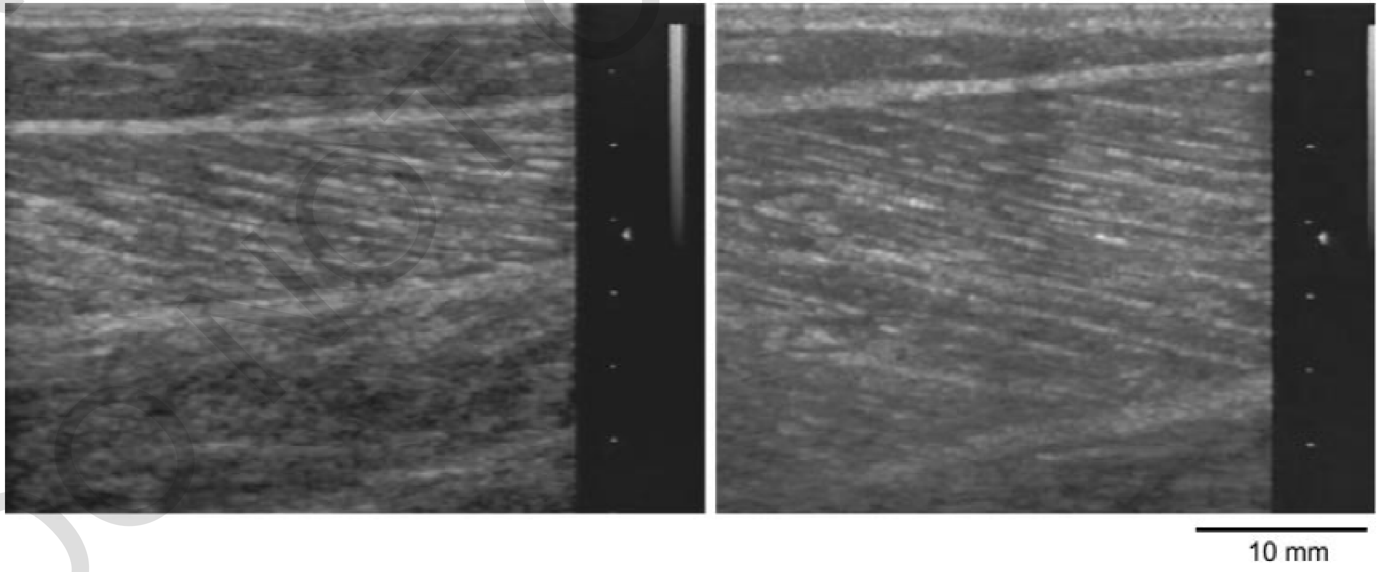
M. V. Narici,[1] C. N. Maganaris,[1] N. D. Reeves,[1] and P. Capodaglio[2]

Pennation angle and fascicle length also decrease with age/disuse… effect on function?



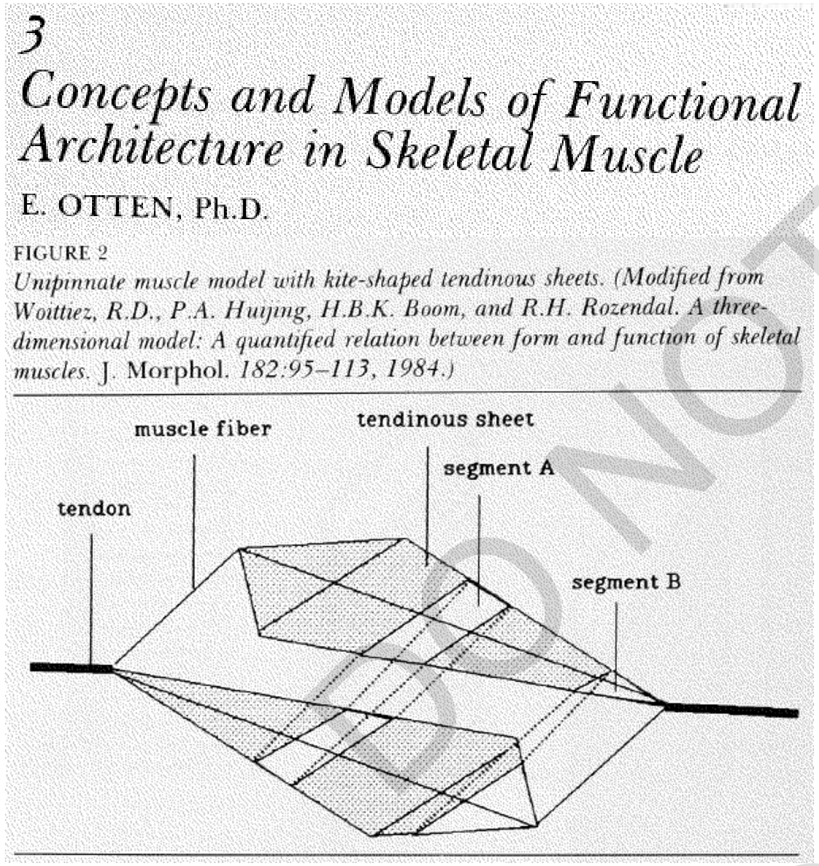
Older

Younger



Muscle Architecture Rules…

Otten 1988, Ex Sports Sci Rev


3

Concepts and Models of Functional Architecture in Skeletal Muscle

E. OTTEN, Ph.D.

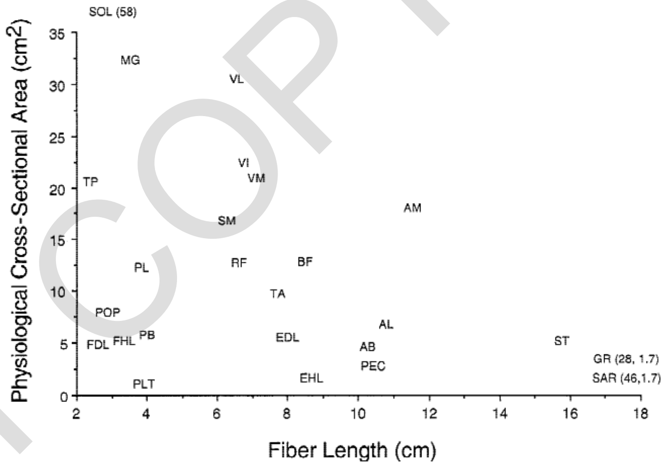
FIGURE 2

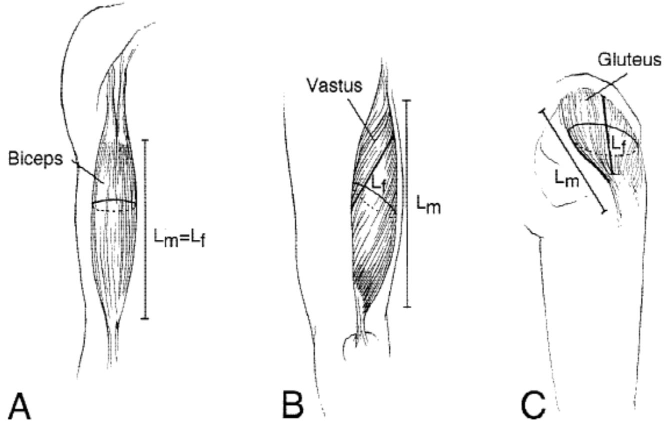
Unipinnate muscle model with kite-shaped tendinous sheets. (Modified from Woittiez, R.D., P.A. Huijing, H.B.K. Boom, and R.H. Rozendal. A three-dimensional model: A quantified relation between form and function of skeletal muscles. J. Morphol. *182:95–113, 1984.)*

Lieber & Fridén 2000, Muscle Nerve

FUNCTIONAL AND CLINICAL SIGNIFICANCE OF SKELETAL MUSCLE ARCHITECTURE

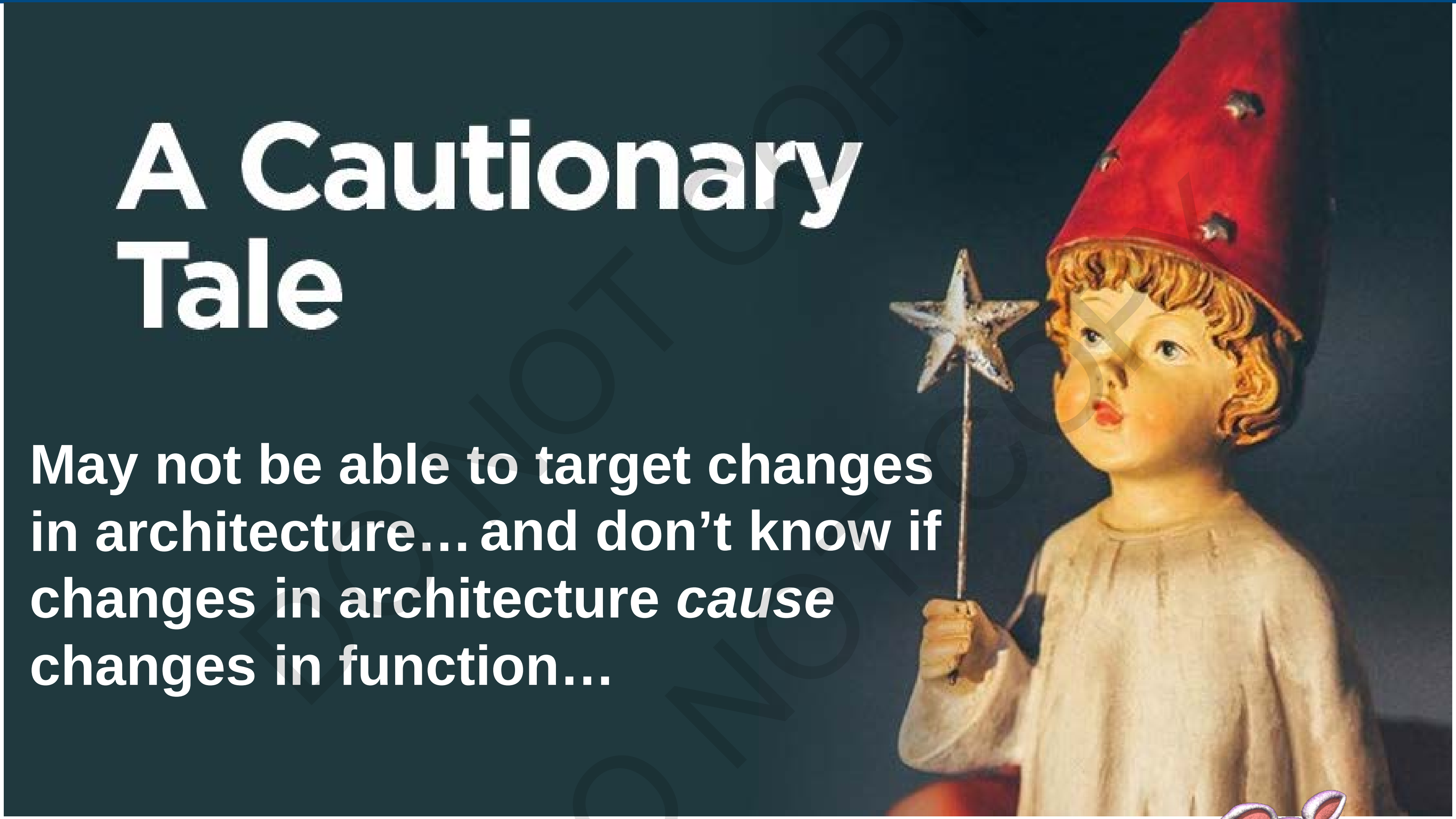
RICHARD L. LIEBER, PhD,[1,2] and JAN FRIDÉN, MD, PhD[3]





…change it,

change function



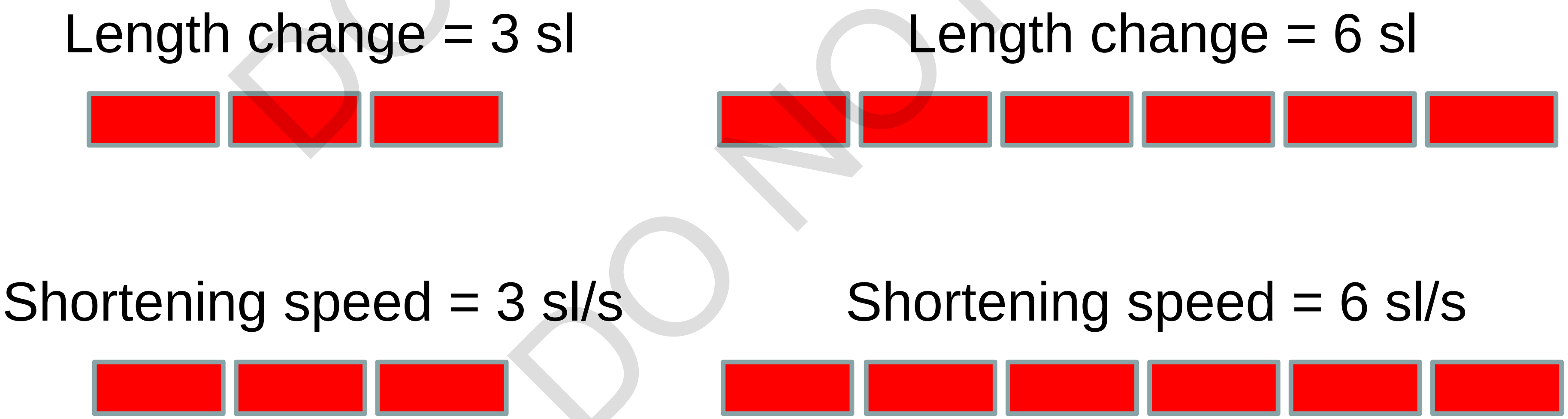
May not be able to target changes in architecture… and don't know if changes in architecture *cause* changes in function…

Are we chasing the wrong rabbit?

Fibre Length and Work Capacity

Longer fibres, or fascicles, should be ideal for increased work capacity and muscle shortening speed

- Examples: gluteus maximus, hamstrings, quadriceps, pectorals, biceps brachii.



Q: Can we increase fascicle length using strength training (also want ↑ CSA)?

Q: Are changes in fascicle length related to muscular properties such as the force-length (torque-angle) relation and high-speed force production?

A: Eccentric training may be the key…?

Decline running produces more sarcomeres in rat vastus intermedius muscle fibers than does incline running

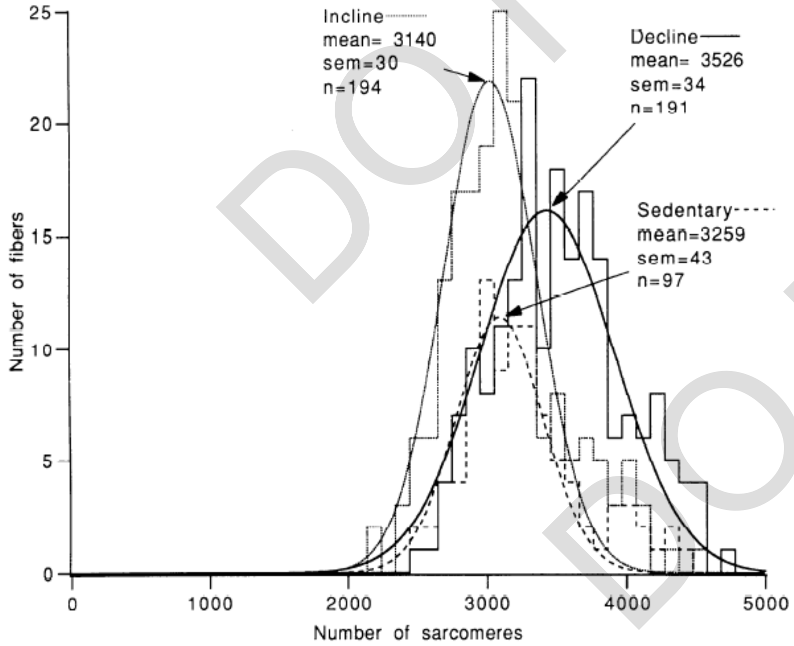
R. LYNN AND D. L. MORGAN *J. Appl. Physiol.* 77(3): 1439–1444, 1994.

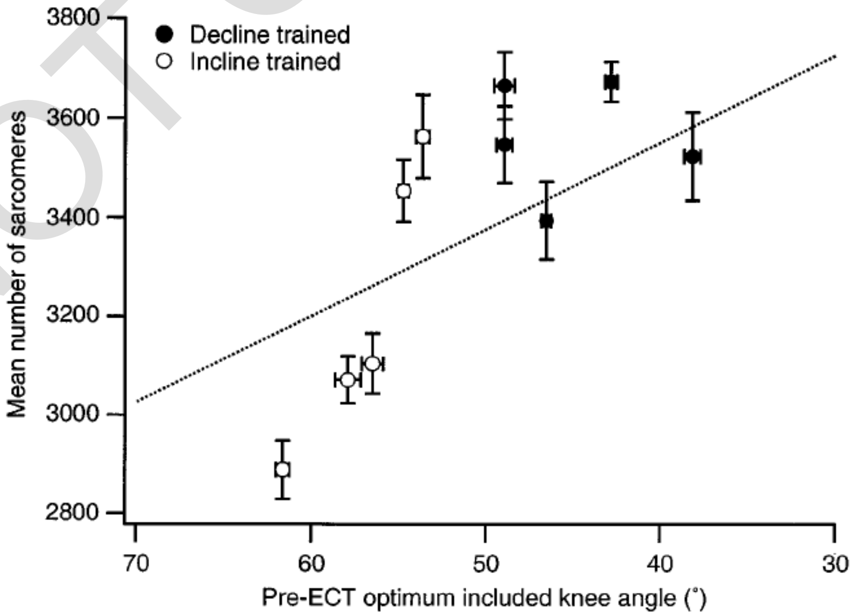
Differences in rat skeletal muscles after incline and decline running

R. LYNN,[1] J. A. TALBOT,[2] AND D. L. MORGAN[1]

J Appl Physiol, 1998

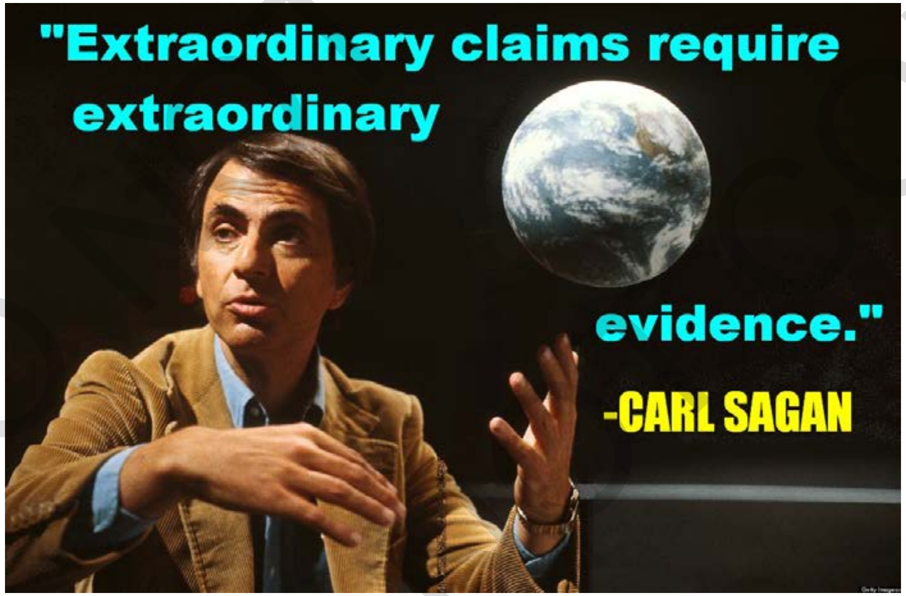
Daily running for 1 wk, 16º incline or decline





Next slides are fast:

I want to present all the evidence…



but don't have time for details…

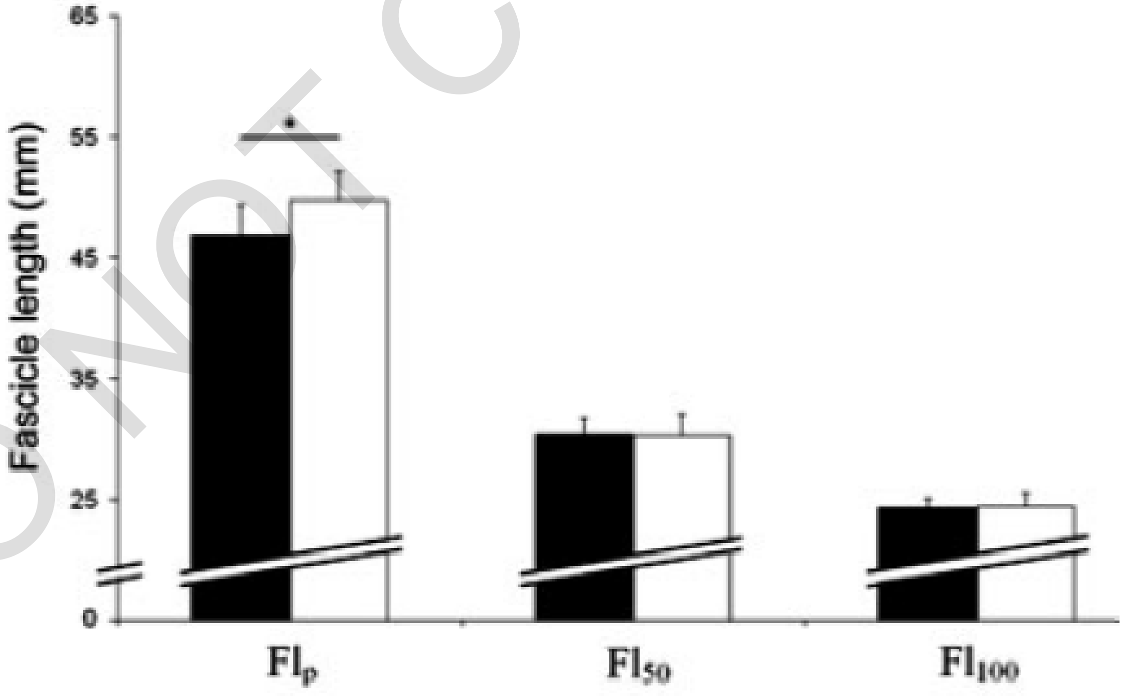
Muscle Nerve 39: 819–827, 2009

BEHAVIOR OF FASCICLES AND THE MYOTENDINOUS JUNCTION OF HUMAN MEDIAL GASTROCNEMIUS FOLLOWING ECCENTRIC STRENGTH TRAINING

JULIEN DUCLAY, PhD,[1] ALAIN MARTIN, PhD,[1] ALICE DUCLAY, MD,[2]
GILLES COMETTI, PhD,[2*] and MICHEL POUSSON, PhD[1]

7 wk eccentric strength training

But no Conc control group: **Contraction mode-specific?**



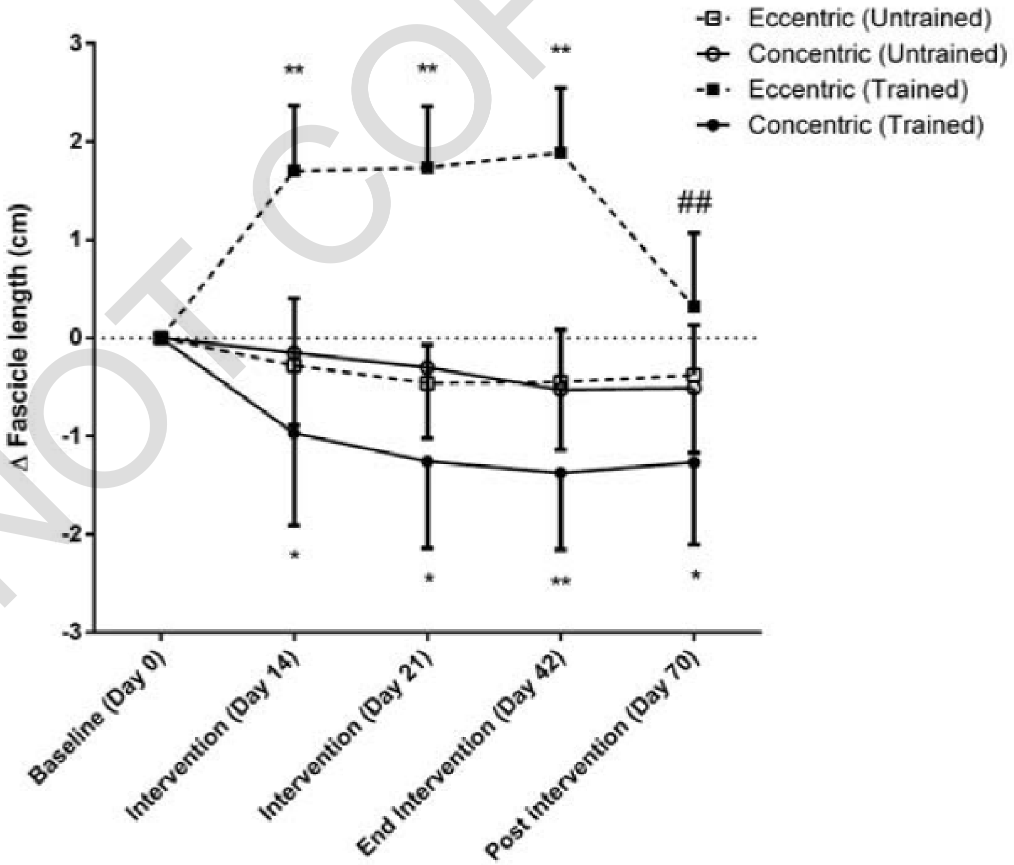
Architectural Changes of the Biceps Femoris Long Head after Concentric or Eccentric Training

RYAN G. TIMMINS[1], JOSHUA D. RUDDY[1], JOEL PRESLAND[1], NIRAV MANIAR[1], ANTHONY J. SHIELD[2], MORGAN D. WILLIAMS[3], and DAVID A. OPAR[1]
Med. Sci. Sports Exerc., Vol. 48, No. 3, pp. 499–508, 2016.
Med. Sci. Sports Exerc., Vol. 48, No. 3, pp. 499–508, 2016.

6 wk isokinetic Ecc vs. Conc training

↑ FL after eccentric,
↓ after concentric training

But, BF imaging difficult:
True effect?



ORIGINAL ARTICLE

ACTA PHYSIOLOGICA

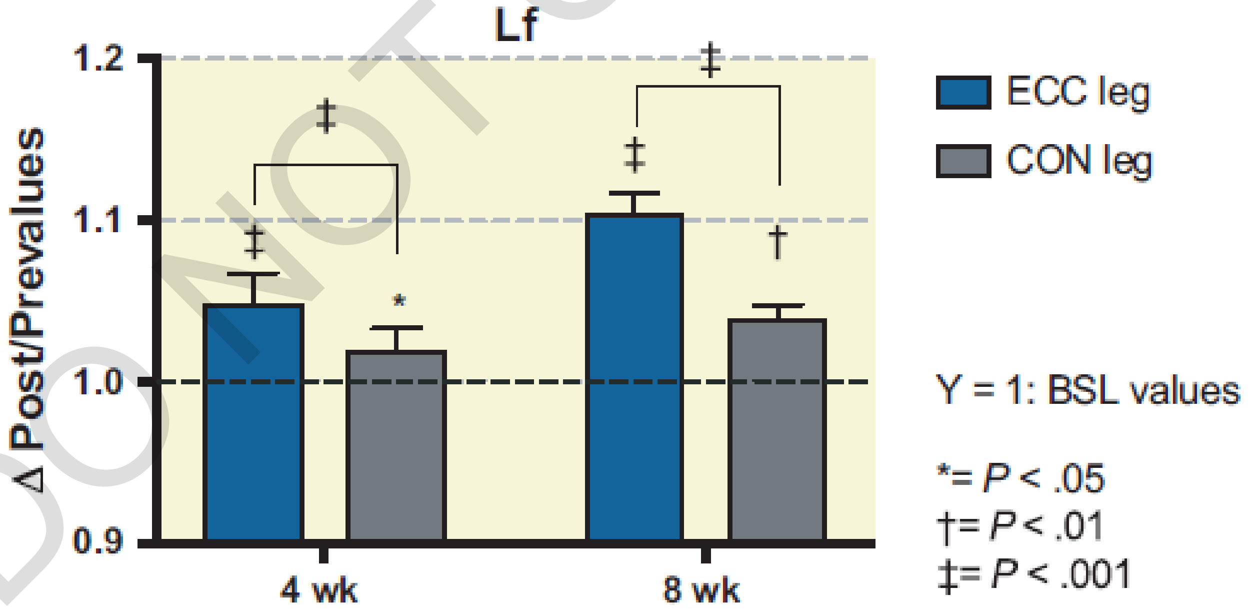
Regional regulation of focal adhesion kinase after concentric and eccentric loading is related to remodelling of human skeletal muscle

M. V. Franchi[1,2] | S. Ruoss[1] | P. Valdivieso[1] | K. W. Mitchell [2] | K. Smith [2] | P. J. Atherton[2] | M. V. Narici[2,3] | M. Flück[1]

Acta Physiologica. 2018;e13056.

8 wk unilateral strength training (Ecc vs. Conc)

But Ecc loading was greater (80% Ecc vs. Conc max): **Mode or Load?**

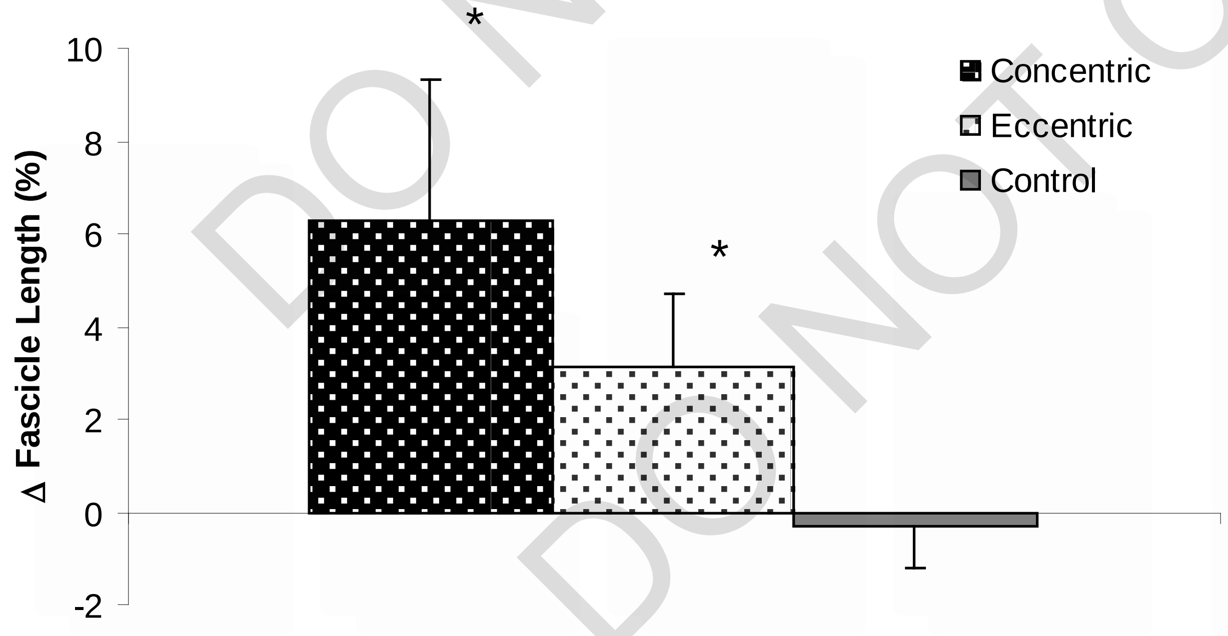


J Appl Physiol 103: 1565–1575, 2007.
First published August 23, 2007; doi:10.1152/japplphysiol.00578.2007.

Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles

Anthony J. Blazevich, Dale Cannavan, David R. Coleman, and Sara Horne

10 wk eccentric vs. concentric training: No difference (vastus lateralis)



Scand J Med Sci Sports. 2018;1–11.

Stretch imposed on active muscle elicits positive adaptations in strain risk factors and exercise-induced muscle damage

Anthony David Kay[1] | Bethanee Rubley[1] | Chris Talbot[1] | Minas Mina[2] | Anthony William Baross[1] | Anthony John Blazevich[3]

6 wk eccentric isokinetic (active stretch): No changes in experimental or control groups

	Experimental group	
Measurements	**Pre-training**	**Post-training**
Knee flexion ROM (°)	147.7 ± 2.6	152.9 ± 2.7*
Elastic energy storage (Nm^2)	152.4 ± 33.1	222.6 ± 43.0*
Stretch tolerance (Nm)	96.2 ± 17.0	133.4 ± 21.5*
MTC stiffness ($Nm°^{-1}$)	5.1 ± 1.1	4.7 ± 1.2
VL tendon stiffness (Nm/mm)	5.1 ± 0.3	5.5 ± 0.4*
VL fascicle length (mm)	127.4 ± 6.3	126.3 ± 6.1
VL pennation angle (°)	12.5 ± 0.4	13.6 ± 0.4*
VL thickness (mm)	27.3 ± 1.1	29.3 ± 1.1*

© 2014. Published by The Company of Biologists Ltd | The Journal of Experimental Biology (2014) 217, 2726-2733 doi:10.1242/jeb.100370

THE COMPANY OF Biologists

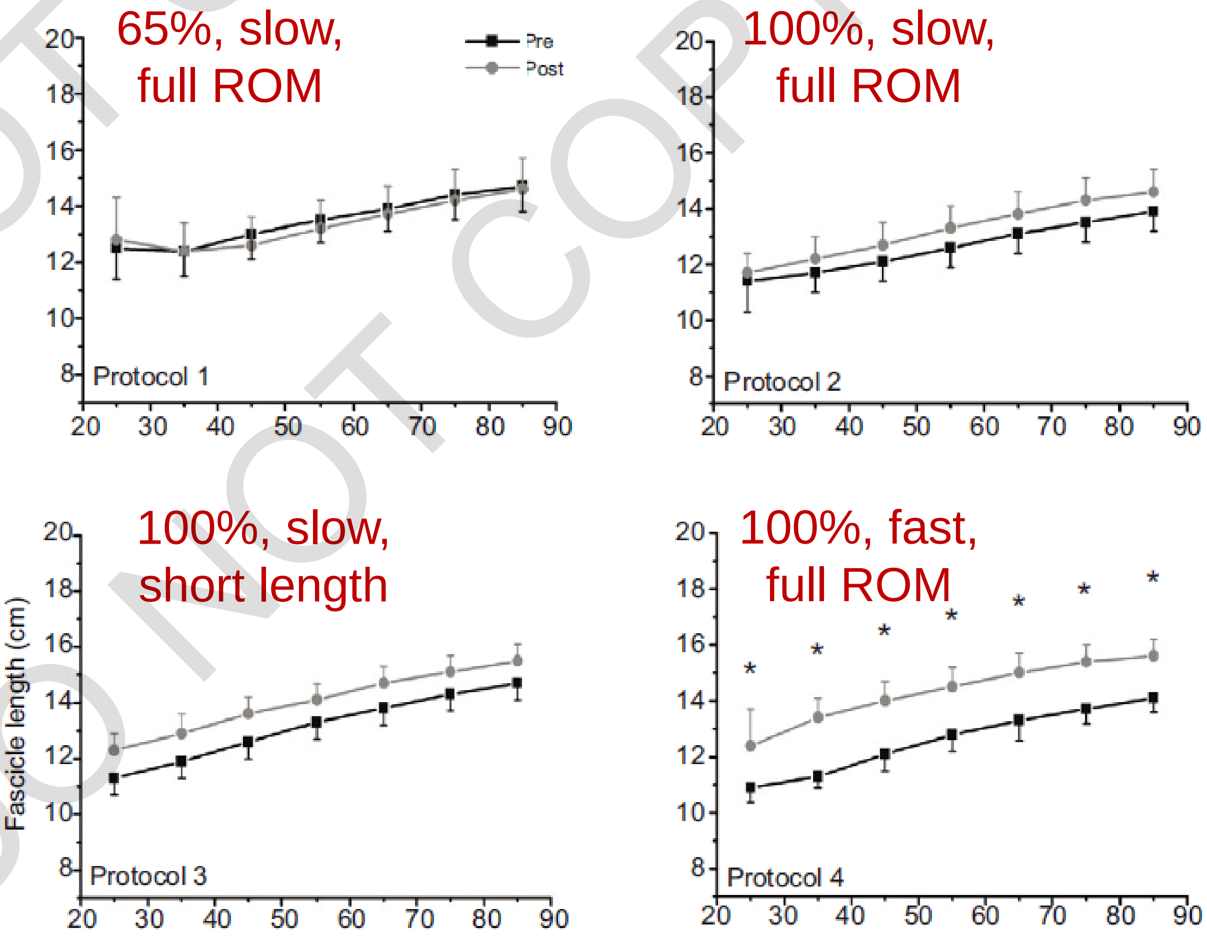
Effects of load magnitude, muscle length and velocity during eccentric chronic loading on the longitudinal growth of the vastus lateralis muscle

Ali Sharifnezhad, Robert Marzilger and Adamantios Arampatzis*

10 wk isokinetic eccentric training

Minimal effect of eccentric on FL…

…some effect in 'fast' condition



Is eccentric training a unique stimulus?

So…

Changes in architecture (at least fascicle length) not always observed as expected:

– Concentric training → increases in fascicle length

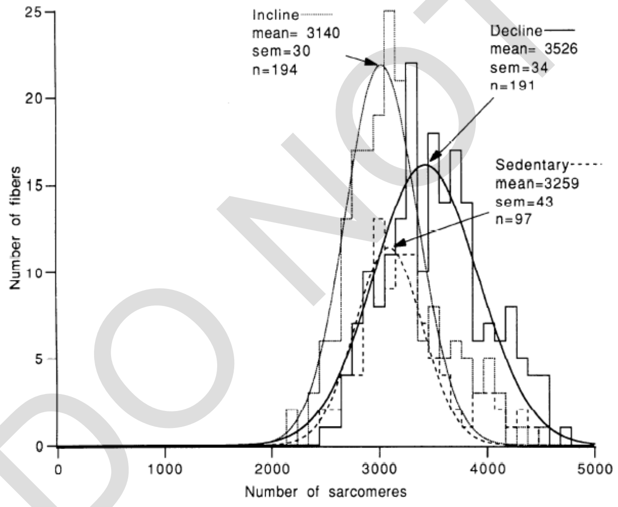
– Fascicle length changes after eccentric training = concentric training

– Fascicle length changes not always seen after eccentric training

Is there a mismatch between human and animal studies?

Decline running produces more sarcomeres in rat vastus intermedius muscle fibers than does incline running

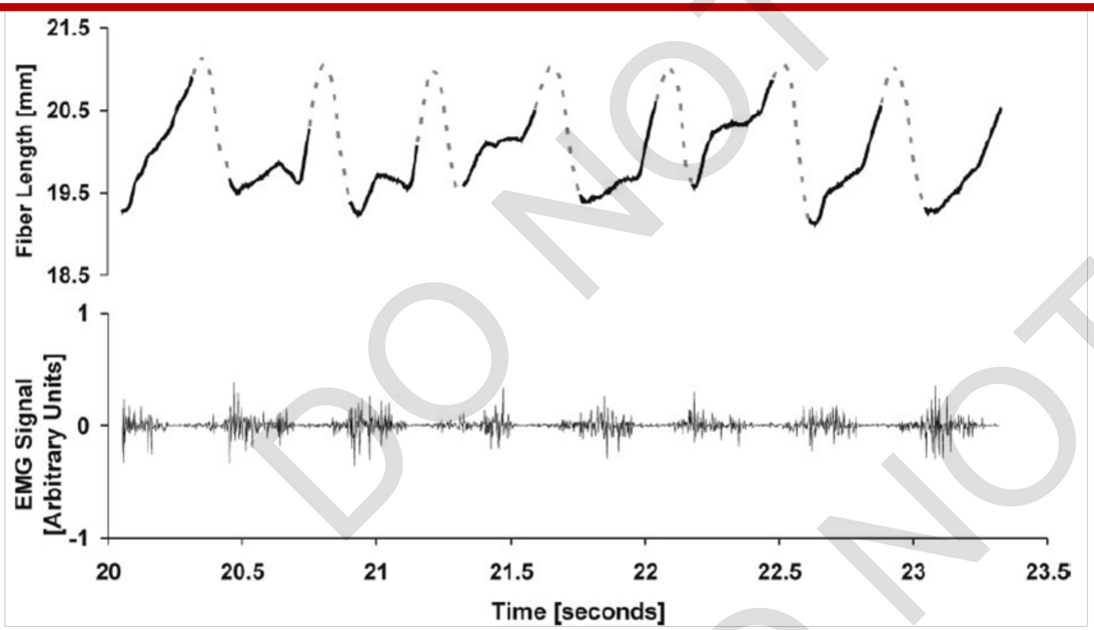
R. LYNN AND D. L. MORGAN   *J. Appl. Physiol.* 77(3): 1439–1444, 1994.



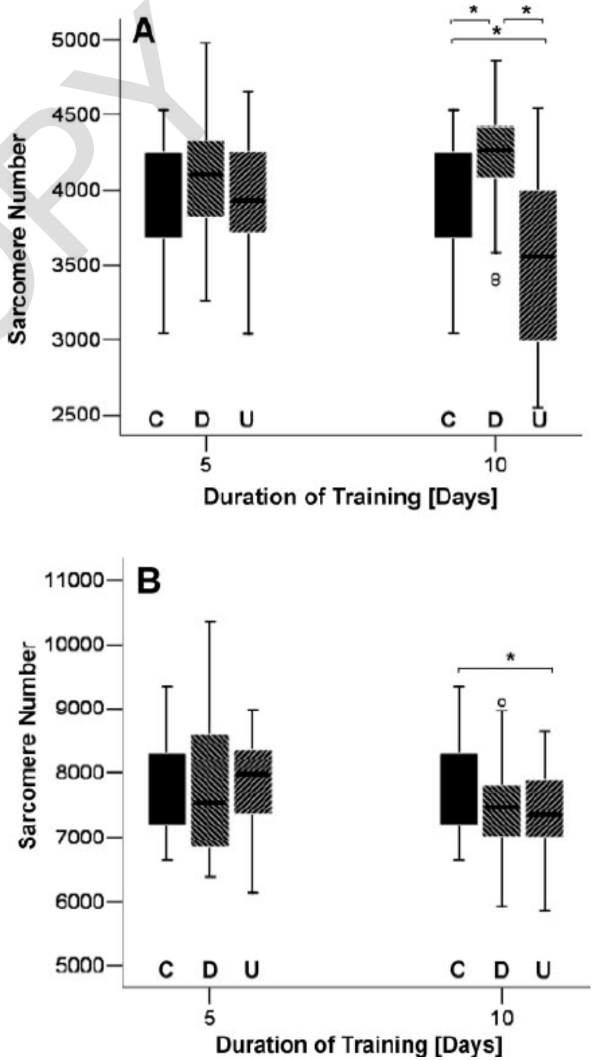
J Appl Physiol 99: 1352–1358, 2005.
First published June 9, 2005; doi:10.1152/japplphysiol.00481.2005.

Differential serial sarcomere number adaptations in knee extensor muscles of rats is contraction type dependent

Timothy A. Butterfield, Timothy R. Leonard, and Walter Herzog



VL is active during eccentric, but also at short muscle length?

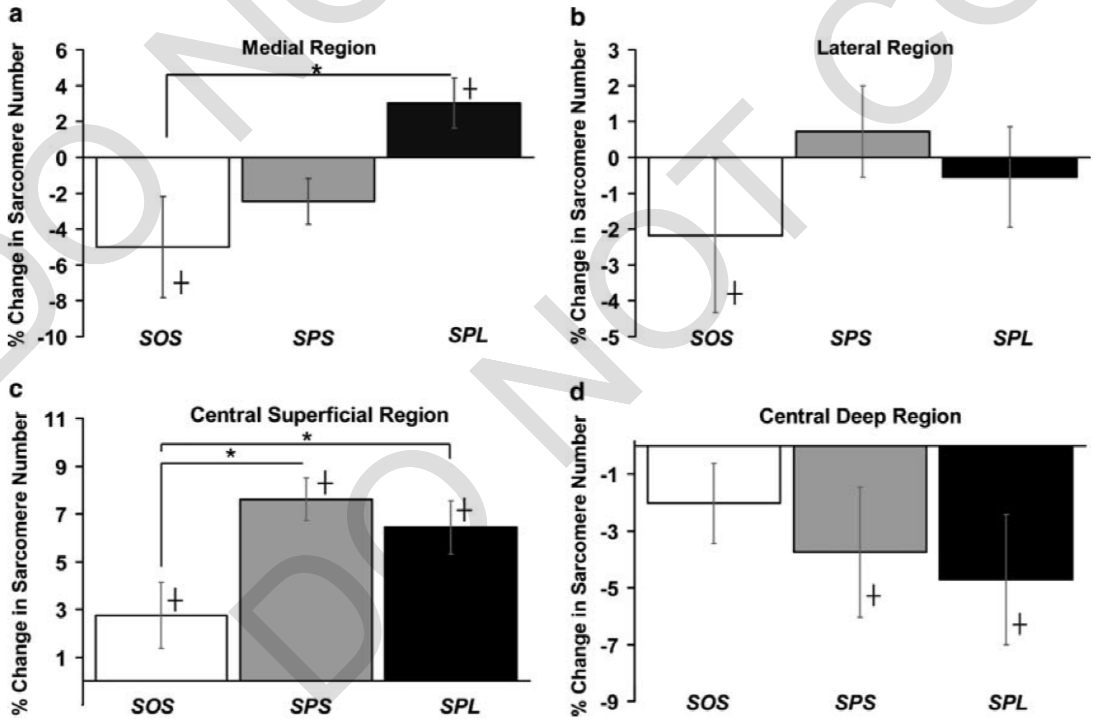


Timothy A. Butterfield · Walter Herzog

Pflugers Arch – Eur J Physiol (2006) 451: 688–700
DOI 10.1007/s00424-005-1503-6

The magnitude of muscle strain does not influence serial sarcomere number adaptations following eccentric exercise

6 wk, rabbit dorsiflexor eccentric (NMES) exercise of same strain from long and short lengths…



Journal of Biomechanics 31 (1998) 499–501

Technical Note

Eccentric training does not increase sarcomere number in rabbit dorsiflexor muscles

Timothy J. Koh*, Walter Herzog

JOURNAL OF BIOMECHANICS

Rabbit muscle, 2/wk, 12 weeks (NMES)

Table 1
Sarcomere numbers for superficial and deep fascicles of the TA and for proximal and distal fascicles of the EDL

	TA superficial	TA deep	EDL proximal	EDL distal
Trained	22098 (1843)	18284 (1940)	6985 (446)	7503 (581)
Contralateral	21467 (1592)	18490 (1884)	6859 (313)	7308 (313)
Difference	631 (326)	– 206 (954)	126 (212)	195 (487)
p-value	< 0.005	0.6	0.2	0.4

- Minimal effect
- No concentric control group

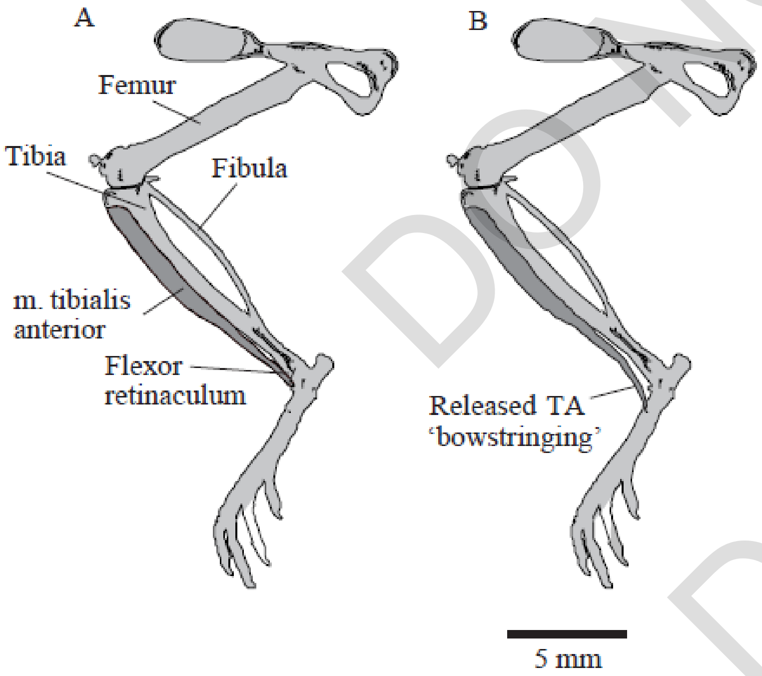
No effect of eccentric contractions in 3 of 4 muscle compartments; 2.9% increase in one compartment.

The Journal of Experimental Biology 201, 309–316 (1998)
Printed in Great Britain © The Company of Biologists Limited 1998

SARCOMERE NUMBER ADAPTATION AFTER RETINACULUM TRANSECTION IN ADULT MICE

THOMAS J. BURKHOLDER AND RICHARD L. LIEBER*

Transection of TA retinaculum for 2 weeks; normal cage activity; sarcomere number = fibre length / sarcomere length



- ↓ muscle length; need ↓ ~10% sarcomeres to shift L-t relation
- ↑ muscle excursion 28%
- ↑ muscle velocity 20%
- ↓ power (at v_{opt}) 20%

Found ↓ 10% sarcomere number; Functional length best predictor

MUSCLE & NERVE 7:161–173 1984

REGULATION OF SARCOMERE NUMBER IN SKELETAL MUSCLE: A COMPARISON OF HYPOTHESES

SUSAN W. HERRING, PhD, ARTHUR F. GRIMM, DDS, PhD,
and BETSY R. GRIMM, BA

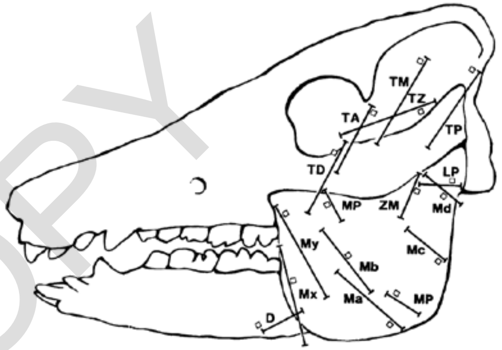


Table 3. Test of predictions of various hypotheses—pig data.

	Grand mean		Measures of dispersion		
Hypothesis	Expected*	Observed†§	Range	Standard deviation†	Coefficient of variation‡
Excursion-Maximum Stretch	4.0 µm	3.12 µm	1.14 µm	0.376	12.1%
Excursion-Average Stretch	2.9 µm	2.65 µm	0.72 µm	0.229	8.6%
Postural Position	2.9 µm	2.35 µm	1.01 µm	0.289	12.3%
Active Position	2.9 µm	2.70 µm	0.46 µm	0.138‖	5.1%

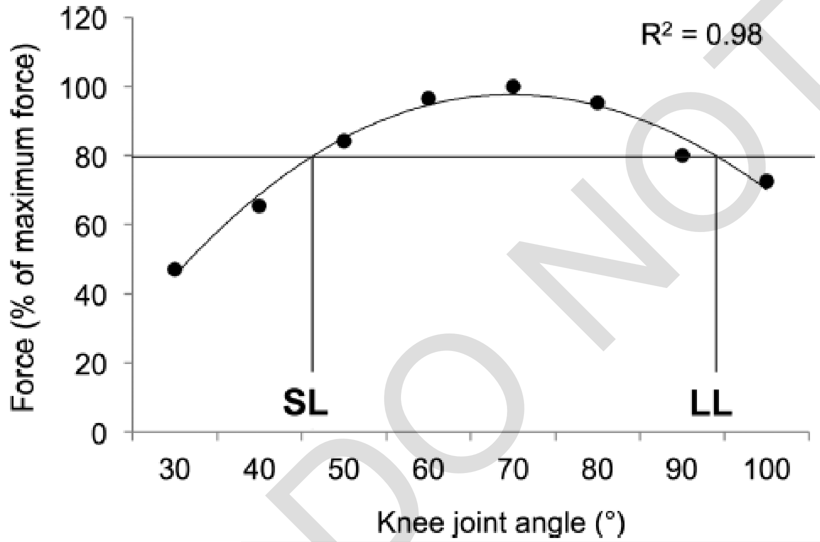
According to the most successful hypothesis, sarcomere number is adjusted so as to achieve an optimum sarcomere length when the muscle is experiencing a high level of tension. Most often, this occurs at jaw positions where the muscle is electrically active.

So muscle force at a fascicle length predicts sarcomere number addition and fascicle length change?

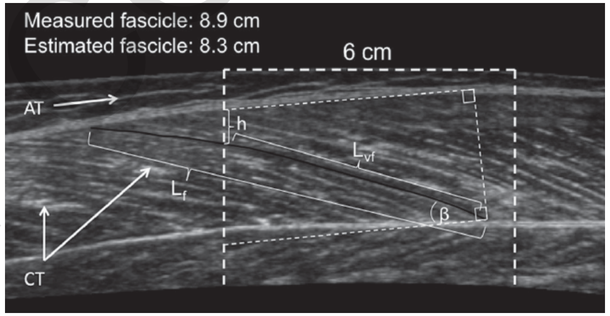
Neuromuscular Adaptations Associated with Knee Joint Angle-Specific Force Change

Medicine and Science in Sports and Exercise, 2014

MARIKA NOORKÕIV, KAZUNORI NOSAKA, and ANTHONY J. BLAZEVICH



Joint angle-dependent strength increase not related to fascicle length changes…



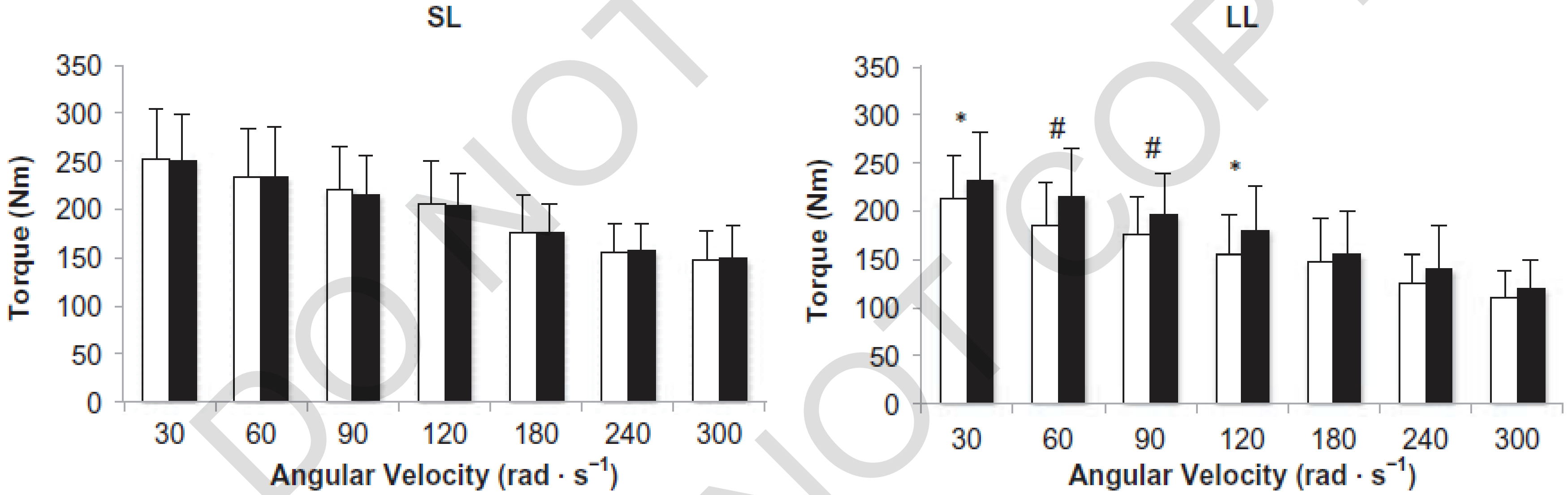
	Short length (SL)		Δ	Long length (LL)		Δ
Quadriceps muscle volume (cm^3)						
VL	680.7 ± 144.4	674.9 ± 152.2	−1.2 ± 1.1	634.7 ± 142.5	677.5 ± 162.8	6.3 ± 1.4**
VM	502.2 ± 89.6	497.7 ± 96.0	−1.2 ± 1.3	468.5 ± 160.2	491.1 ± 166.4	4.8 ± 0.9**
VI	570.4 ± 134.1	573.7 ± 132.9	0.5 ± 1.8	532.1 ± 197.9	548.7 ± 200.9	3.1 ± 1.8
RF	294.8 ± 67.4	294.2 ± 63.0	0.04 ± 1.1	267.2 ± 64.4	290.7 ± 67.4	8.2 ± 1.5**
Quadriceps	2048.2 ± 391.1	2040.6 ± 395.6	−0.5 ± 1.1	1902.5 ± 530.1	2008.0 ± 567.6	5.2 ± 1.0**
Fascicle length (L_f, mm)						
VL_{prox}	88.2 ± 10.2	90.2 ± 11.7	1.9 ± 6.1	86.6 ± 11.2	89.5 ± 8.9	1.3 ± 5.9
VL_{mid}	82.8 ± 7.6	87.8 ± 8.3	5.6 ± 3.7**	83.0 ± 10.8	86.2 ± 7.9	3.8 ± 7.2
VL_{dist}	84.4 ± 14.9	83.8 ± 16.2	1.1 ± 7.2	77.9 ± 15.1	83.1 ± 16.8	5.8 ± 6.4*
RF_{mid}	119.0 ± 11.2	119.4 ± 13.3	0.1 ± 4.2	97.7 ± 20.9	98.5 ± 17.8	2.2 ± 13.8

Journal of Sports Sciences, 2015
http://dx.doi.org/10.1080/02640414.2015.1020843

Routledge
Taylor & Francis Group

Effects of isometric quadriceps strength training at different muscle lengths on dynamic torque production

MARIKA NOORKÕIV, KAZUNORI NOSAKA & ANTHONY J. BLAZEVICH



No torque change at faster speeds despite increases in fascicle length (increase slow speeds only in LL).

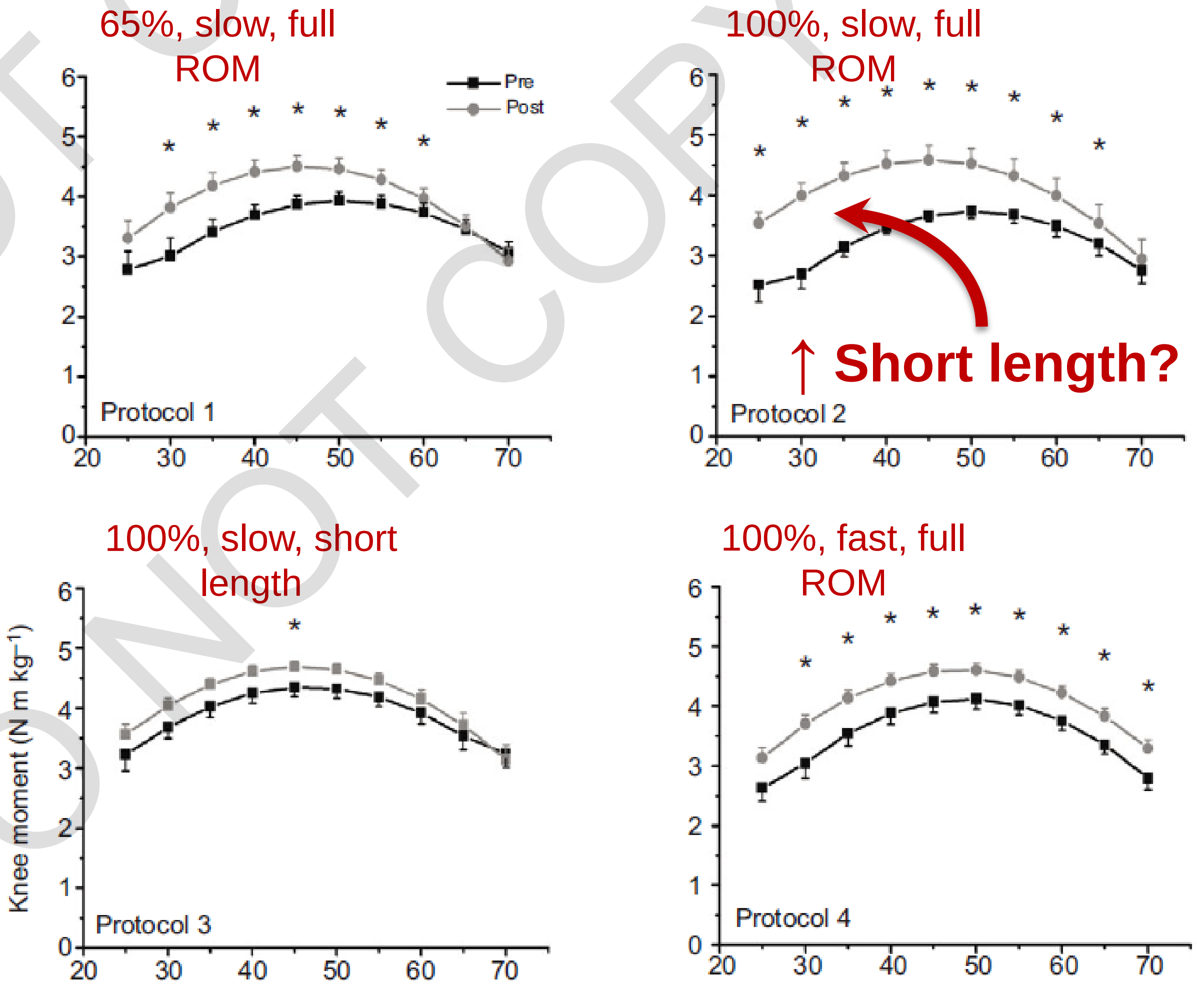
© 2014. Published by The Company of Biologists Ltd | The Journal of Experimental Biology (2014) 217, 2726-2733 doi:10.1242/jeb.100370

Effects of load magnitude, muscle length and velocity during eccentric chronic loading on the longitudinal growth of the vastus lateralis muscle

Ali Sharifnezhad, Robert Marzilger and Adamantios Arampatzis*

10 wk isokinetic eccentric training

Minimal effect on torque-angle relationship…lots of other factors!?!



So:

- Eccentric training not a unique stimulus for fascicle length change?
- Eccentric training not a unique stimulus for torque-angle shift or high-speed force production?
- Most unaccustomed loading of muscle leads to fascicle length increase, in some muscles/regions

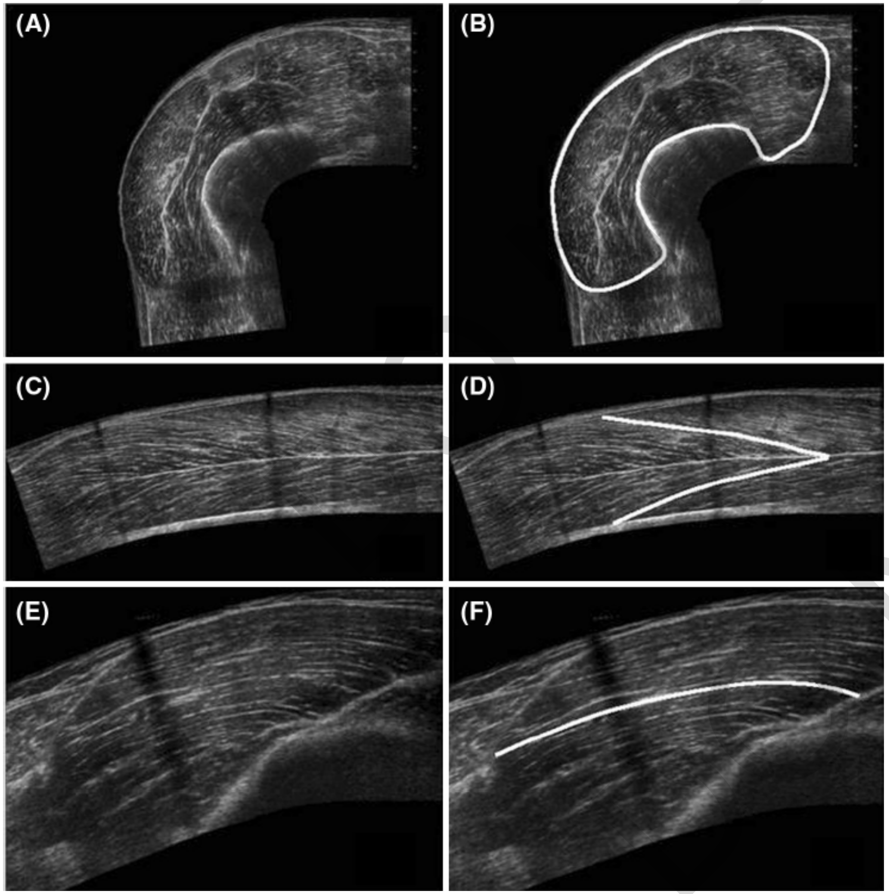
So ends the cautionary tale…

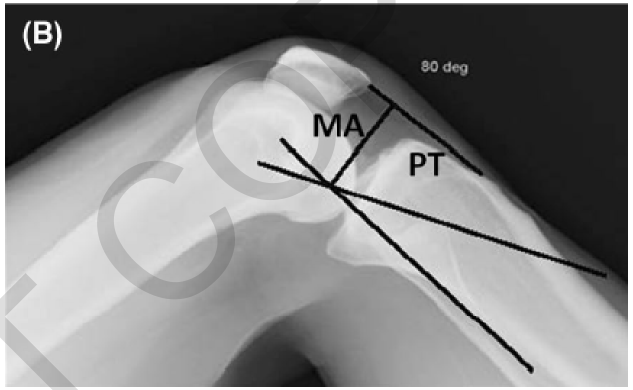
Where to now?

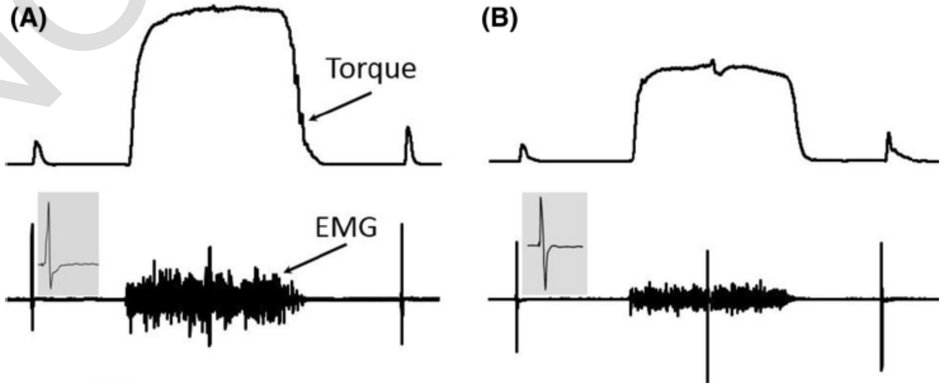
Eur J Appl Physiol (2016) 116:1159–1177
DOI 10.1007/s00421-016-3352-8

Anatomical and neuromuscular variables strongly predict maximum knee extension torque in healthy men

J. Trezise[1] · N. Collier[2] · A. J. Blazevich[1,3]



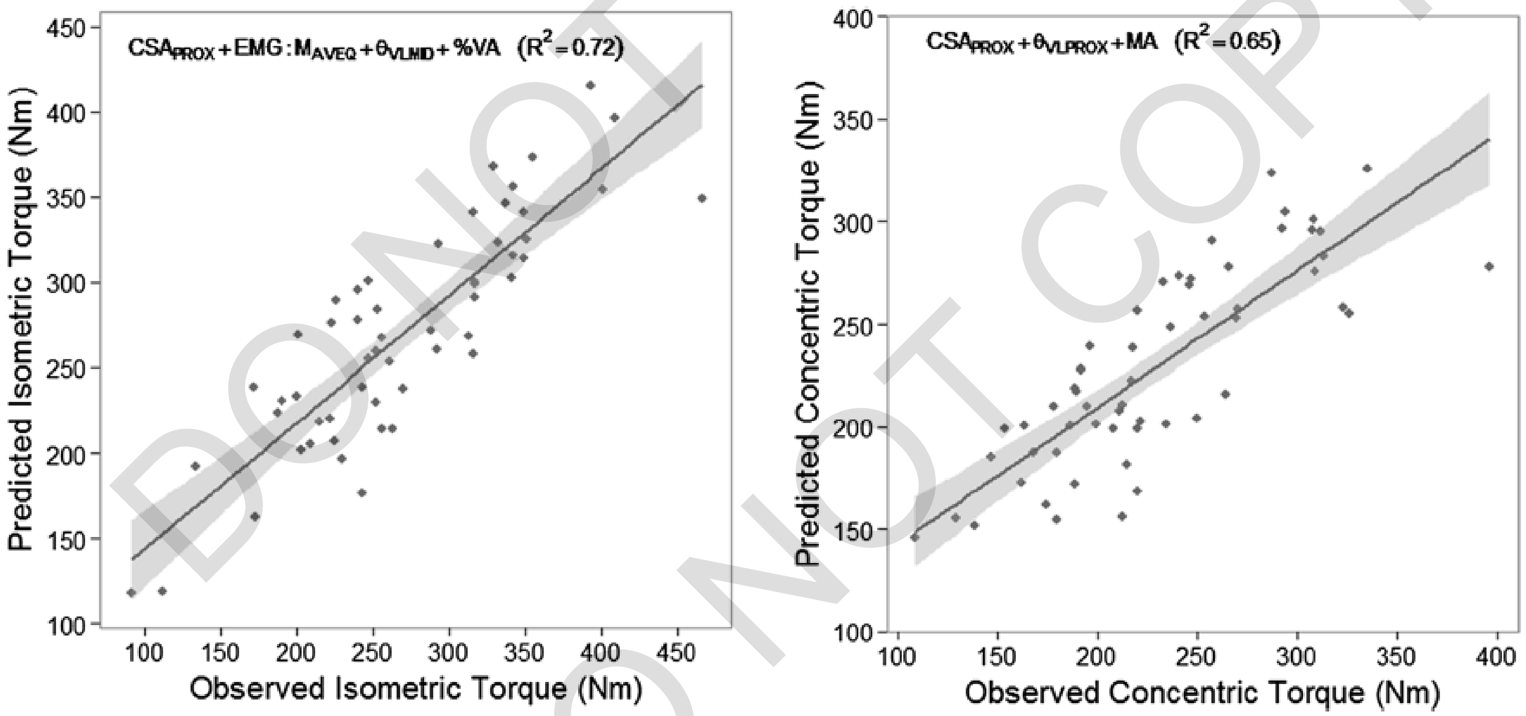




Eur J Appl Physiol (2016) 116:1159–1177

Anatomical and neuromuscular variables strongly predict maximum knee extension torque in healthy men

J. Trezise[1] · N. Collier[2] · A. J. Blazevich[1,3]

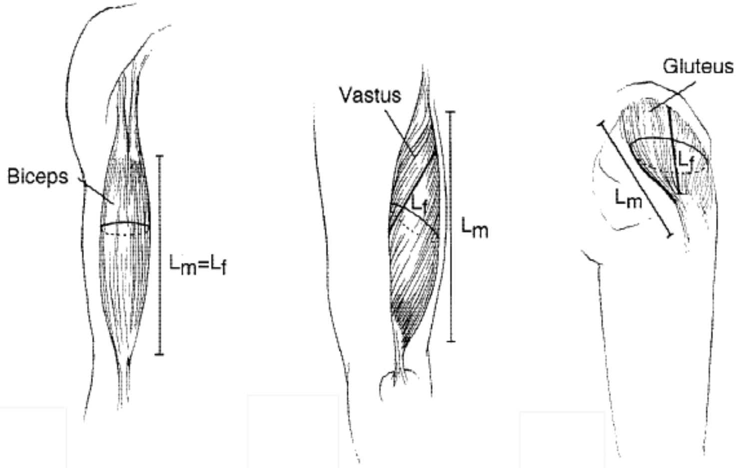


Relationship between fascicle angle and torque ranged $R^2 = 0.04 – 0.19$!

So, using modelling approaches to…

– examine combinations of variables, or
– synergies between variables

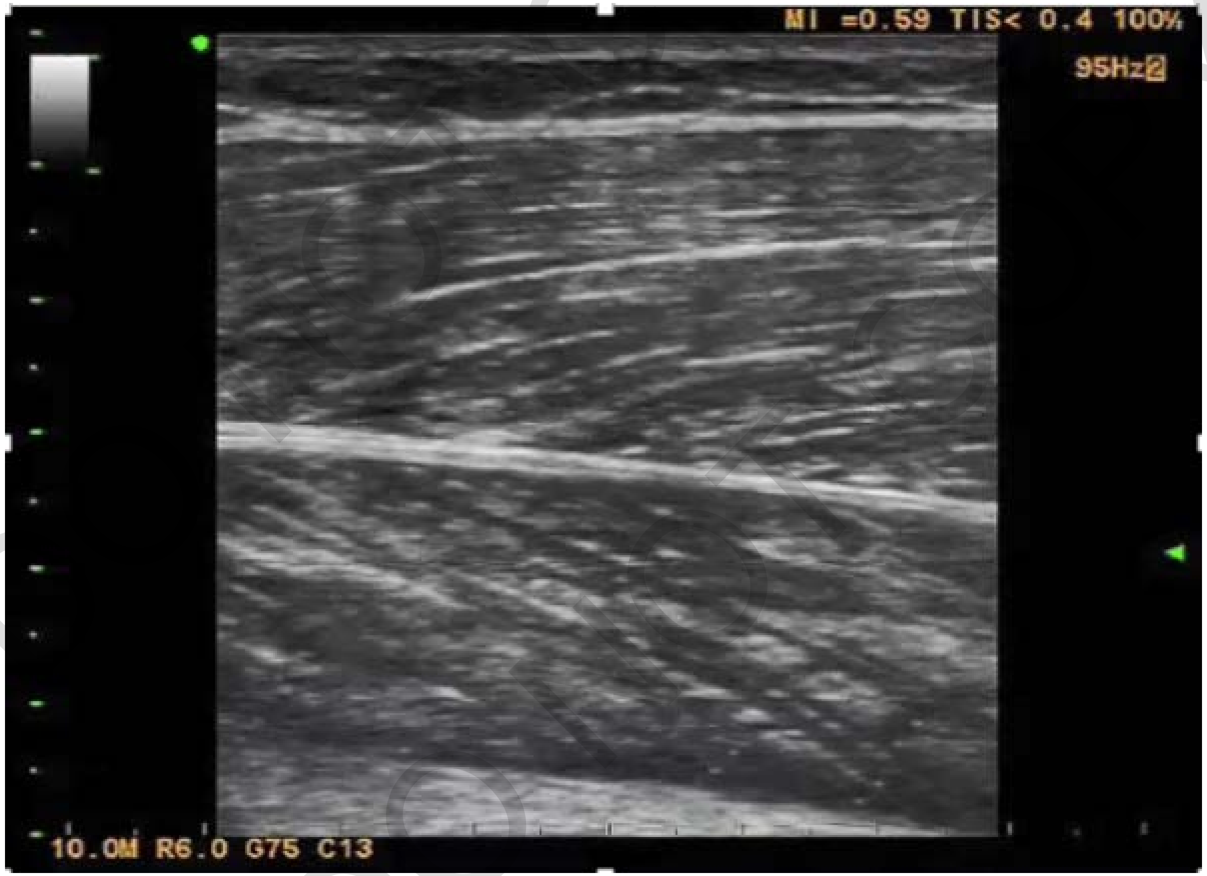
…may be required to understand the structure-function relationship *in vivo*



Variable gearing in pennate muscles

Emanuel Azizi*, Elizabeth L. Brainerd, and Thomas J. Roberts

PNAS | February 5, 2008 | vol. 105 | no. 5 | 1745–1750



Muscle shape changes during contraction influence function – we believe – so measure after interventions?

The Journal of Experimental Biology 208, 3249-3261

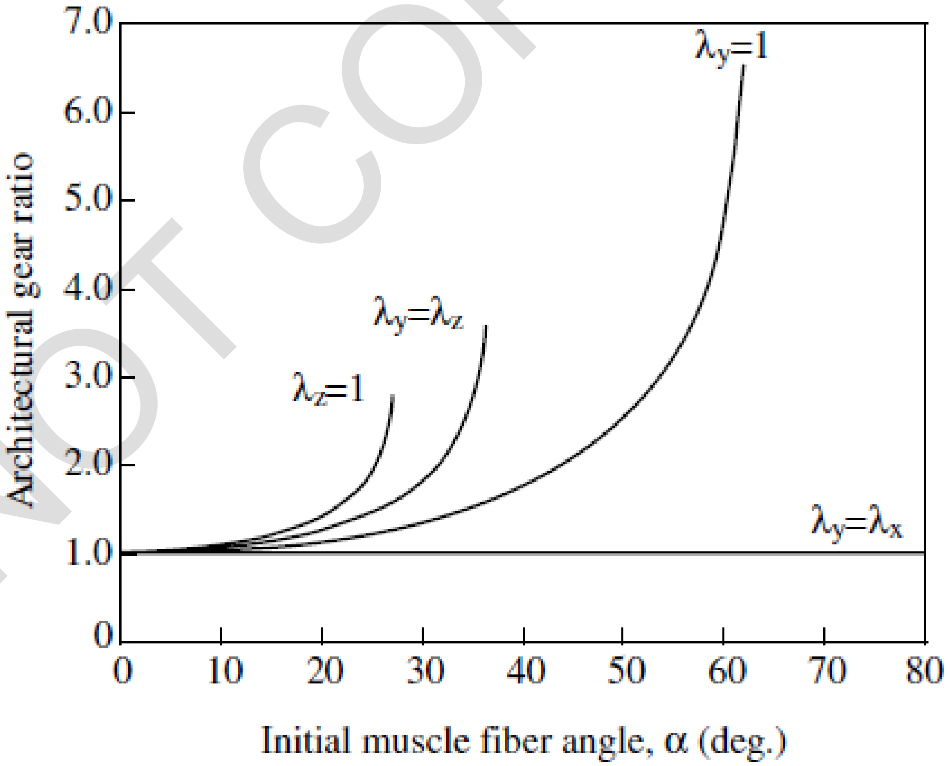
Muscle fiber angle, segment bulging and architectural gear ratio in segmented musculature

Elizabeth L. Brainerd*,† and Emanuel Azizi*

Resting fascicle angle matters…

increased fascicle angle = increased gear ratio.

Gear ratio = muscle/fibre



Muscle-fiber pennation angles are greater in hypertrophied than in normal muscles

J. Appl. Physiol. 74(6): 2740–2744, 1993.–

YASUO KAWAKAMI, TAKASHI ABE, AND TETSUO FUKUNAGA

Modelling studies, and images like that below, show that fascicle curvature can occur…greater in weight trainers.

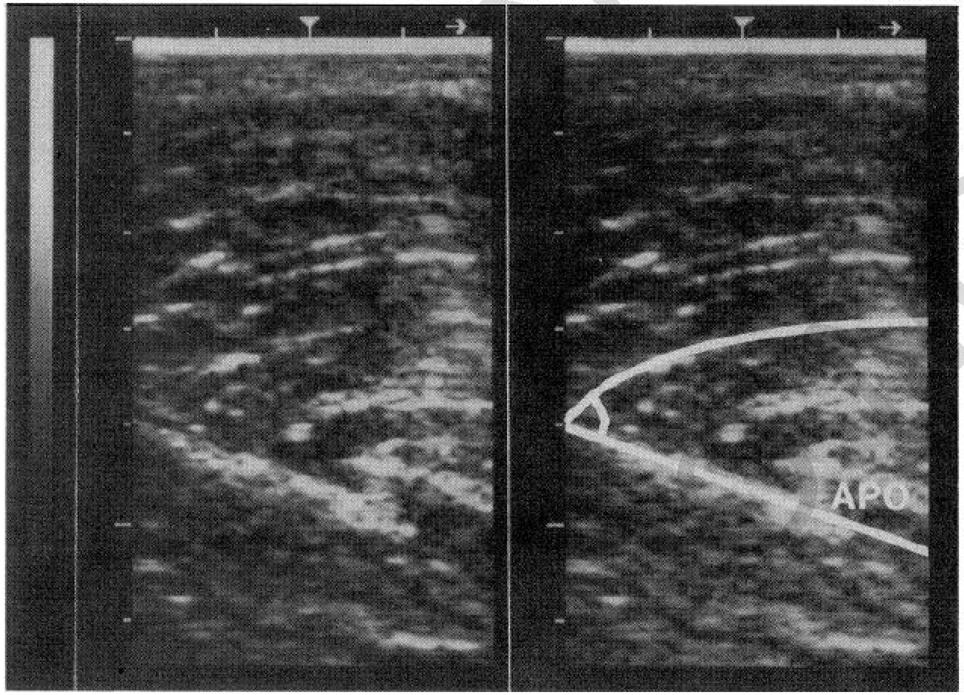
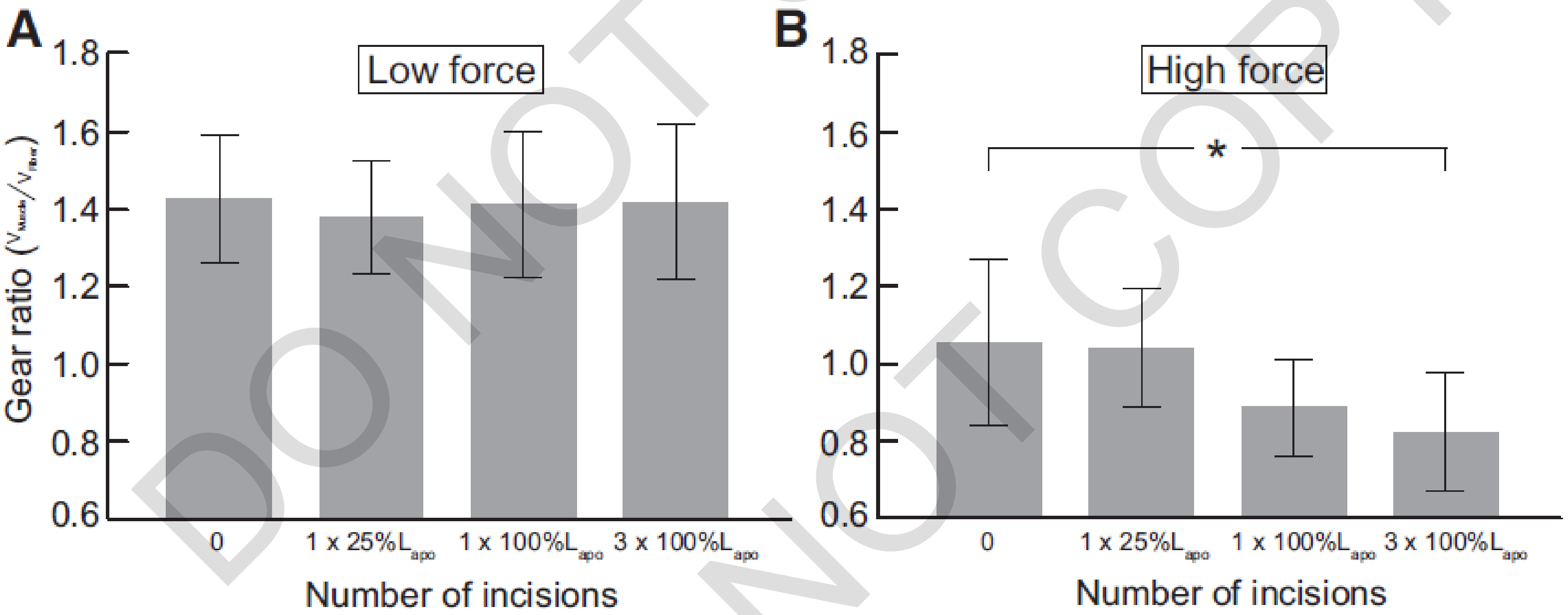


FIG. 2. Ultrasonographic image from 1 highly trained bodybuilder. Fascicles were arranged curvilinearly and fiber pennation angles were steeper where fascicles attached to APO rather than in midposition.

J Appl Physiol 125: 513–519, 2018.

Aponeurosis influences the relationship between muscle gearing and force

Carolyn M. Eng and Thomas J. Roberts



Greater aponeurosis stiffness associated with increased architectural gear ratio – greater rotation, shortening speed, intramuscular pressure(?)

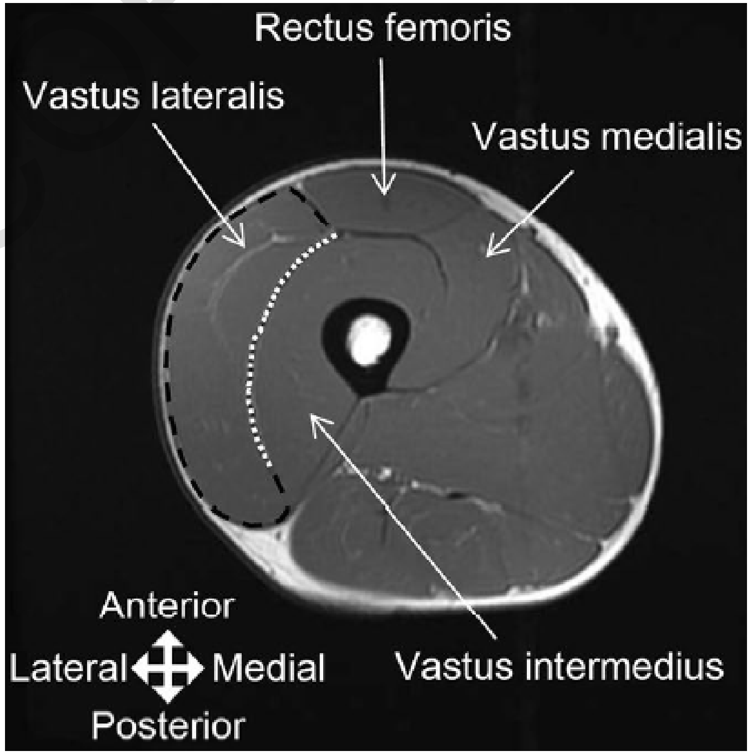
Eur J Appl Physiol (2015) 115:309–316

Increase in vastus lateralis aponeurosis width induced by resistance training: implications for a hypertrophic model of pennate muscle

Taku Wakahara · Ryoichi Ema · Naokazu Miyamoto · Yasuo Kawakami

Strength training increases pennation… but also aponeurosis width

	Training group		
	Before	After	Relative change (%)
ACSA (cm^2)	27.7 ± 3.8	30.6 ± 4.0*	10.7 ± 7.6
Pennation angle (°)	18.0 ± 1.9	19.9 ± 2.5*	10.8 ± 7.3
Fascicle length (cm)	7.2 ± 0.2	7.2 ± 0.3	−0.9 ± 1.5
Aponeurosis width (cm)	8.3 ± 1.1	8.5 ± 1.1*	1.9 ± 3.1

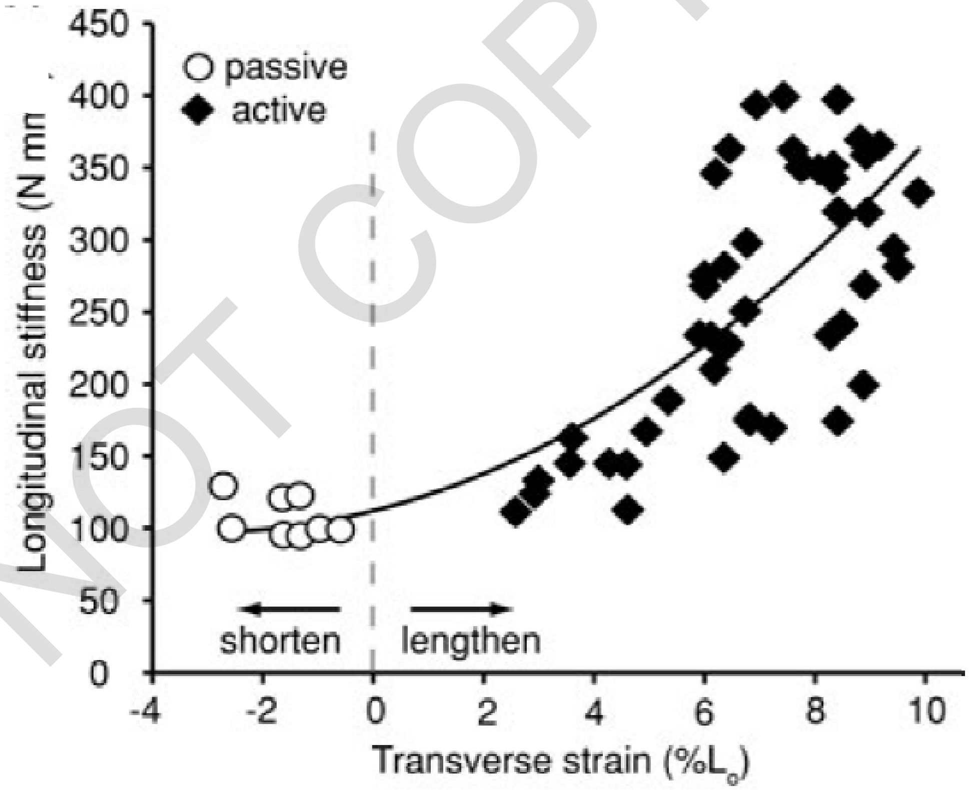


J Physiol 587.17 (2009) pp 4309–4318

Biaxial strain and variable stiffness in aponeuroses

Emanuel Azizi and Thomas J. Roberts

Transverse strain of aponeurosis increases longitudinal stiffness

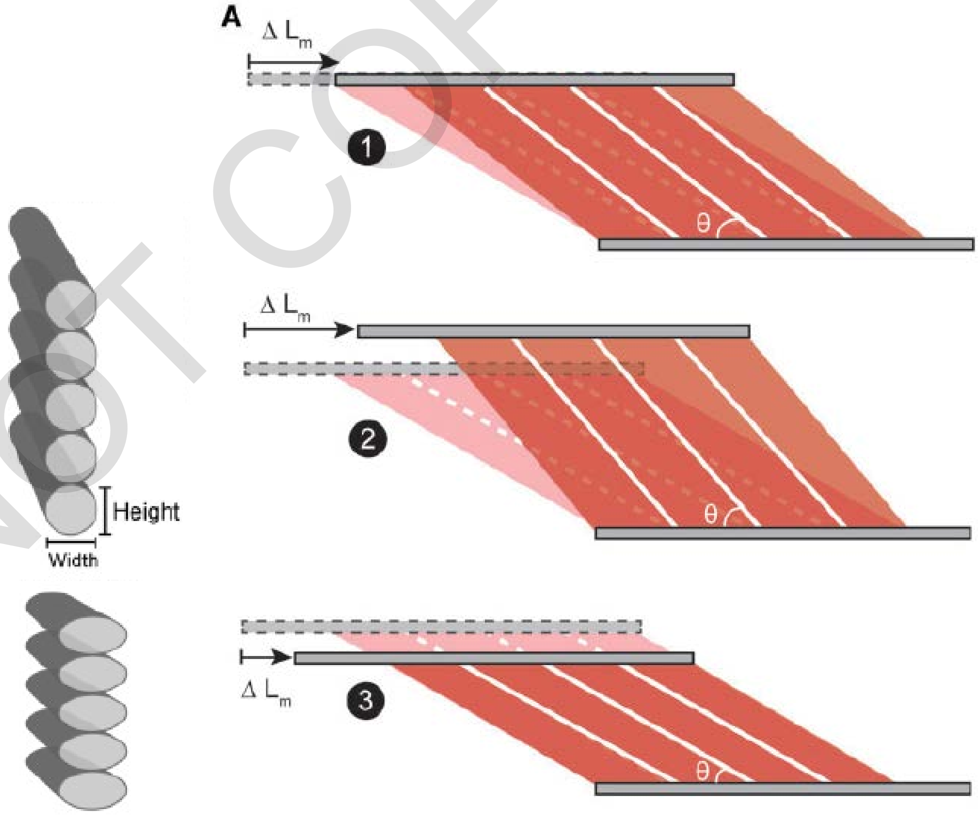


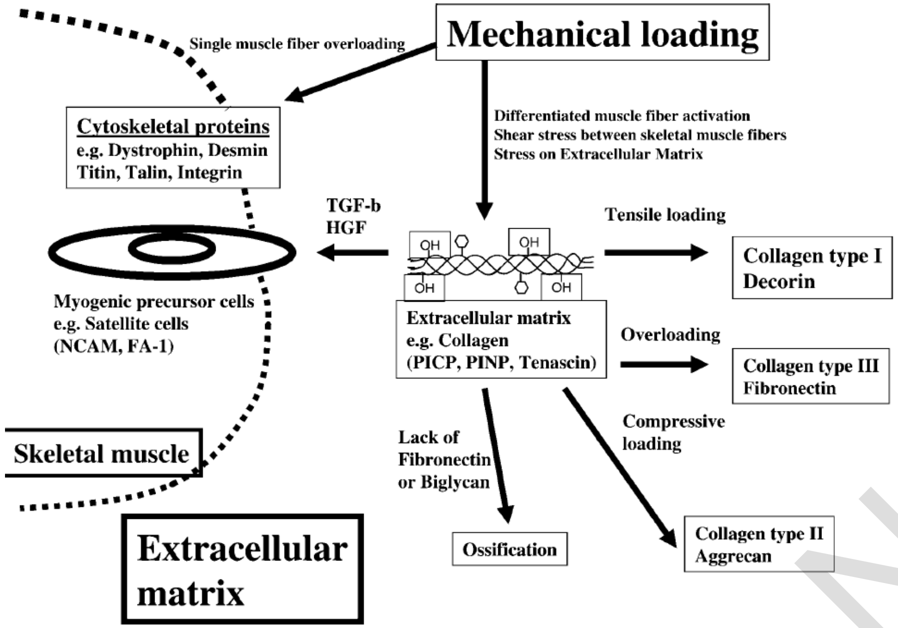
Integrative and Comparative Biology, volume 58, number 2, pp. 207–218

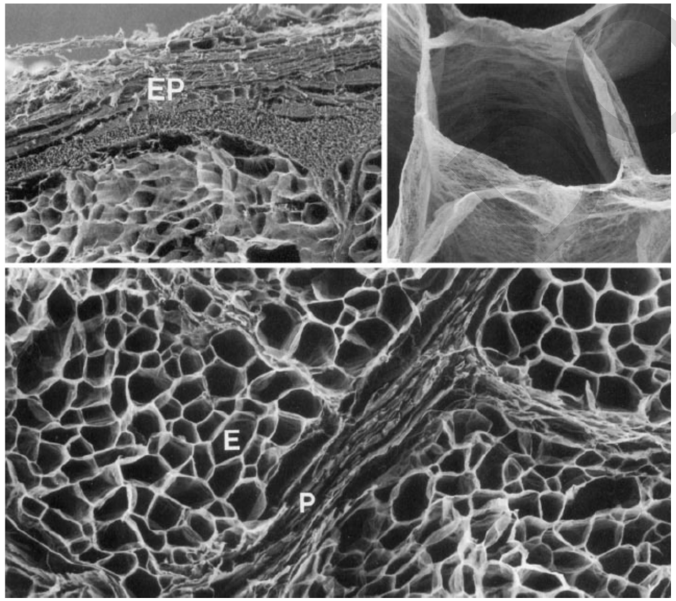
Structural Determinants of Muscle Gearing During Dynamic Contractions

Carolyn M. Eng,[1,*] Emanuel Azizi[†] and Thomas J. Roberts[*]

Increases in fluid pressure increase fibre rotation and increase architectural gear ratio







Physiol Rev
84: 649–698, 2004; 10.1152/physrev.00031.2003.

Role of Extracellular Matrix in Adaptation of Tendon and Skeletal Muscle to Mechanical Loading

MICHAEL KJÆR

Extracellular matrix and connective tissues key for:

- gearing (fluid-connective tissue interaction)
- lateral and longitudinal force transmission

Strength (& other) training stimulates ECM and connective tissues

- Strength training can
  - Increase fascicle angle
  - Increase fibre curvature
  - Increase fibre diameter (water)
  - Stretch and thicken, and therefore stiffen, aponeurosis
  - Stiffen connective tissues

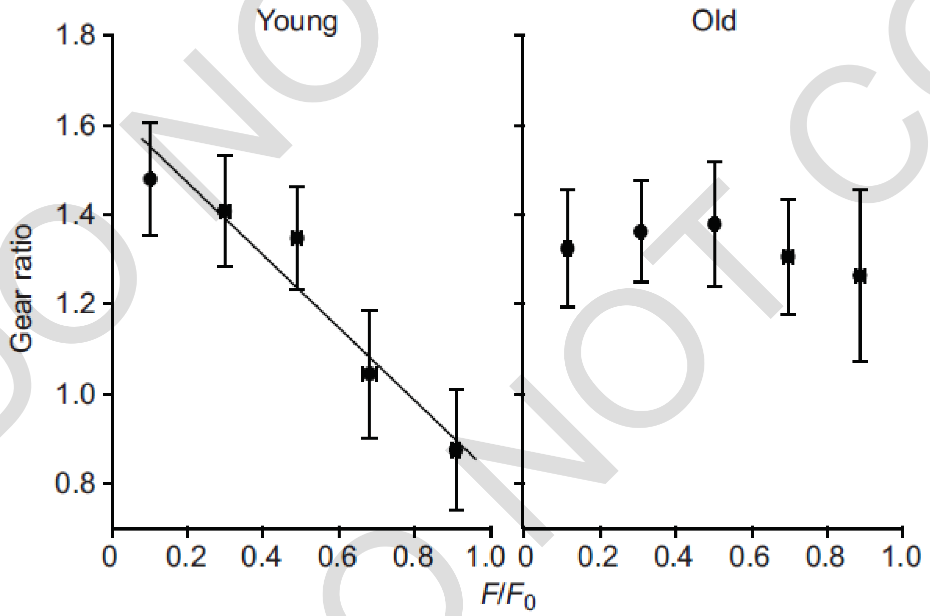
- Should have a significant effect on muscle gearing…but this is yet to be tested

© 2016. Published by The Company of Biologists Ltd | Journal of Experimental Biology (2016) 219, 998-1003 doi:10.1242/jeb.133009

Stuck in gear: age-related loss of variable gearing in skeletal muscle

Natalie C. Holt[1,*], Nicole Danos[1], Thomas J. Roberts[2] and Emanuel Azizi[1]

Important: Gearing is restricted in ageing…at least in rats…



Results from increased transverse aponeurosis modulus, reduced pennation, reduced intramuscular pressures…?

Need to understand specific effects of different forms of training on different elements within muscle, and effects on whole muscle function…

…then may get close to personalised training as part of personalised medicine.

Questions?

Thank you to the organisers:

First International Motor Impairment Conference

Sydney Australia 26-28 Nov 2018