UNIVERSITÉ DE NANTES

Laboratoire
Motricité - Interactions - Performance
EA 4334 Nantes - Le Mans

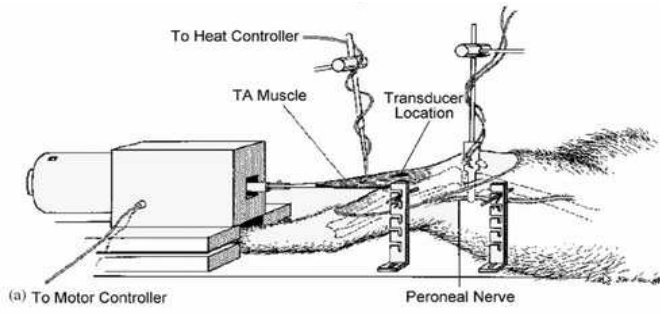
Elastography for muscle biomechanics

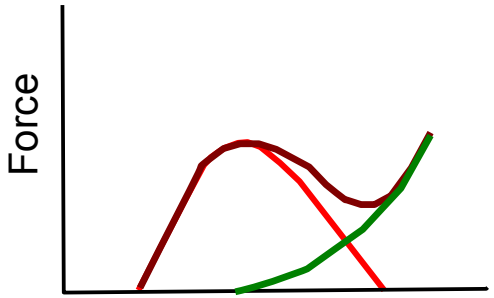
Antoine Nordez

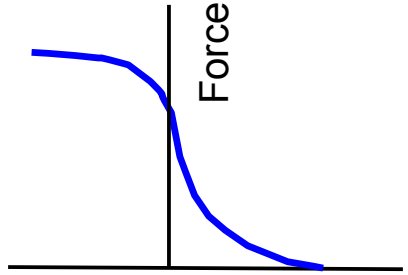
25th October 2014

Characterization of muscle-tendon mechanical properties

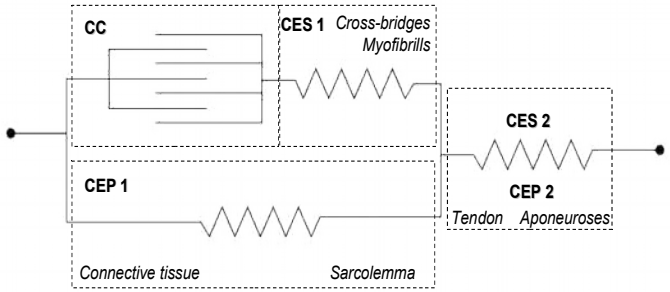
In vitro / ex vivo







Contractile and viscoelastic properties of one muscle, one muscle fiber



Hill, 1938, 1951

Zajac, 1989

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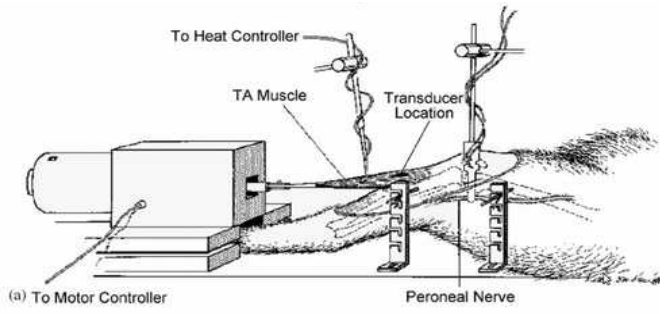

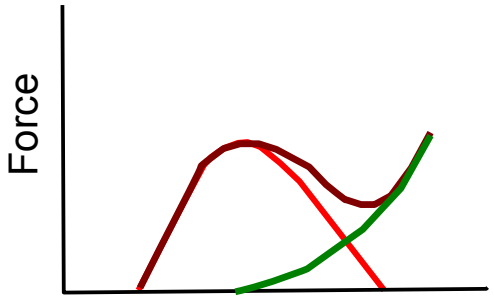

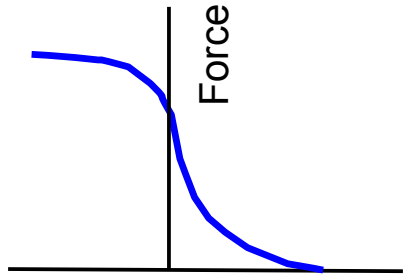

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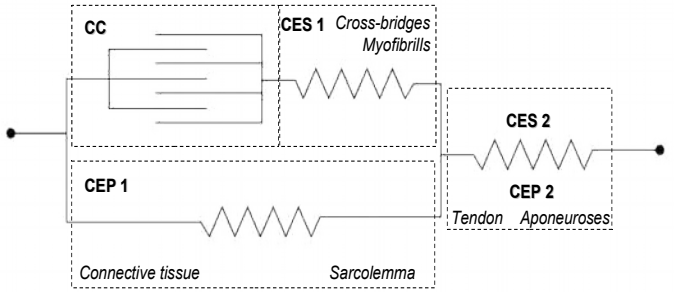

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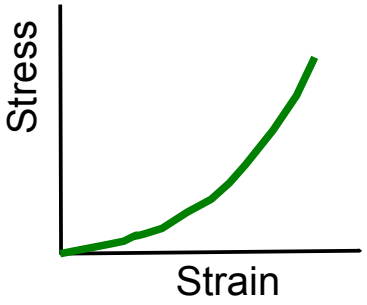
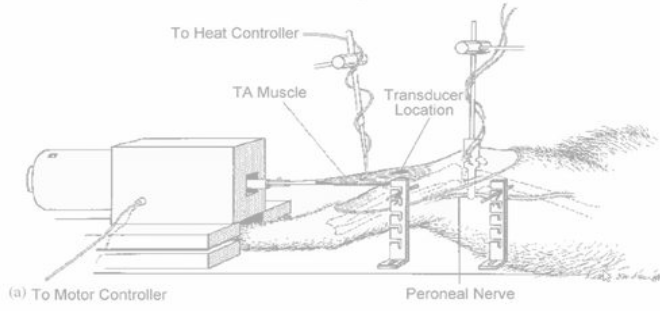


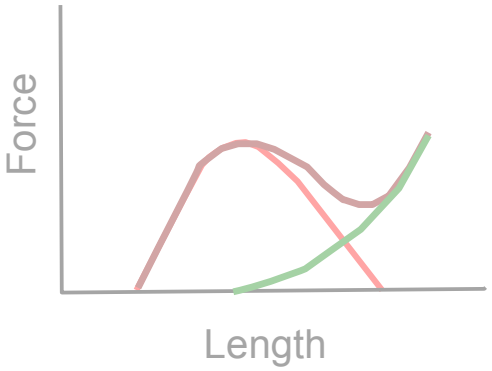
Viscoelastic properties of tendons, nerves, ligaments, skin...

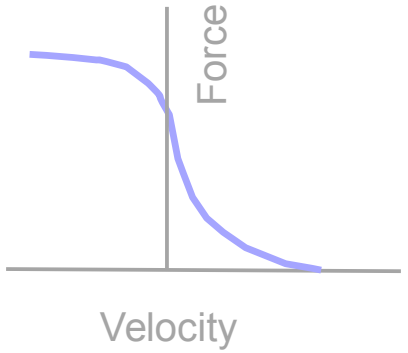
Introduction

Characterization of muscle-tendon mechanical properties

In vitro / ex vivo







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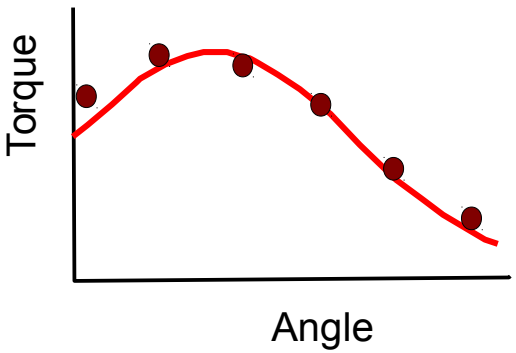

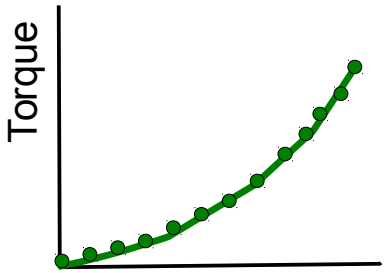

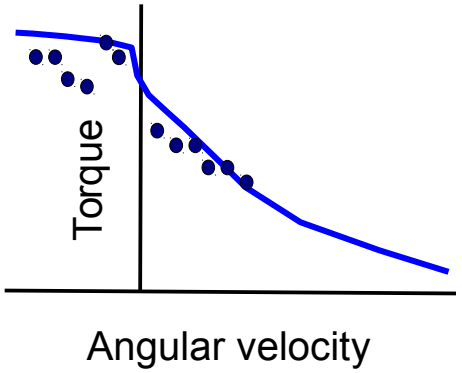

e.g., Forrester et al., 2011; Nordez et al., 2008

In vivo: ergometers

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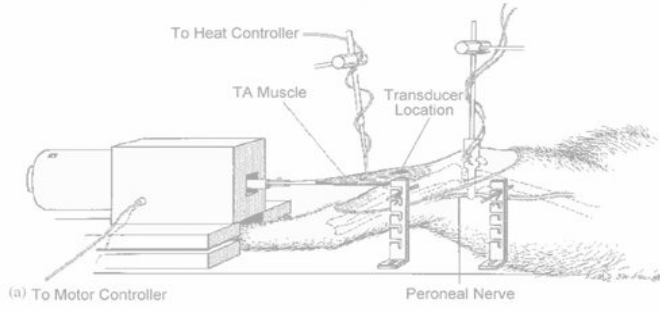
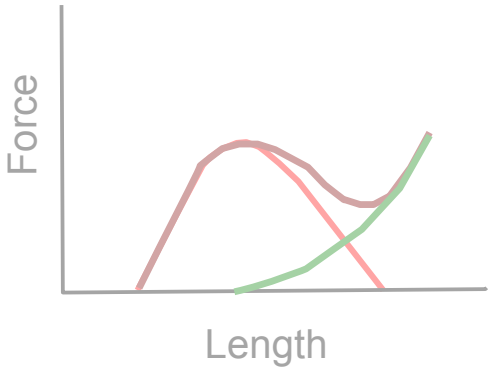
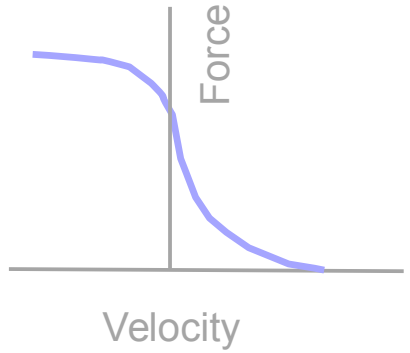
Characterization of muscle-tendon mechanical properties

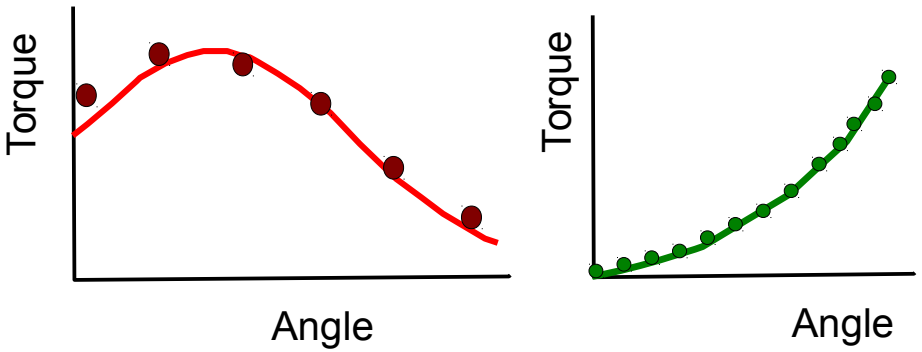
In vitro / ex vivo



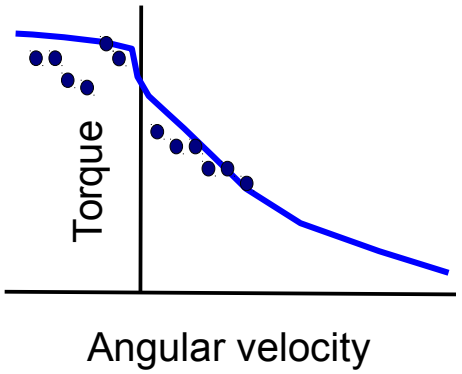




Torque ≠ Force



Several muscles and structures (tendons, ligaments, skin...) implied



e.g., Forrester et al., 2011; Nordez et al., 2008

In vivo: ergometers

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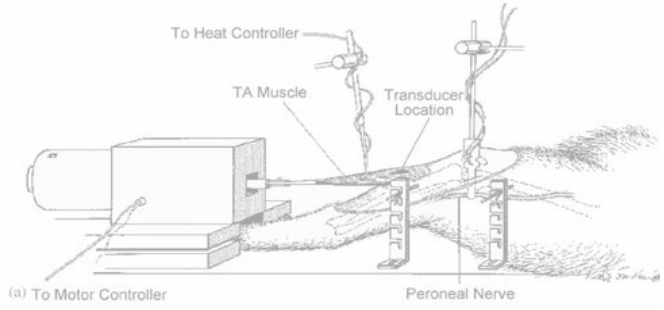
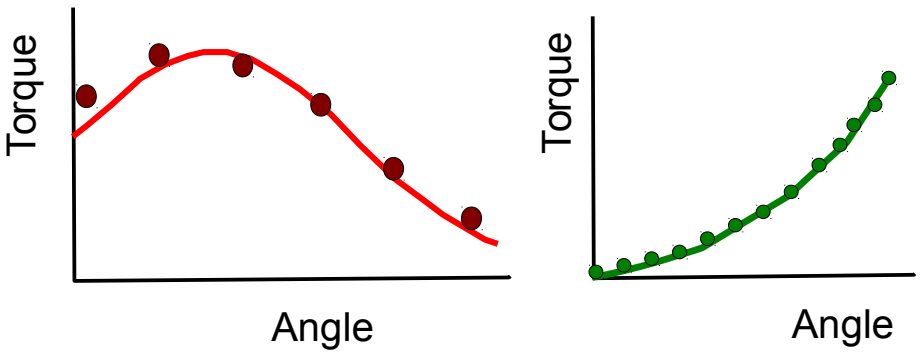


Need of more localized methods

Revisit basic concepts & Study new hypothesis

Torque ≠ Force



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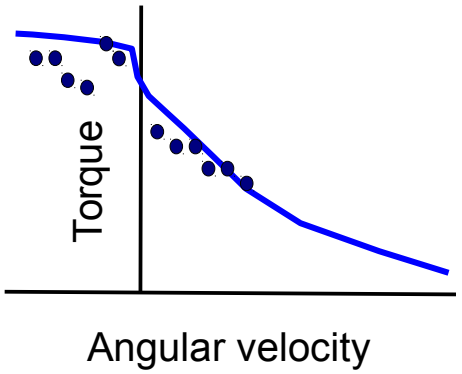

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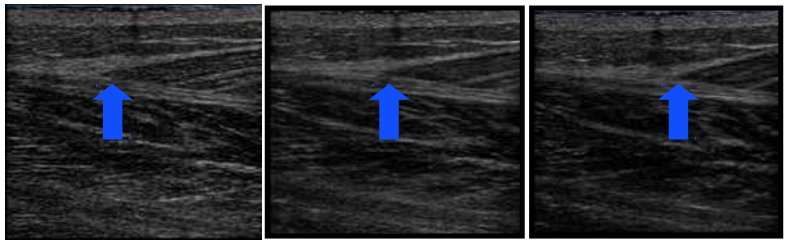
In vivo: ergometers

Introduction

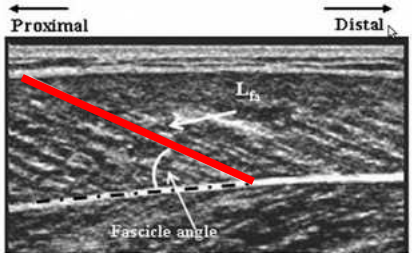
Ultrasound for muscle-tendon biomechanics

Tendon strain



e.g., Fukashiro et al., 1995 ; Maganaris et Paul, 1999 ; Kubo et al., 1999

Fascicle length



e.g., Ishikawa et al., 2005, 2007 ; Lichtwark et al., 2007, 2008

Measurement of displacements

no information on the muscle force, stress or stiffness

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Ultrasound for muscle-tendon biomechanics

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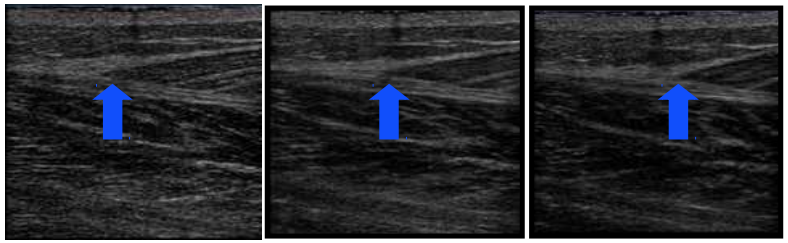

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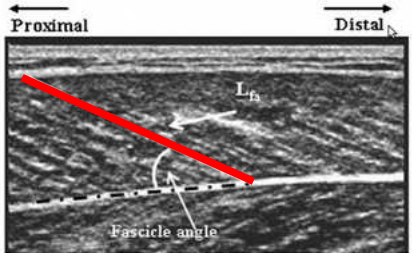

e.g., Ishikawa et al., 2005, 2007 ; Lichtwark et al., 2007, 2008

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Elastography

Medical imaging (ultrasound, MRI) to assess mechanical properties of biological tissues

Introduction

1- Elastography methods

Institut Langevin
ONDES ET IMAGES

Supersonic Shear Imaging

Aixplorer

SUPERSONIC imagine

Muscle-tendon biomechanics

2- Passive muscle

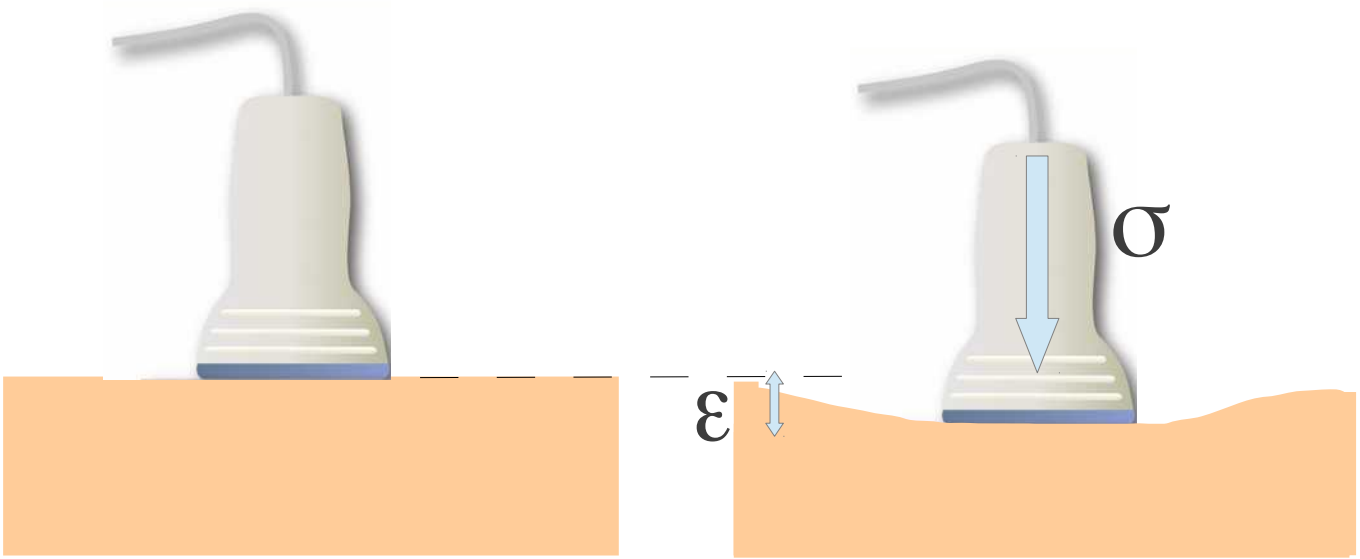
3- Muscle contraction

Estimation of passive muscle tension

Estimation of individual muscle force

1/ Static elastography (tissue strain)

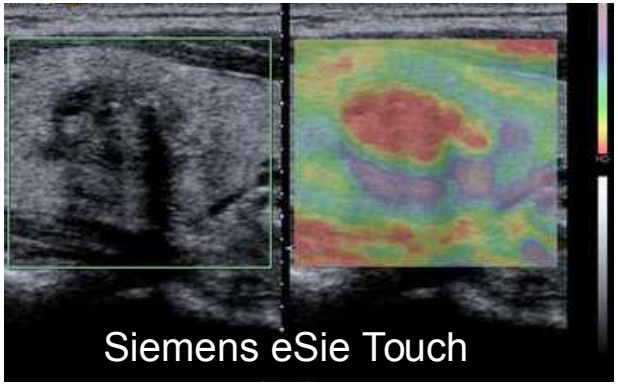
e.g., Ophir et al., 1991

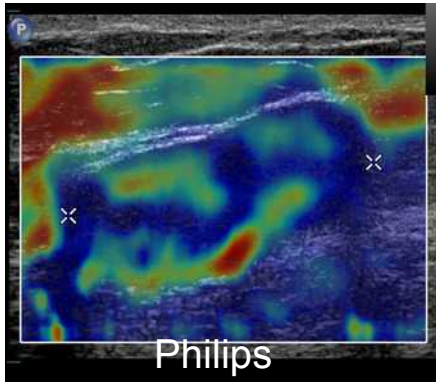


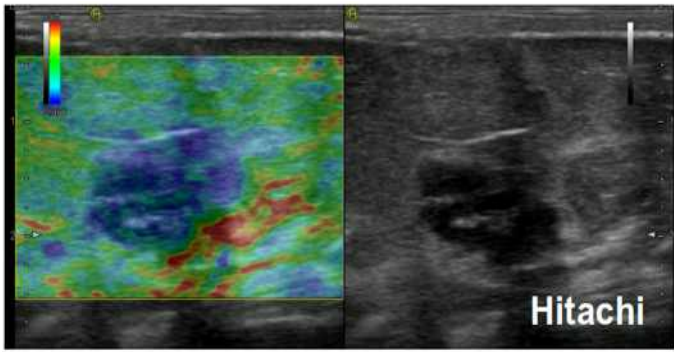
σ constant

ε Measured using ultrasound by a comparison between images

$\sigma = constant$ ⇒ Regions with larger strain are less stiff







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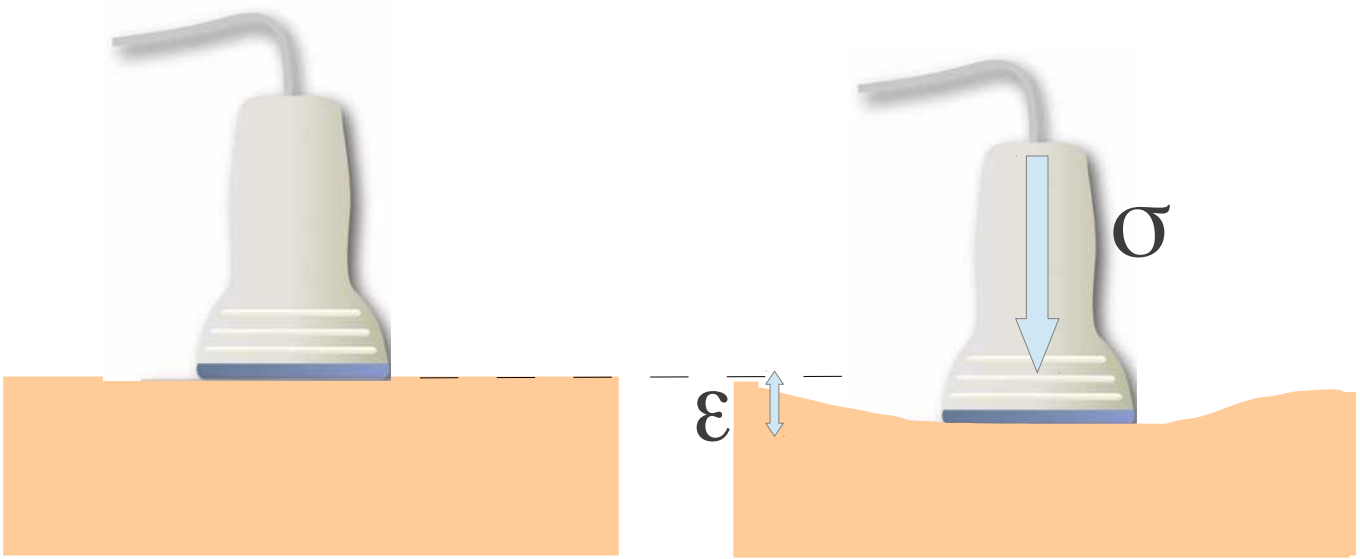

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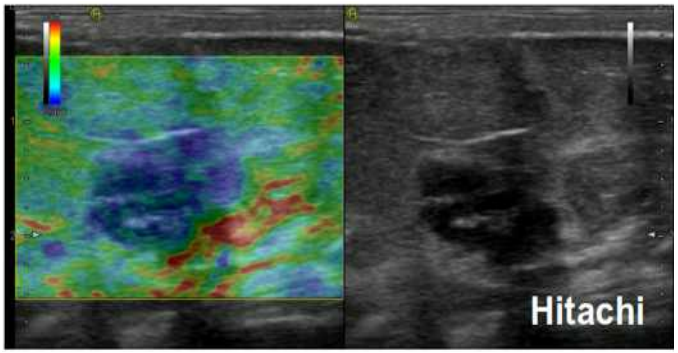
Non uniform stress field => qualitative method

Limited to superficial tissues

Influence of skinfold for muscle-tendon studies

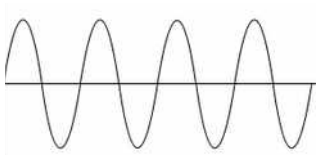
Static measurements



2/ Dynamic elastography (Shear Wave Elastography)

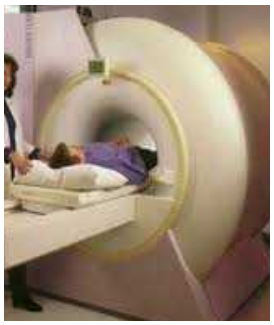
- **Magnetic Resonance Elastography**

Mechanical perturbation



Shear wave propagation

MRI



Shear wave velocity (Vs)

Shear elastic modulus

$$\mu = \rho V_S^2$$

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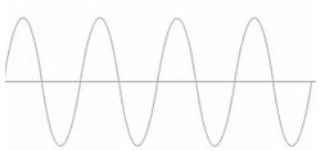

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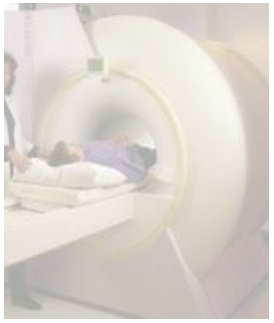

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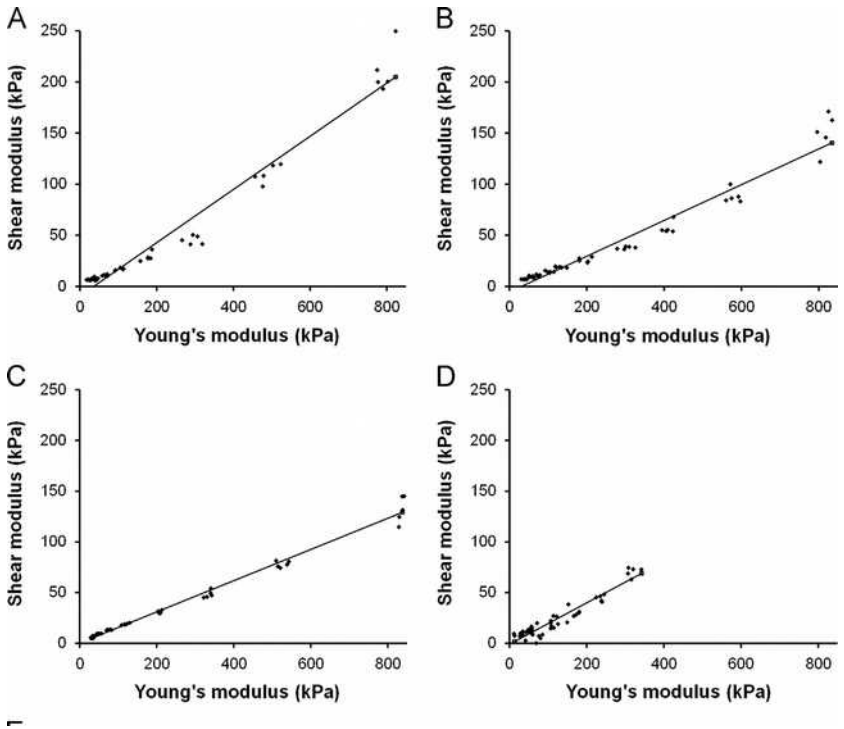
$$E \approx 3\mu$$



Relevant measurement of muscle stiffness

Eby et al., 2013

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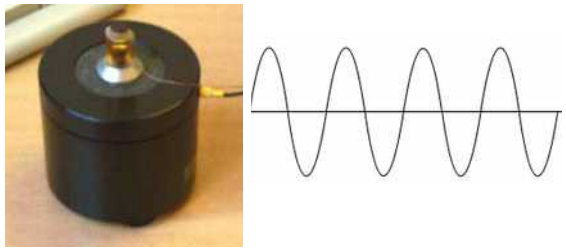

Shear wave propagation

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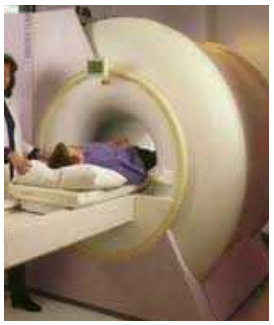

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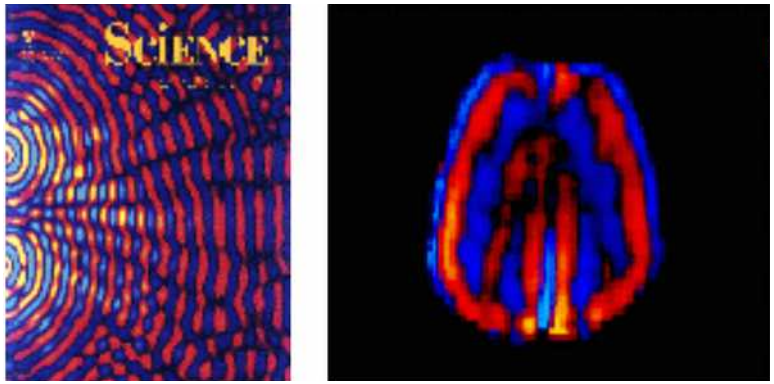
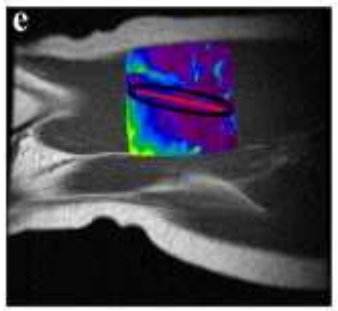
Muthupillai et al., Science, 1995



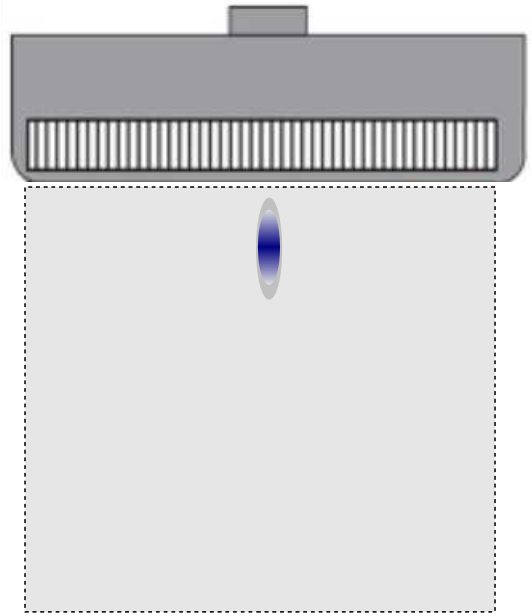


e.g., Bensamoun et al., 2011

Acquisition time:
30s -> 3min

2/ Dynamic elastography (Shear Wave Elastography)

- Magnetic Resonance Elastography
- **Acoustic Radiation Force => ARFI-SWS and SSI**



Push : ultrasound focused in one region

Sarvazyan, 1998

Bercoff et al., 2004

Deffieux, 2008

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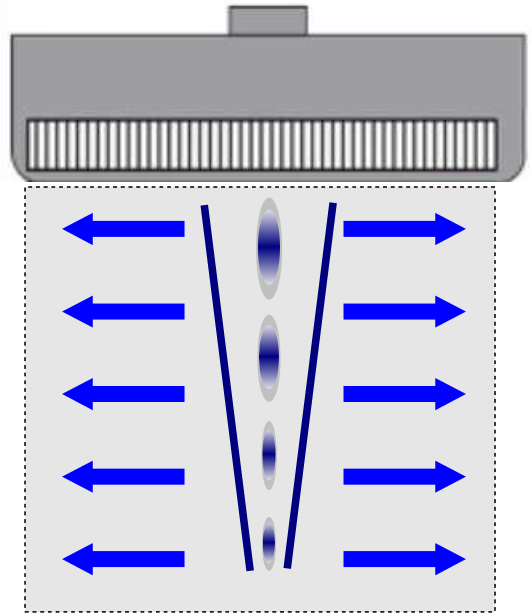

Shear wave propagation along the probe direction

Push : ultrasound focused in one region

Very fast displacement of the push

Sonic boom (like aircraft)
=> Supersonic Mac Cone

Sarvazyan, 1998

Bercoff et al., 2004

Deffieux, 2008

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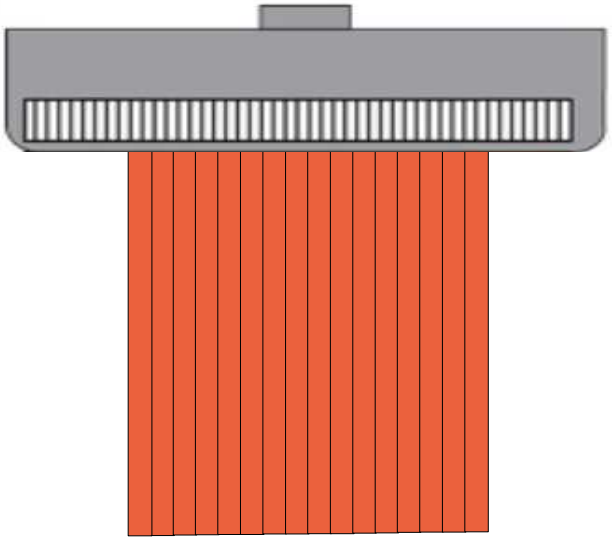
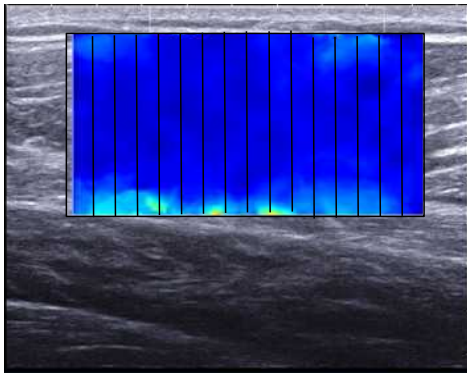
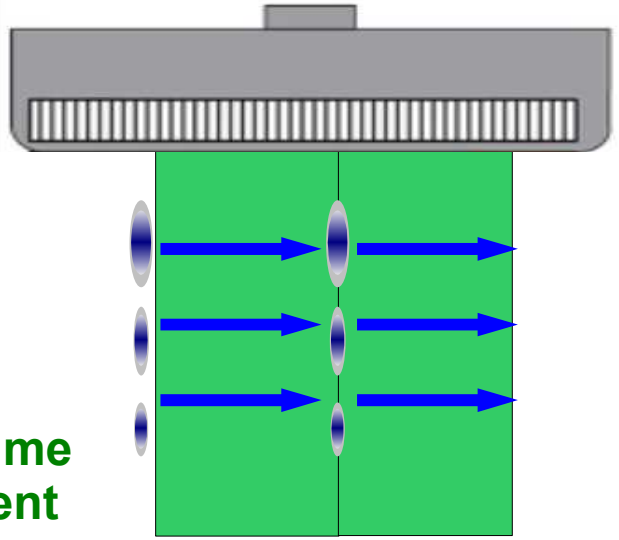
ARFI-SWS



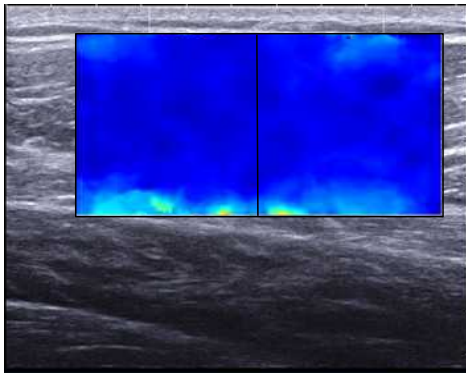
Not real time
Motion between push



SSI (Ultrafast Ultrasound)



Real time
Instantaneous measurement



Mainly used for cancer detection
(breast, thyroid, liver...)

SSI better for muscle-tendon studies (stretching and contractions)

1- Elastography methods

Institut Langevin
ONDES ET IMAGES

Supersonic Shear Imaging

Muscle-tendon biomechanics

Aixplorer

SUPERSONIC imagine

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Supersonic Shear Imaging

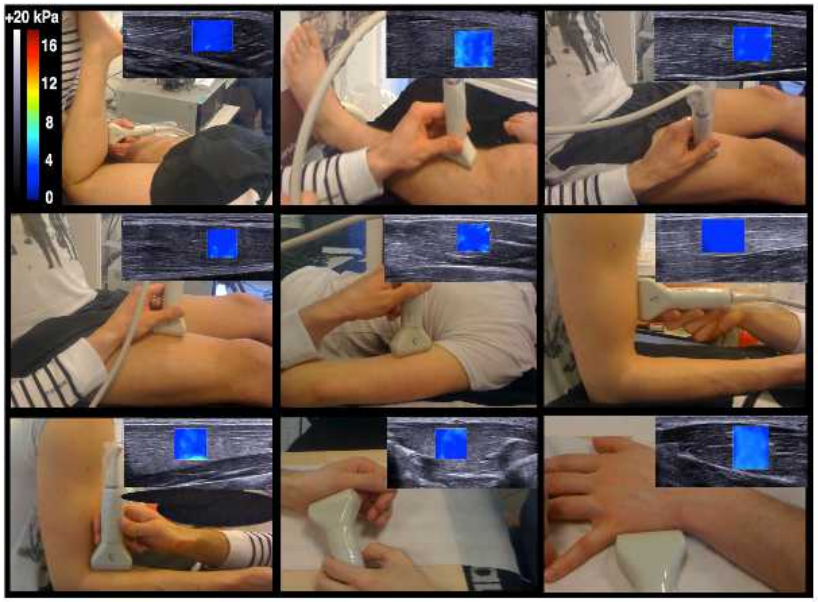
Aixplorer

SUPERSONIC imagine

Muscle-tendon biomechanics

- n=30
- **Muscle at rest (static)**
  - No contraction
  - Standardization of muscle length
- Intra day, inter day and inter operator reliability
- 9 muscles (20 min)

CV < 8%



Lacourpaille, Hug, Bouillard, Hogrel & Nordez. Physiol Meas, 2012

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Aixplorer

SUPERSONIC imagine

Muscle-tendon biomechanics

“Dynamic” measurements

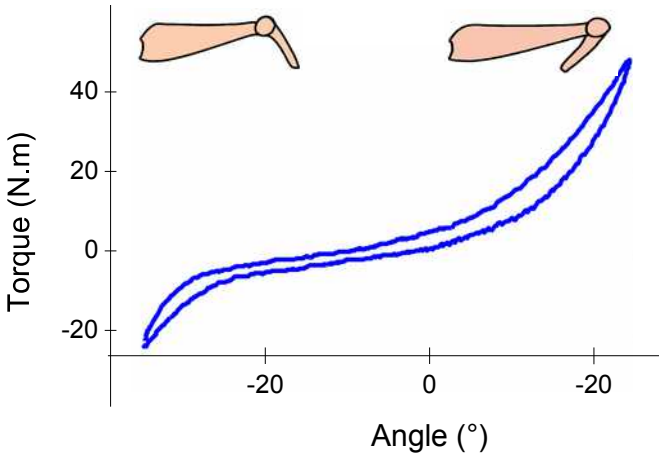
2- Passive muscle

Estimation of passive muscle tension

3- Muscle contraction

Estimation of individual muscle force

Mechanical properties of the passive musculo-articular complex



e.g., Magnusson, 1998 ; Gajdosick, 2001 ; McNair et al., 2001 Nordez et al., 2006, 2008, 2009

Passive torque : global resistance of the musculo-articular complex to the motion

Muscles, tendons, joint capsule, ligaments, nerves, fascias, skin...

➡ **Homogeneous stiffness & stretching level ?**

➡ **Homogeneous effects of interventions (stretching, damage...) ?**

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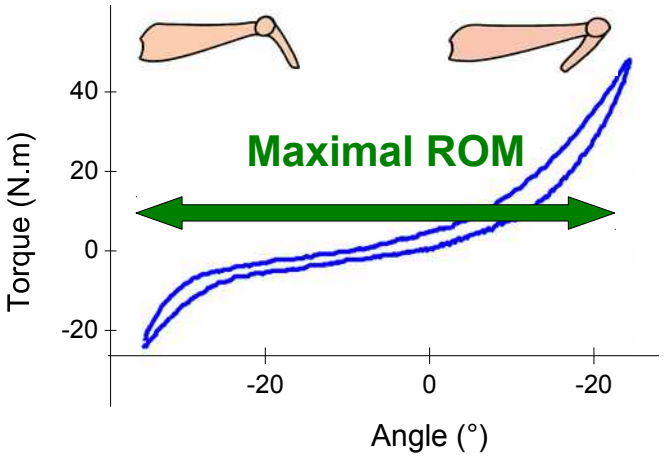

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Due to muscle tension and perception of tension inside muscles

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➡ **Other structure(s) ?**

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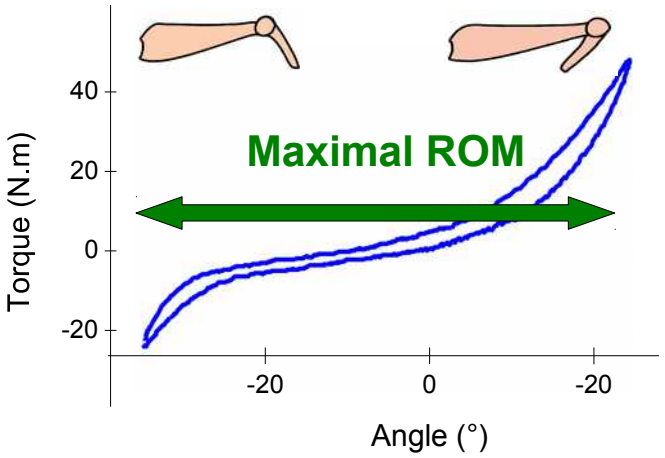

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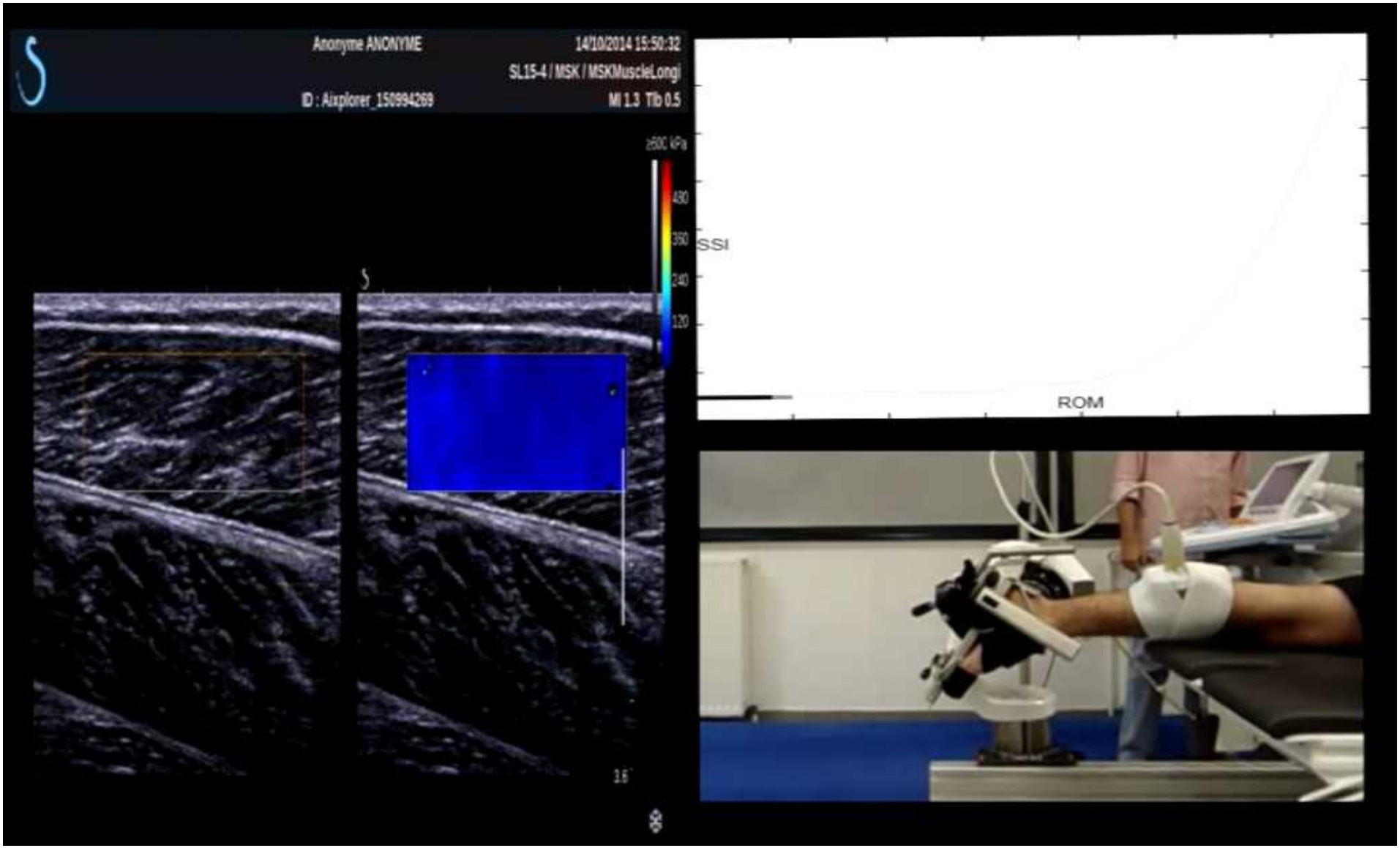
Need of localized measurements to revisit passive muscle biomechanics => SSI

1/ SSI measurements during passive muscle stretching



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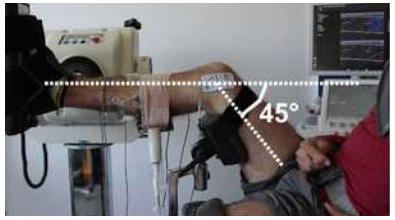
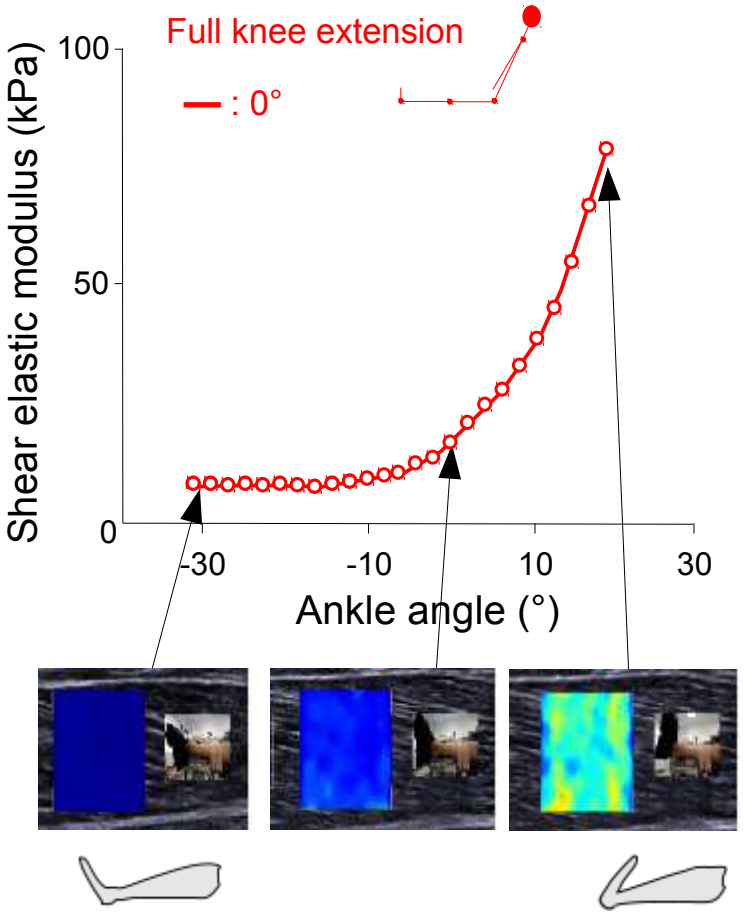
Maïsetti, Hug, Bouillard & Nordez. J Biomech, 2012



8 subjects

Shear elastic modulus-angle relationship



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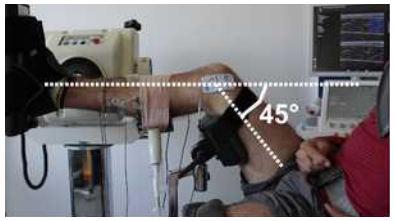
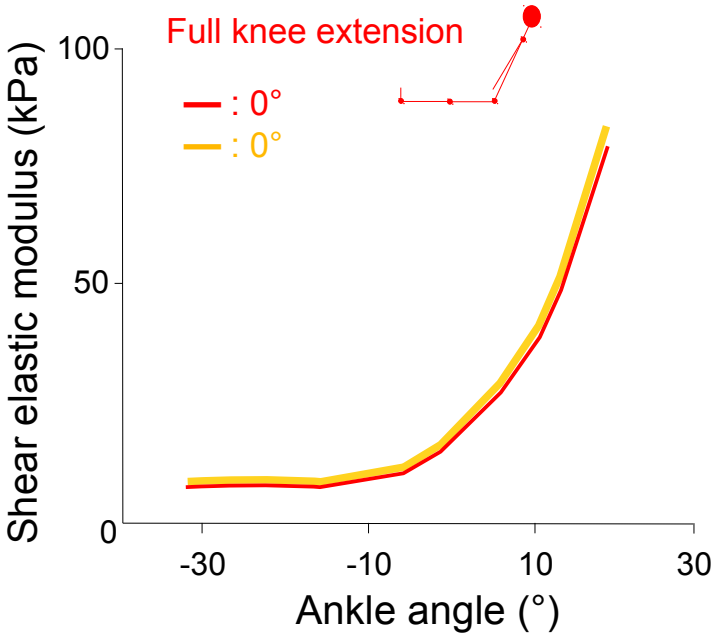
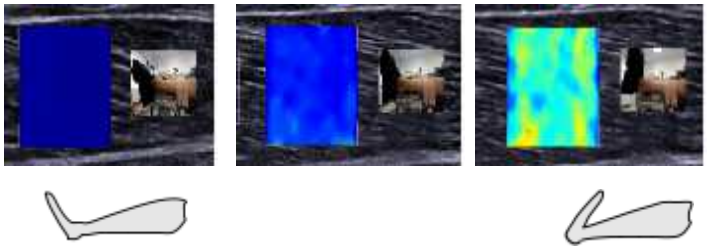


Maïsetti, Hug, Bouillard & Nordez. J Biomech, 2012

- Shear elastic modulus-angle relationship
- **Repeatability**





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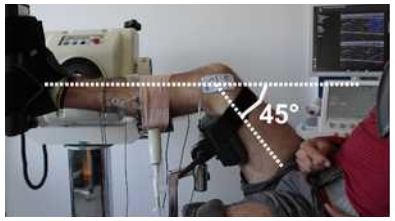

Maïsetti, Hug, Bouillard & Nordez. J Biomech, 2012

- Shear elastic modulus-angle relationship
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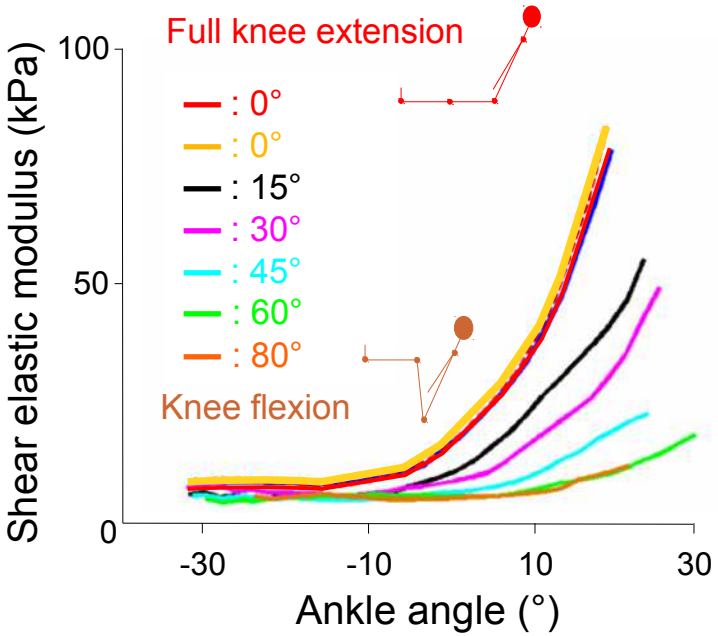
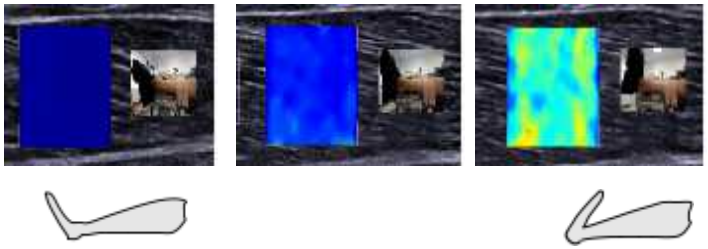
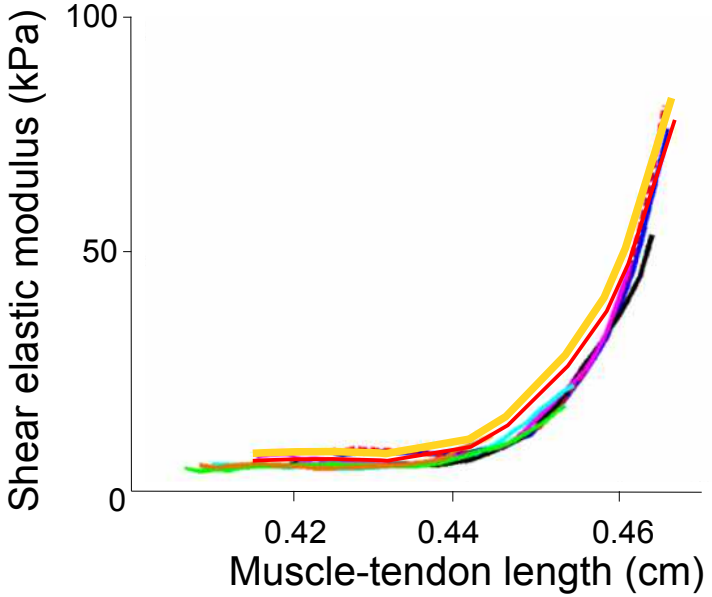
- **Experiment at several knee angles**

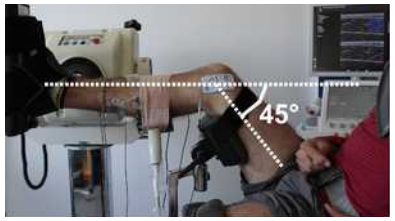






Grieve et al., 1978

1/ SSI measurements during passive muscle stretching



Maïsetti, Hug, Bouillard & Nordez. J Biomech, 2012

- Shear elastic modulus-angle relationship
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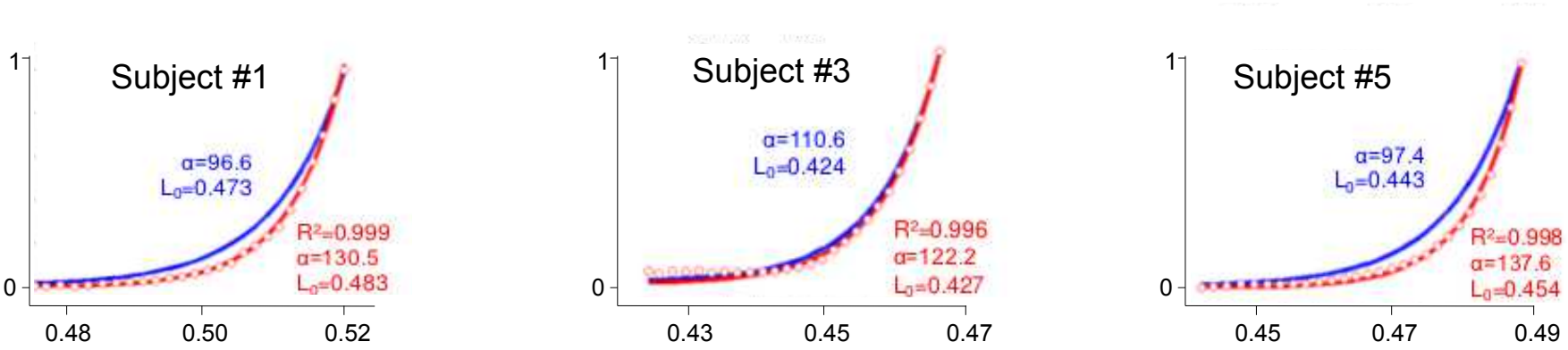
- Experiment at several knee angles
- **Comparison with the force-length relationship**

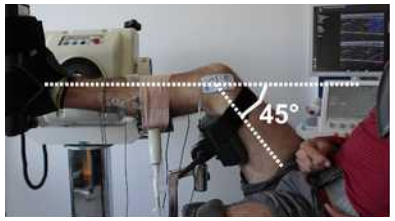


— **Force - length** — **Shear elastic modulus - length**

Hoang et al., 2005; Nordez et al., 2010

SSI provides a good estimate of muscle stretching level or passive muscle tension

1/ SSI measurements during passive muscle stretching



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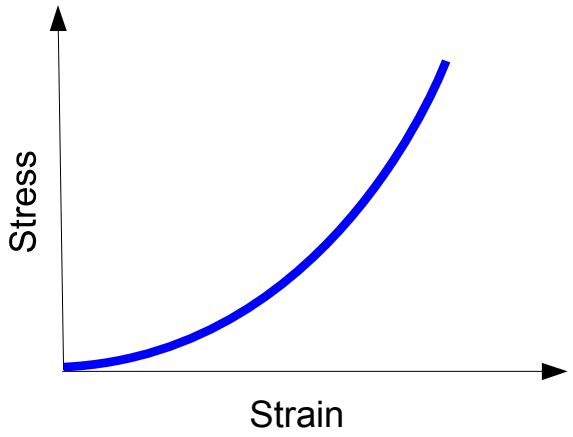

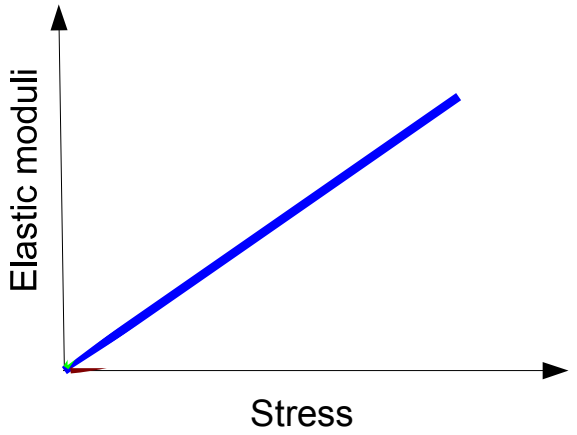

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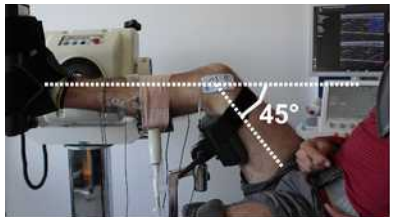

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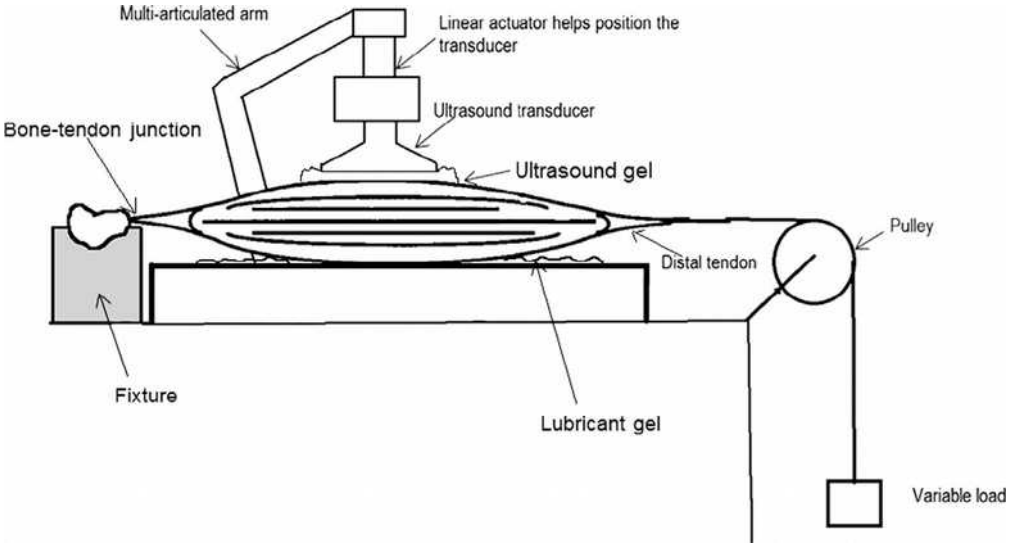
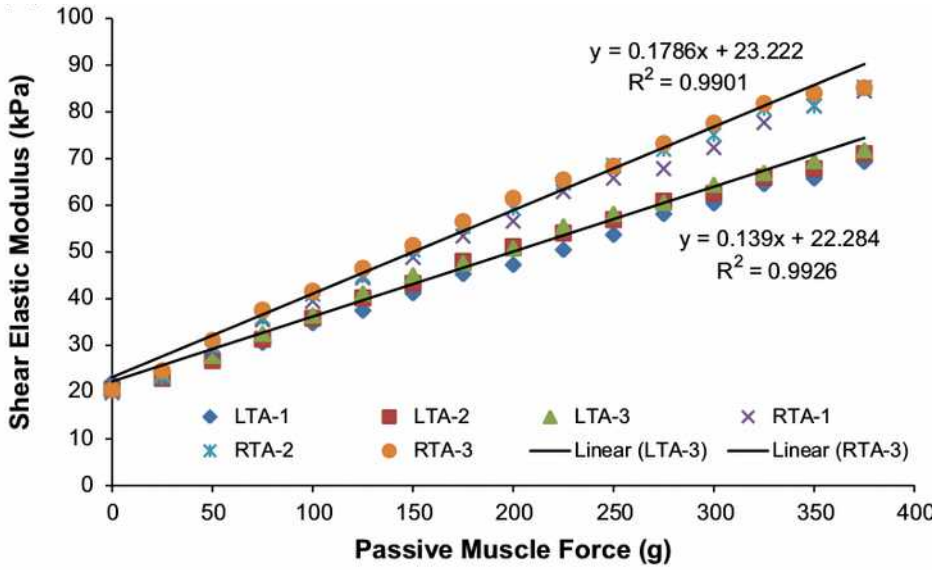


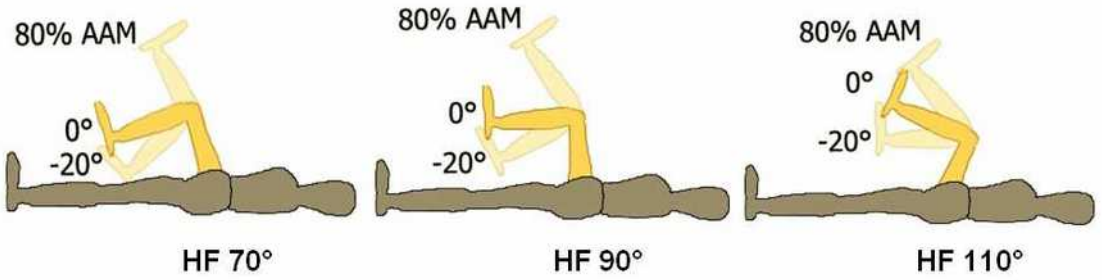


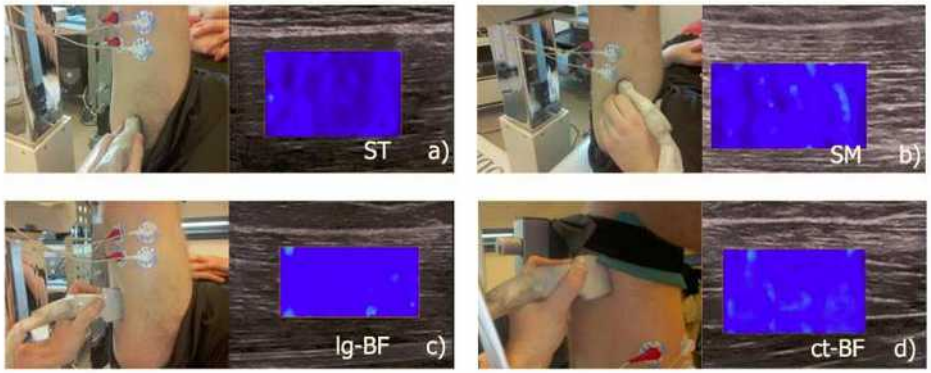
(Koo *et al.*, 2013)

SSI provides a good estimate of muscle stretching level or passive muscle tension

2/ Hamstrings stretching

LeSant, Brasseur & Nordez to be submitted





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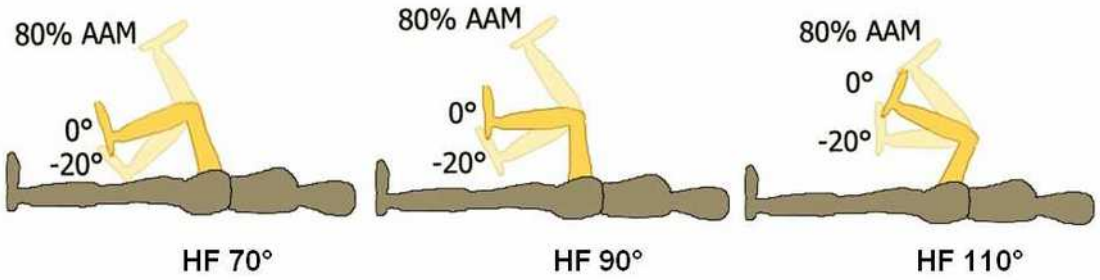
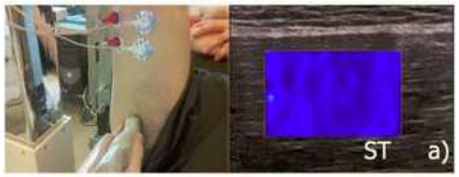
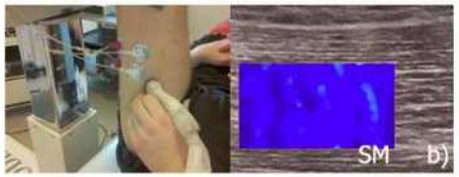


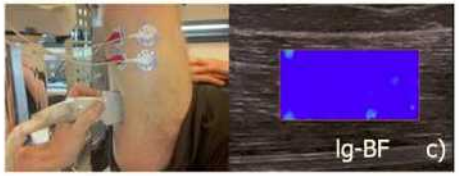
CV = 8.9 – 13.4 %

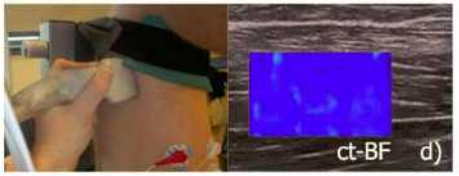




CV = 10.3 – 11.2 %

CV = 8.6 – 13.3 %



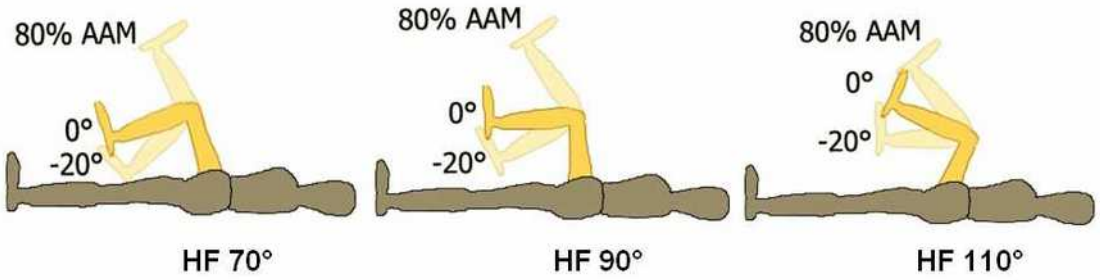


CV = 20.3 – 44.9 %

- **Ct-BF not reliable**

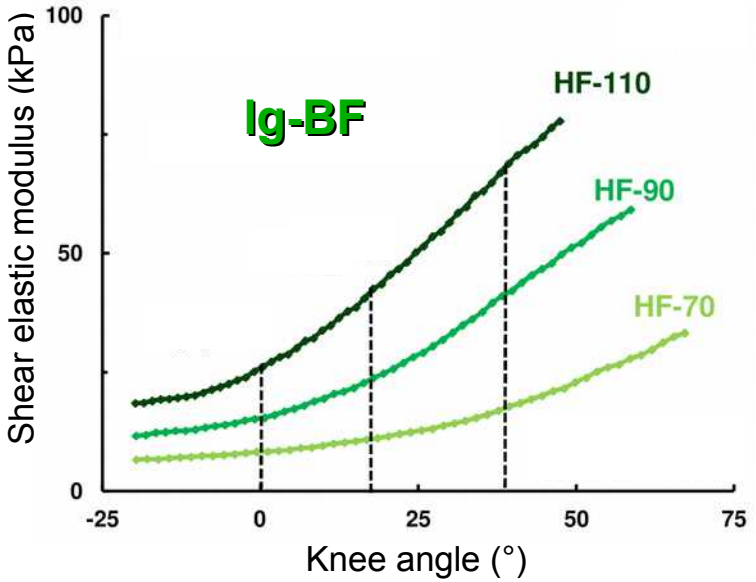
2/ Hamstrings stretching

LeSant, Brasseur & Nordez to be submitted



Bi-articular muscles

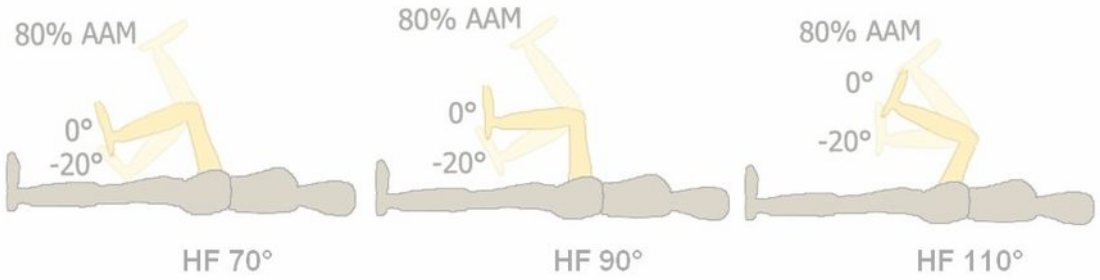
Recommendation for stretching exercises



- **Ct-BF not reliable**
- **Effects of hip and knee angles**
- **Hip flexed more efficient**

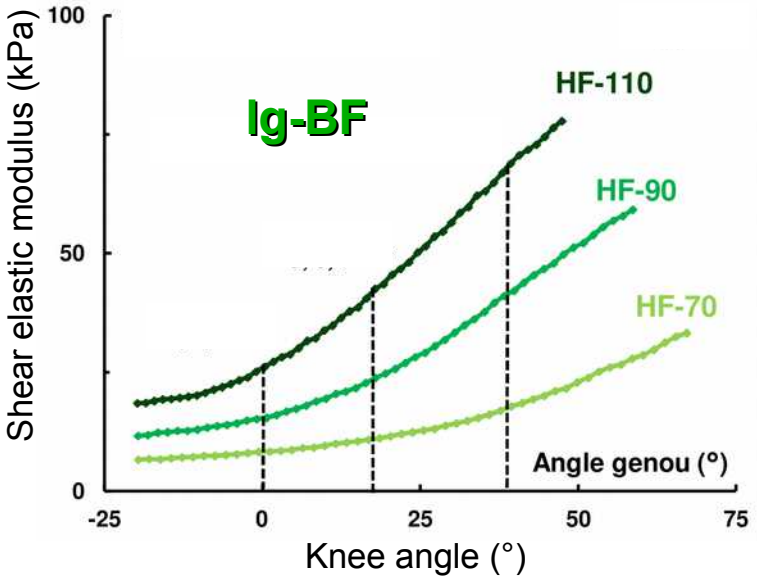
2/ Hamstrings stretching

LeSant, Brasseur & Nordez to be submitted

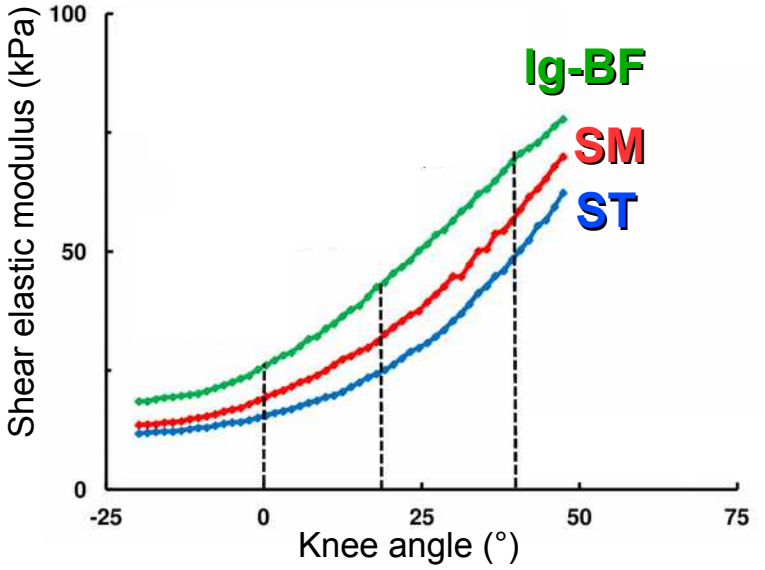


Prevalence of injuries : 1/ BF, 2/ SM, 3/ ST

Mendiguchia et al., 2012



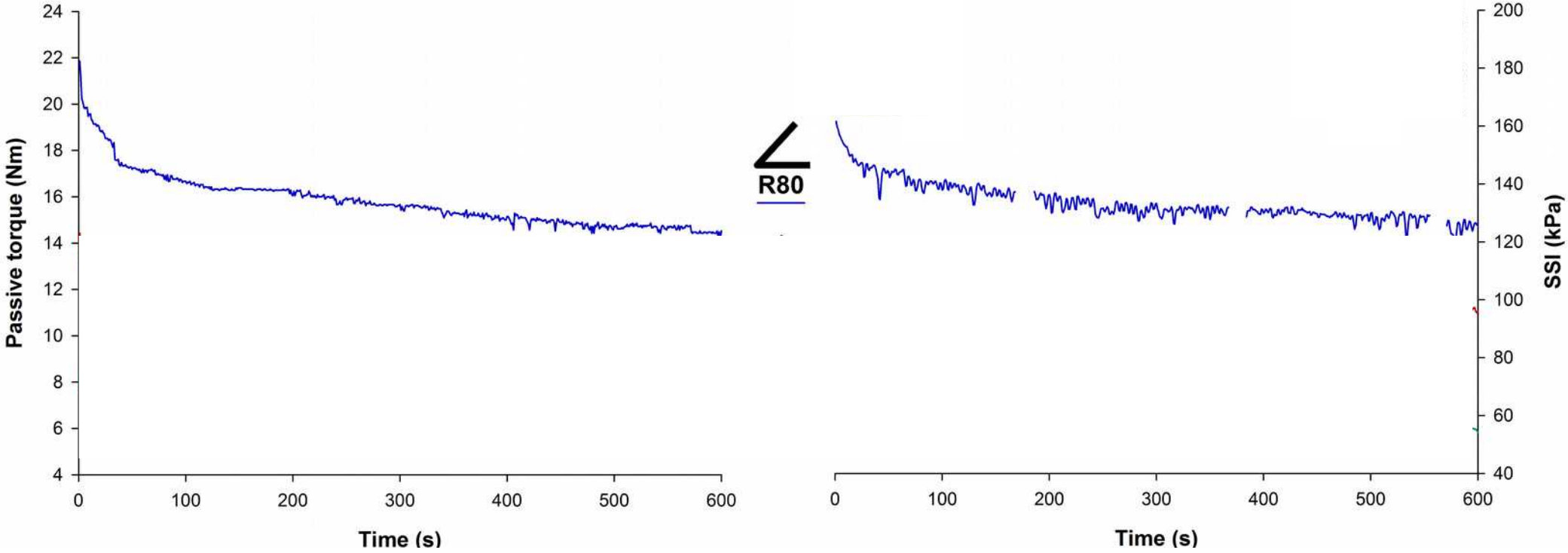
- Ct-BF not reliable
- Effects of hip and knee angles
- Hip flexed more efficient
- Lg-BF stiffer



3/ Acute effects of static stretching (relaxation)

Freitas, Andrade, Lacourpaille, Mil-homens & Nordez. Eur J Appl Physiol, Submitted

3 sessions : 10 minutes of static stretching at 40, 60 and 80% of maximal ROM (randomized)



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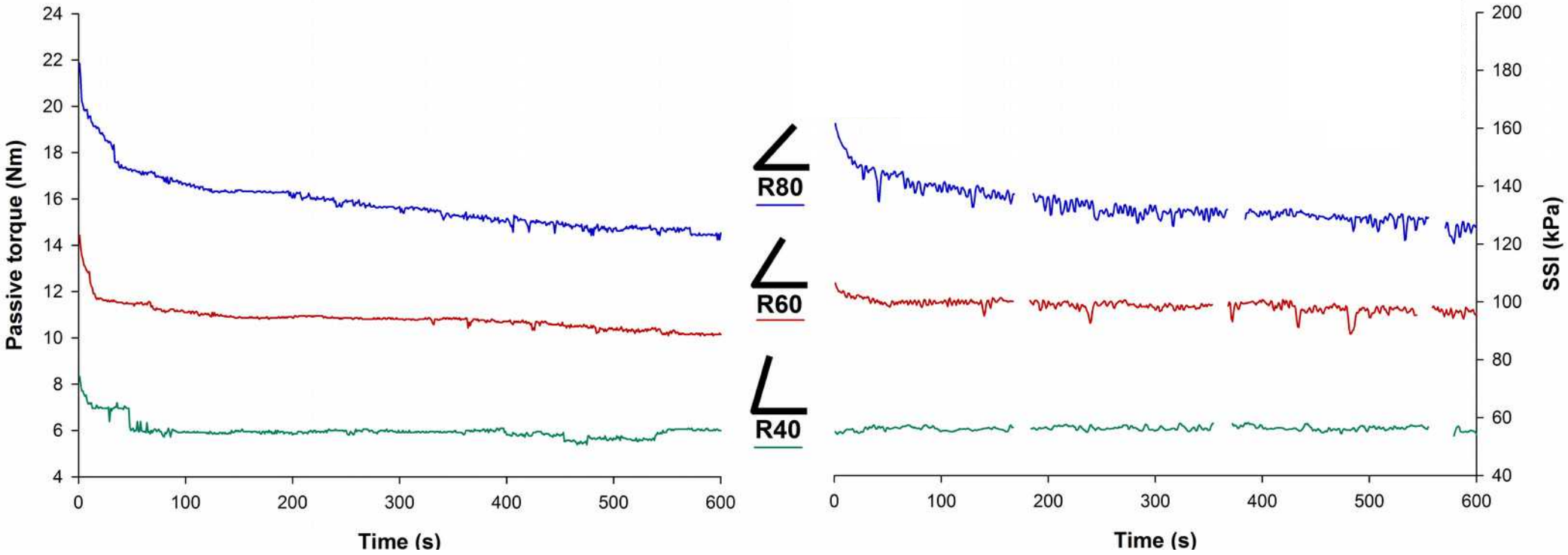

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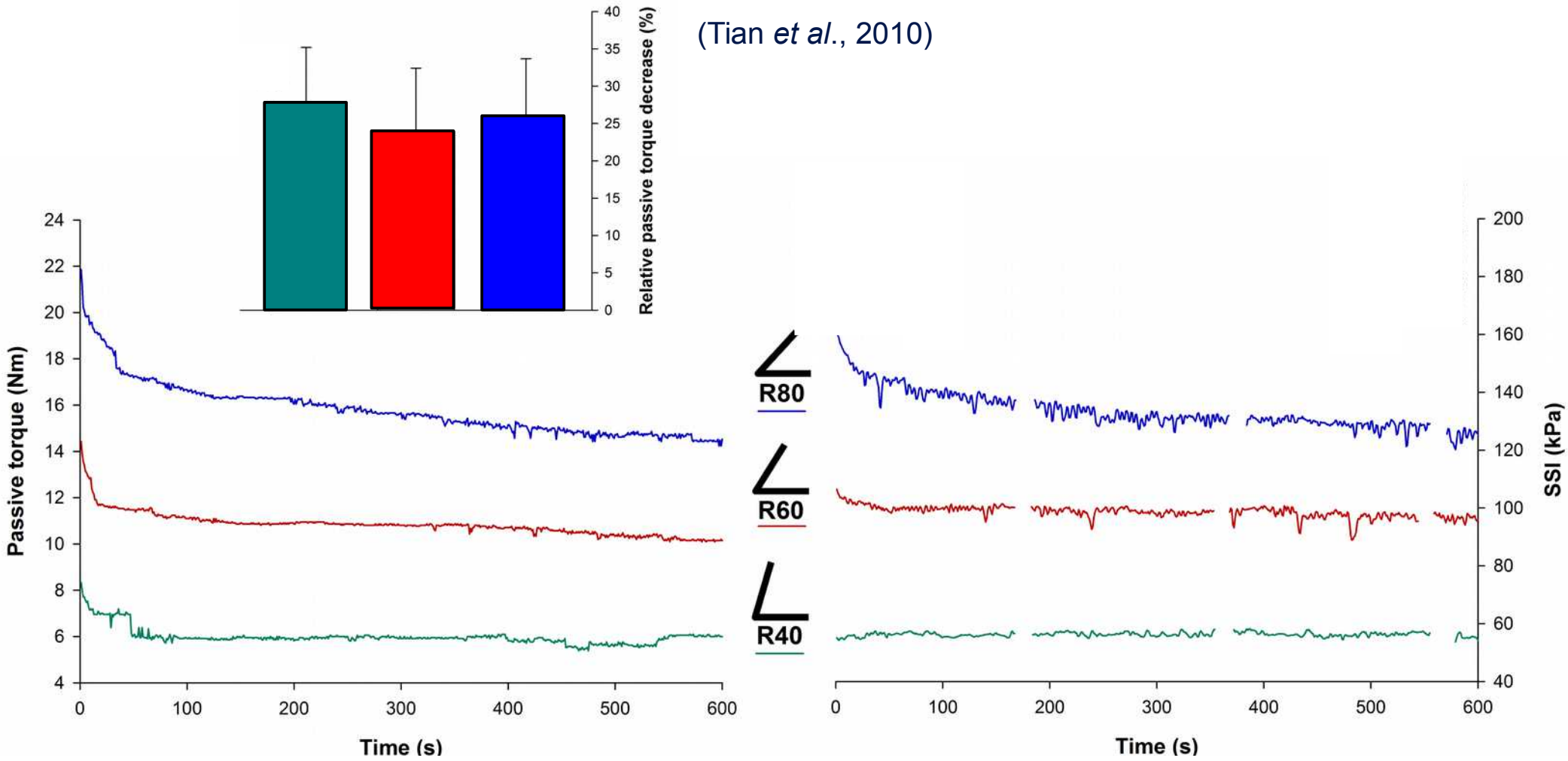
(Tian *et al*., 2010)



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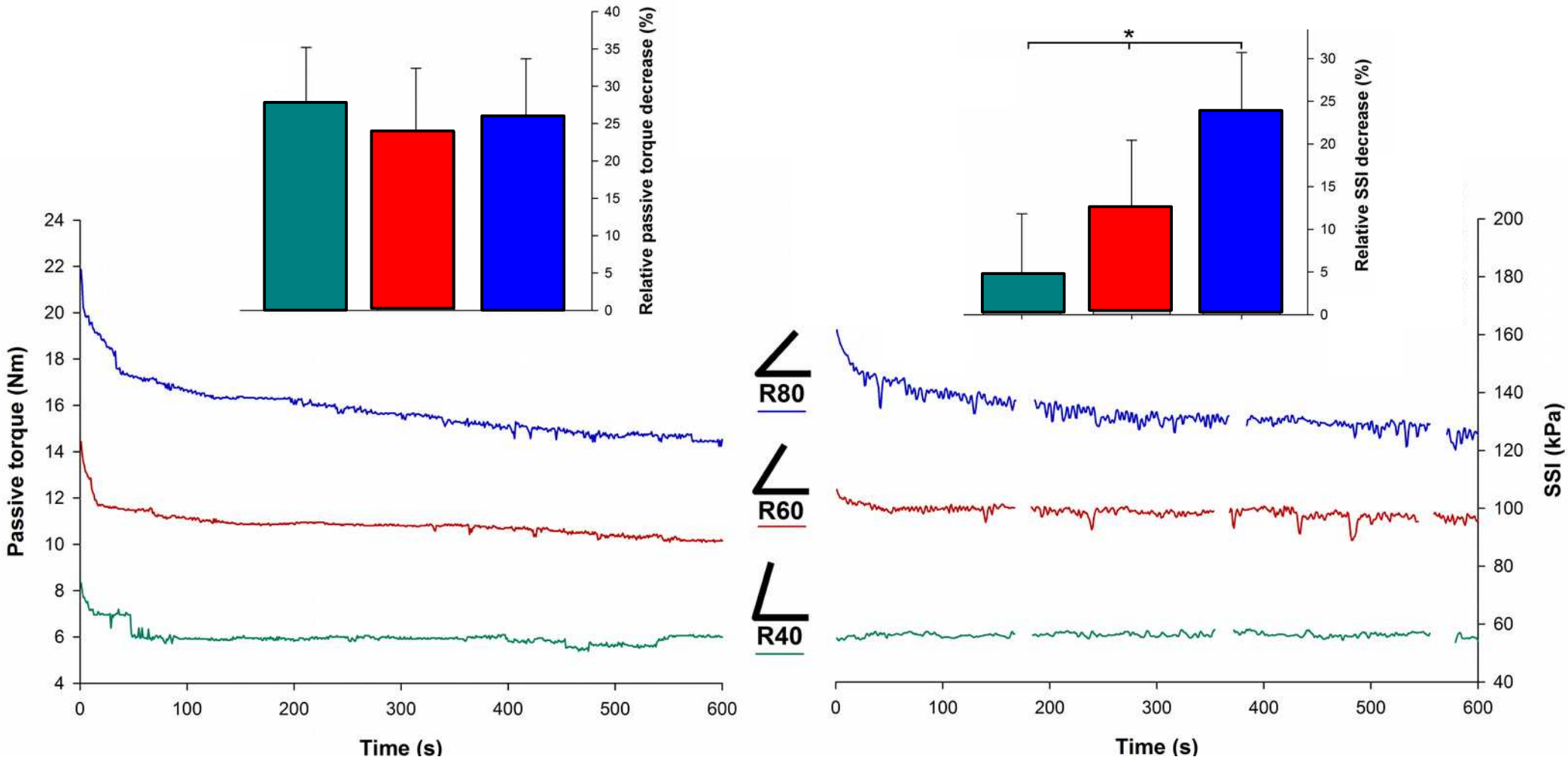

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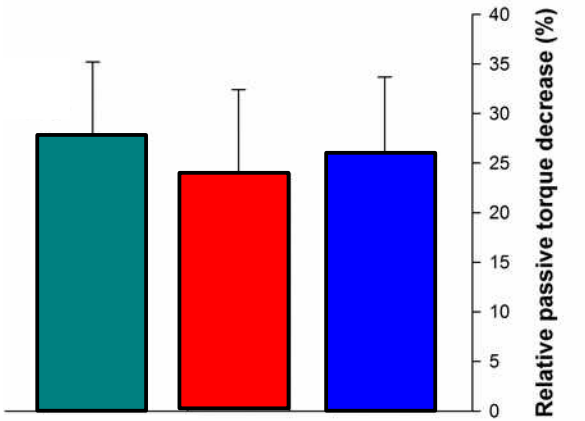
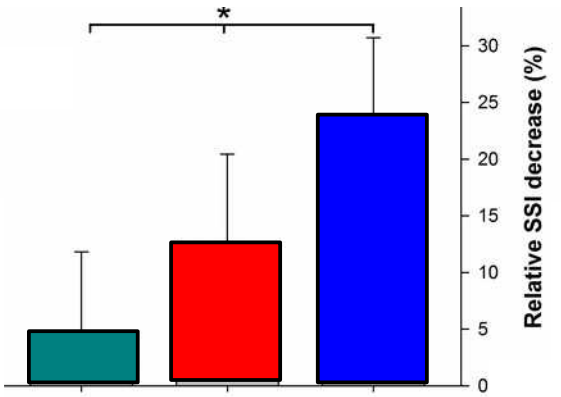




Targeted tissues ?

Specific stretching exercises ?

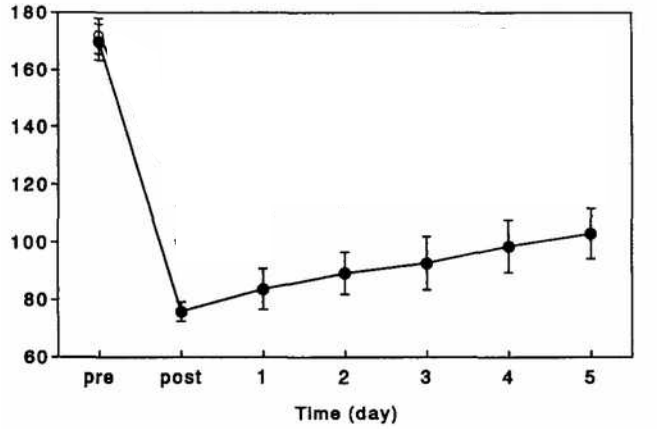
Confirm the need of measurements on all the muscles involved

4/ Effects of eccentric exercise

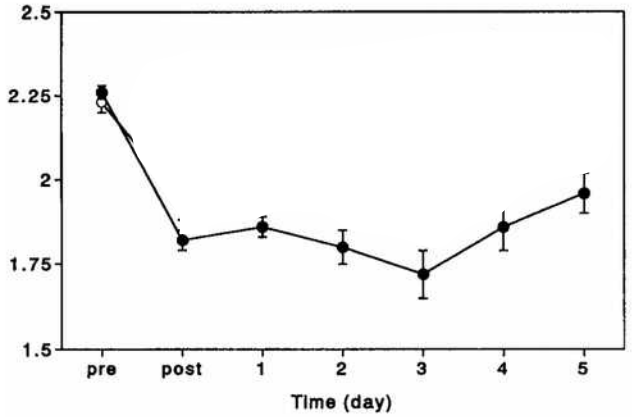
Lacourpaille, Nordez et al., Acta Physiologica, 2014

Nosaka et al., 2001

MVC



Maximal ROM



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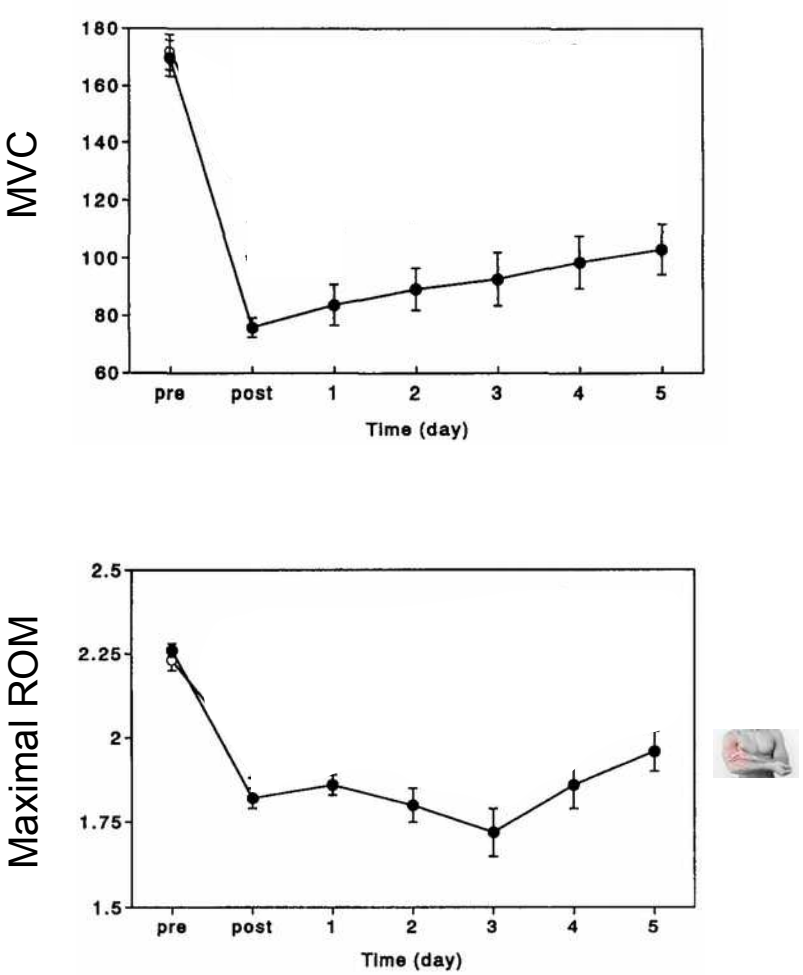
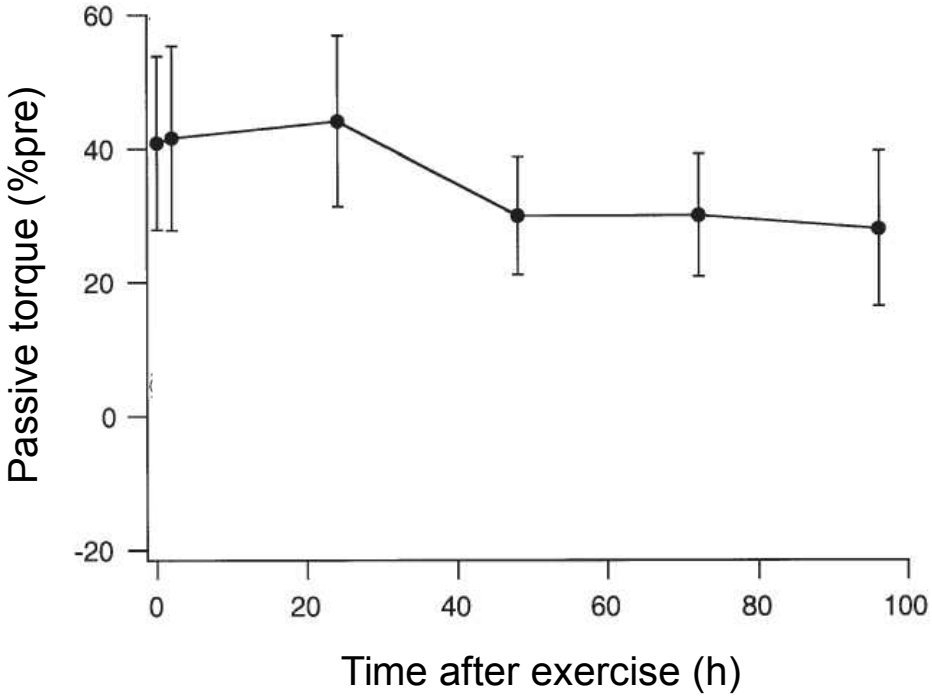
Lacourpaille, Nordez et al., Acta Physiologica, 2014

Nosaka et al., 2001



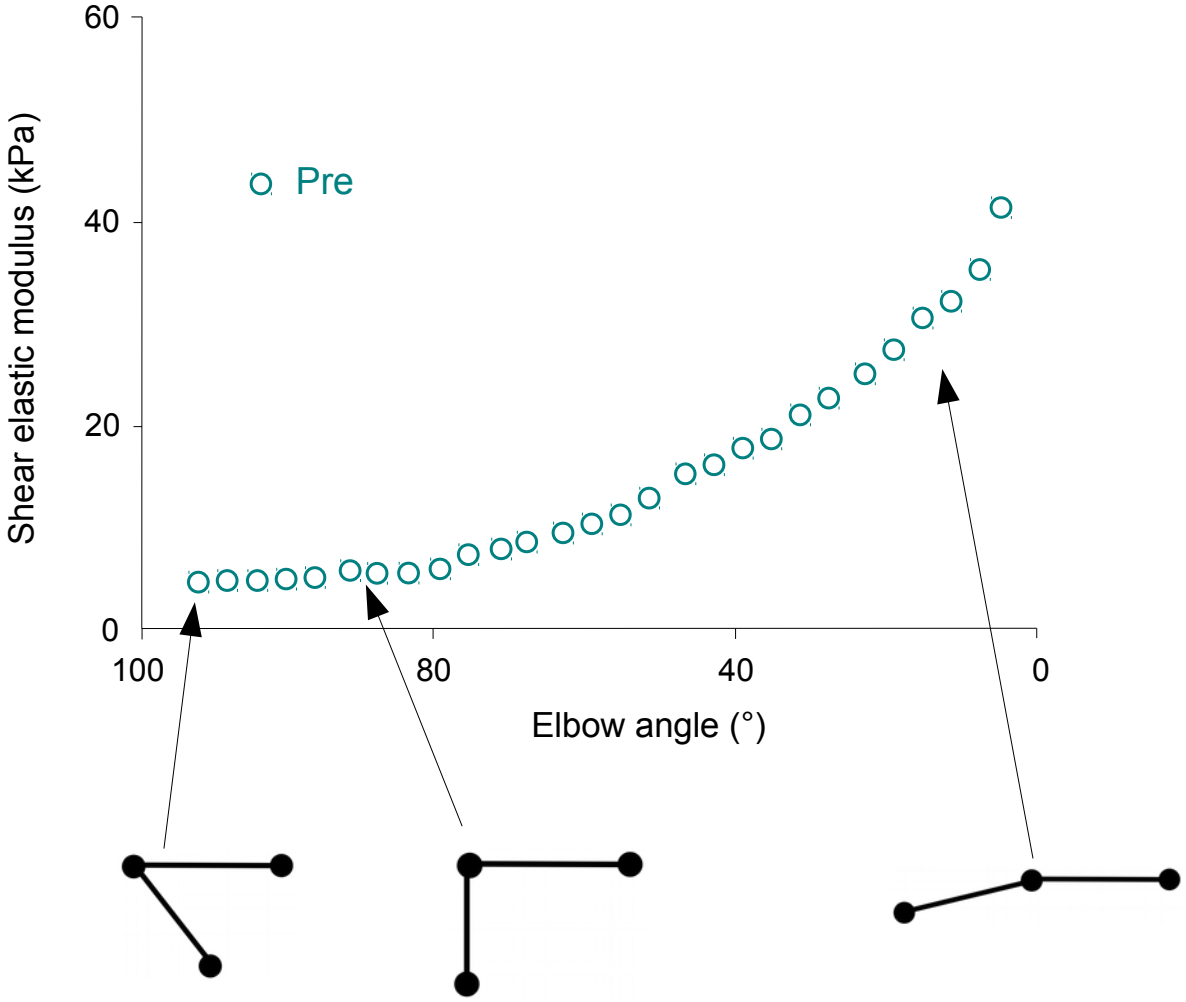


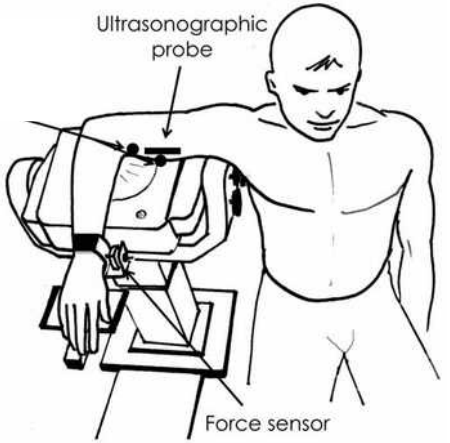
Whitehead et al., 2001

Homogeneous changes among muscles?

4/ Effects of eccentric exercise

Lacourpaille, Nordez et al., Acta Physiologica, 2014



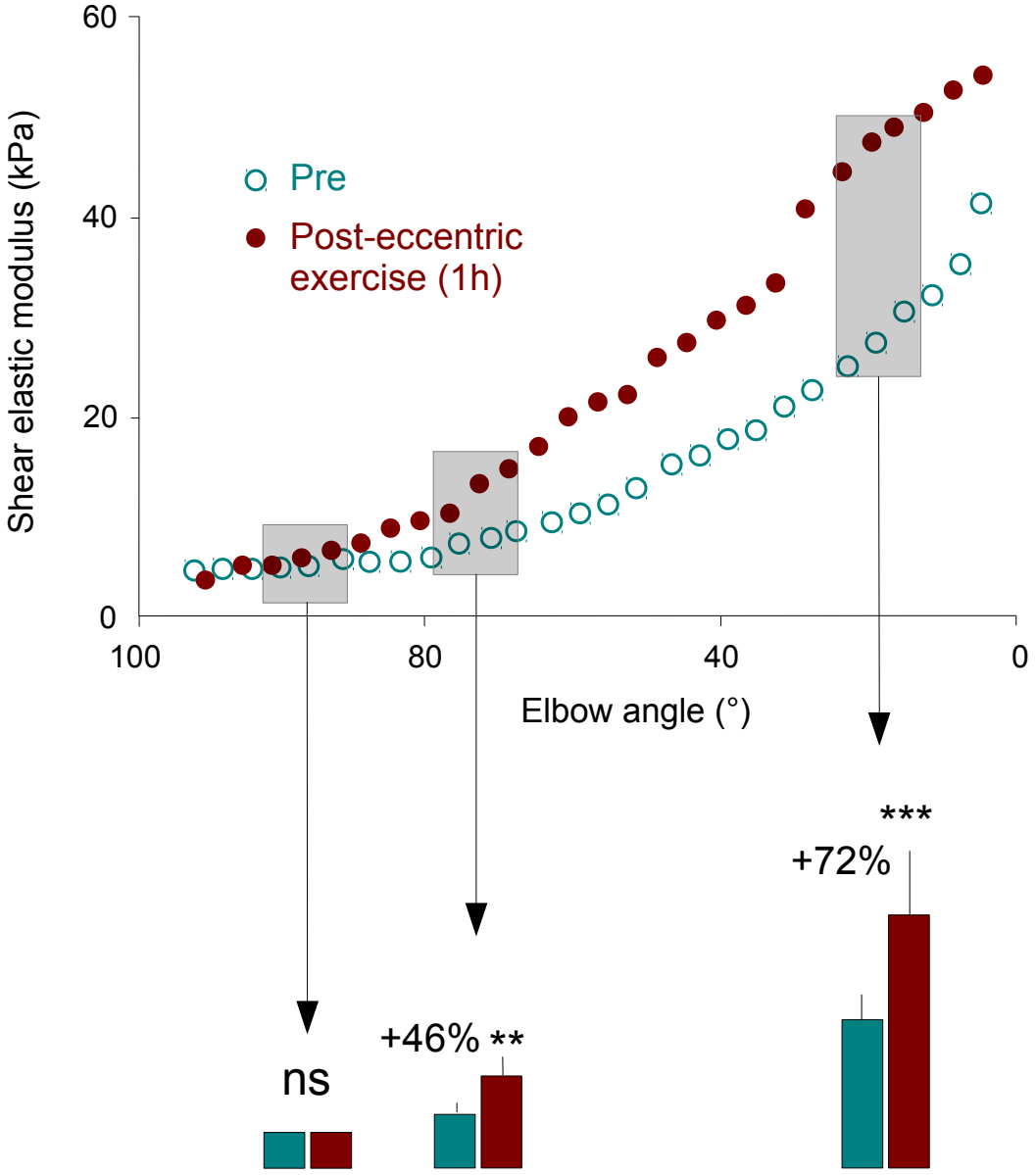


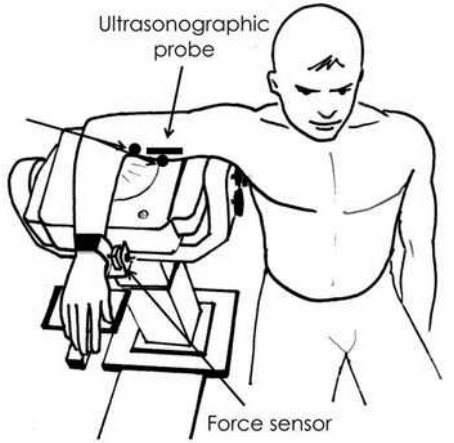
3 x 10 eccentric contractions

Pre +1h +48h +21D

4/ Effects of eccentric exercise

Lacourpaille, Nordez et al., Acta Physiologica, 2014





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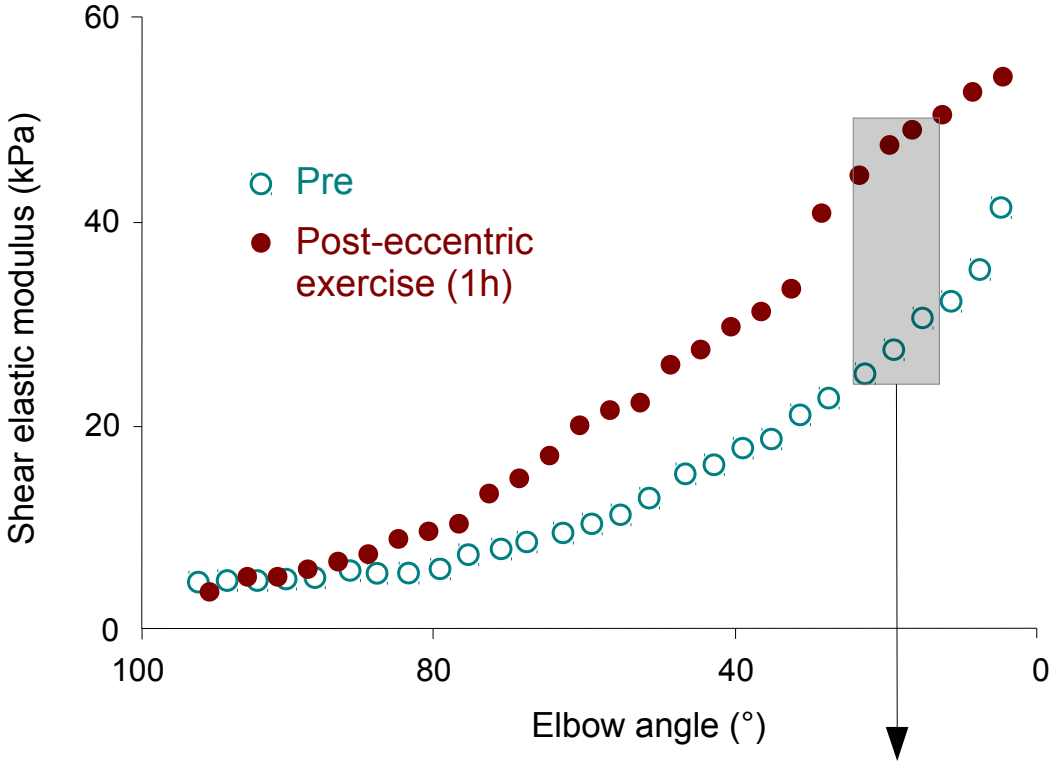
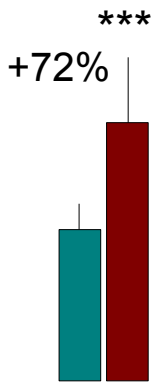
Pre +1h +48h +21D

Length dependent changes

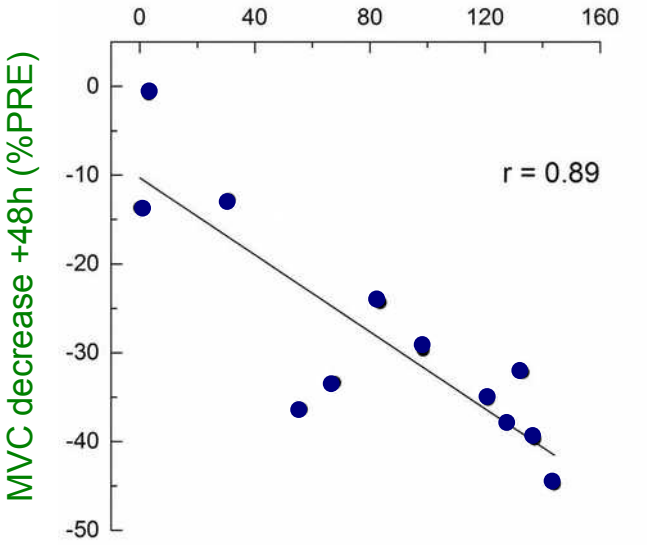
4/ Effects of eccentric exercise

Lacourpaille, Nordez et al., Acta Physiologica, 2014





Shear elastic modulus increase +1h (%PRE)



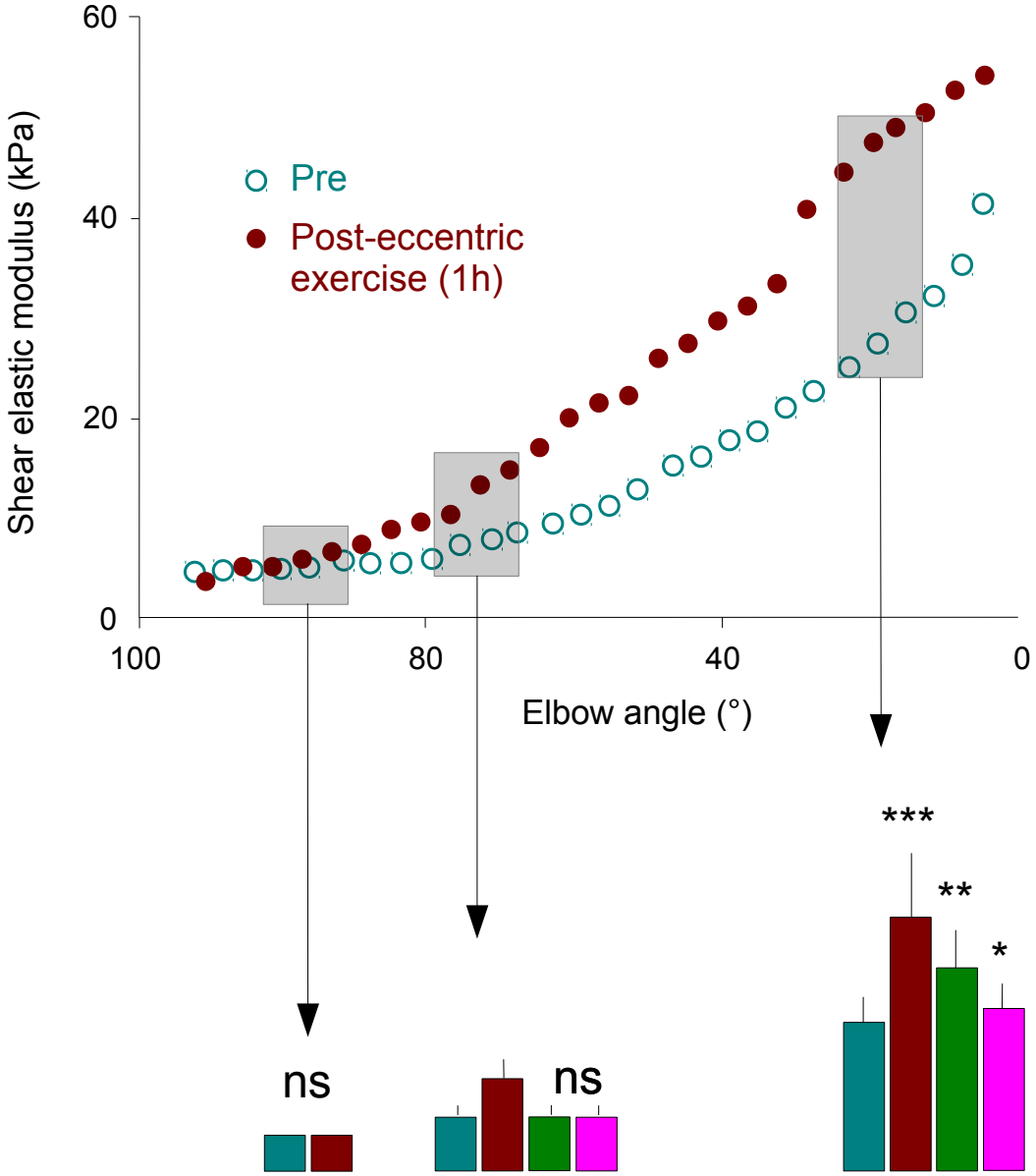
- Length dependent changes
- **Changes in modulus predict the decrease in MVC**

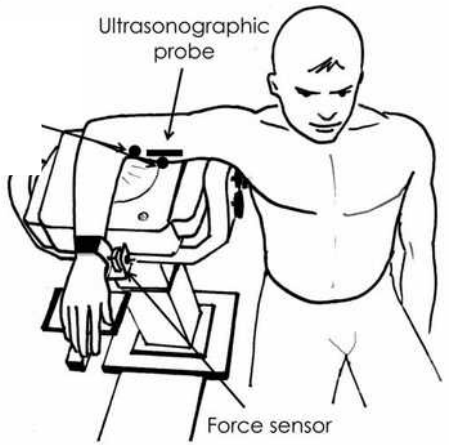
Indicator of the amount of damage?

Experiments on knee extensors and plantar flexors

4/ Effects of eccentric exercise

Lacourpaille, Nordez et al., Acta Physiologica, 2014





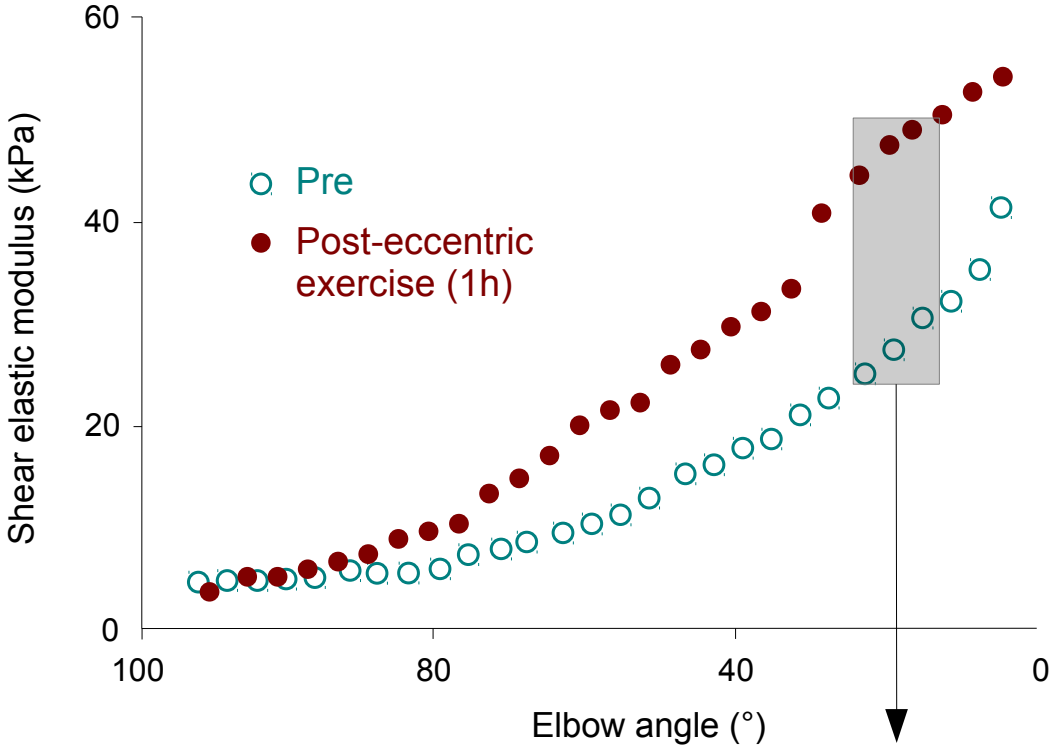
3 x 10 eccentric contractions

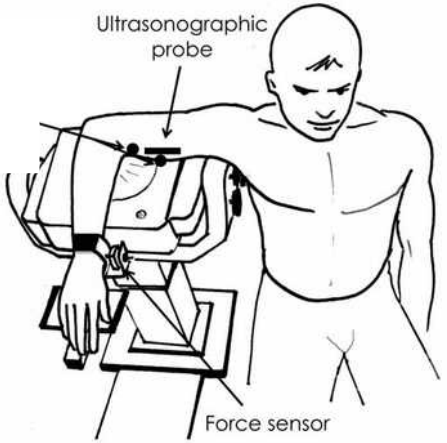
Pre +1h +48h +21D

- Length dependent changes
- Change in modulus predict the decrease in MVC
- **Adaptation? Repeated bout effect?**

4/ Effects of eccentric exercise

Lacourpaille, Nordez et al., Acta Physiologica, 2014



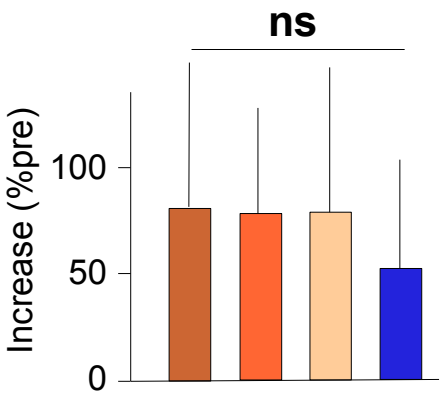


3 x 10 eccentric contractions

Pre +1h +48h +21D

- Length dependent changes
- Change in modulus predict the decrease in MVC
- Adaptation? Repeated bout effect?
- **Homogeneous changes**

Biceps (proximal)
Biceps (medial)
Biceps (distal)
Brachialis

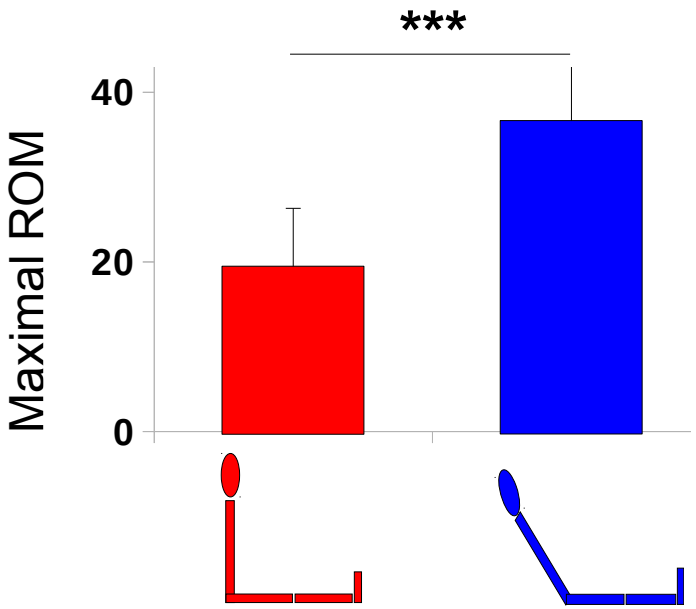


5/ Factors that affects the maximal ROM of a joint

Andrade, Lacourpaile, Freitas, McNair & Nordez. Scand J Med Sci Sports, in revision

Maximal ROM at a joint: limited by passive muscle tension and perception of muscle tension

e.g., Gajdosik, 2001 ; Weppler and Magnusson, 2010



Mitchell et al., 2008

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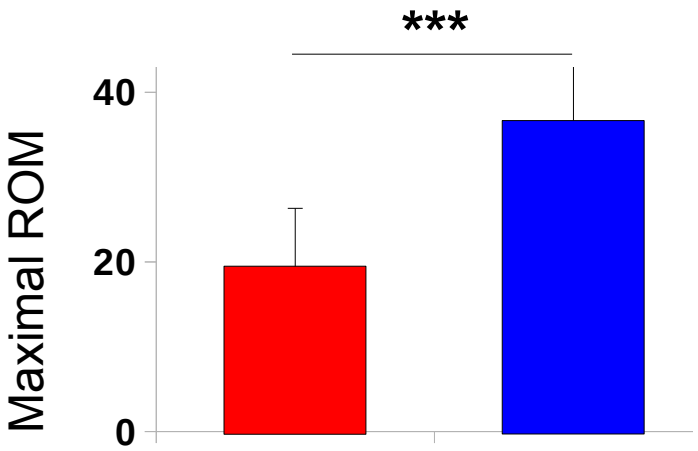
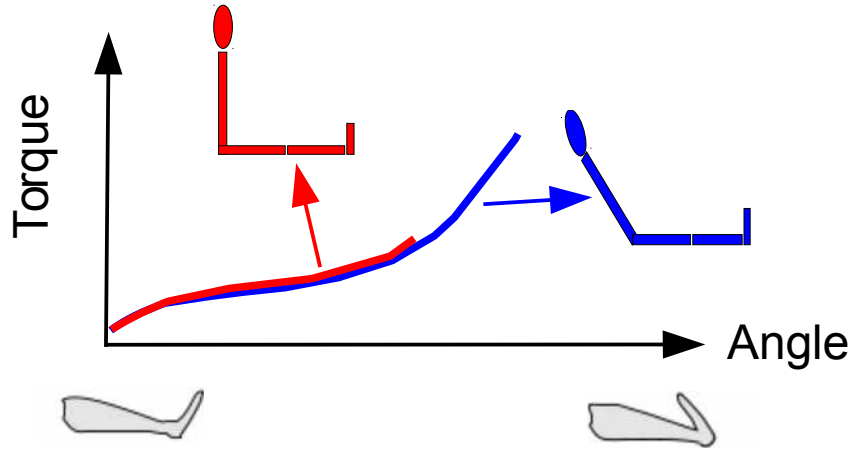
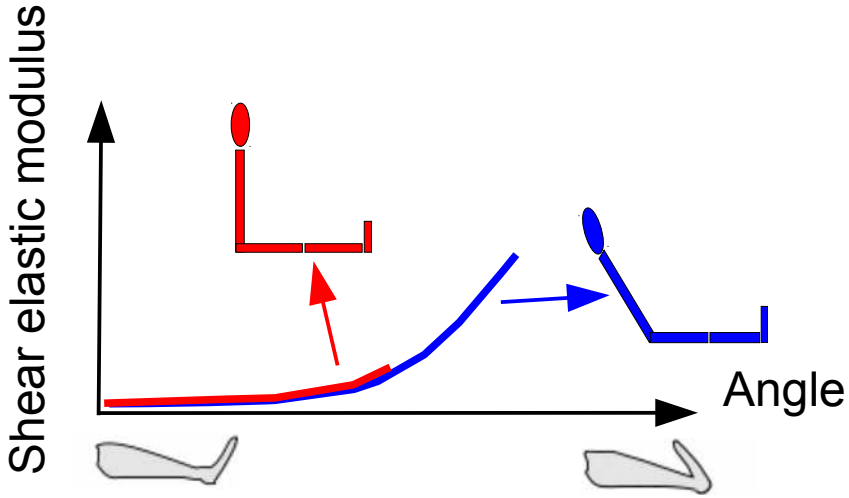


Mitchell et al., 2008

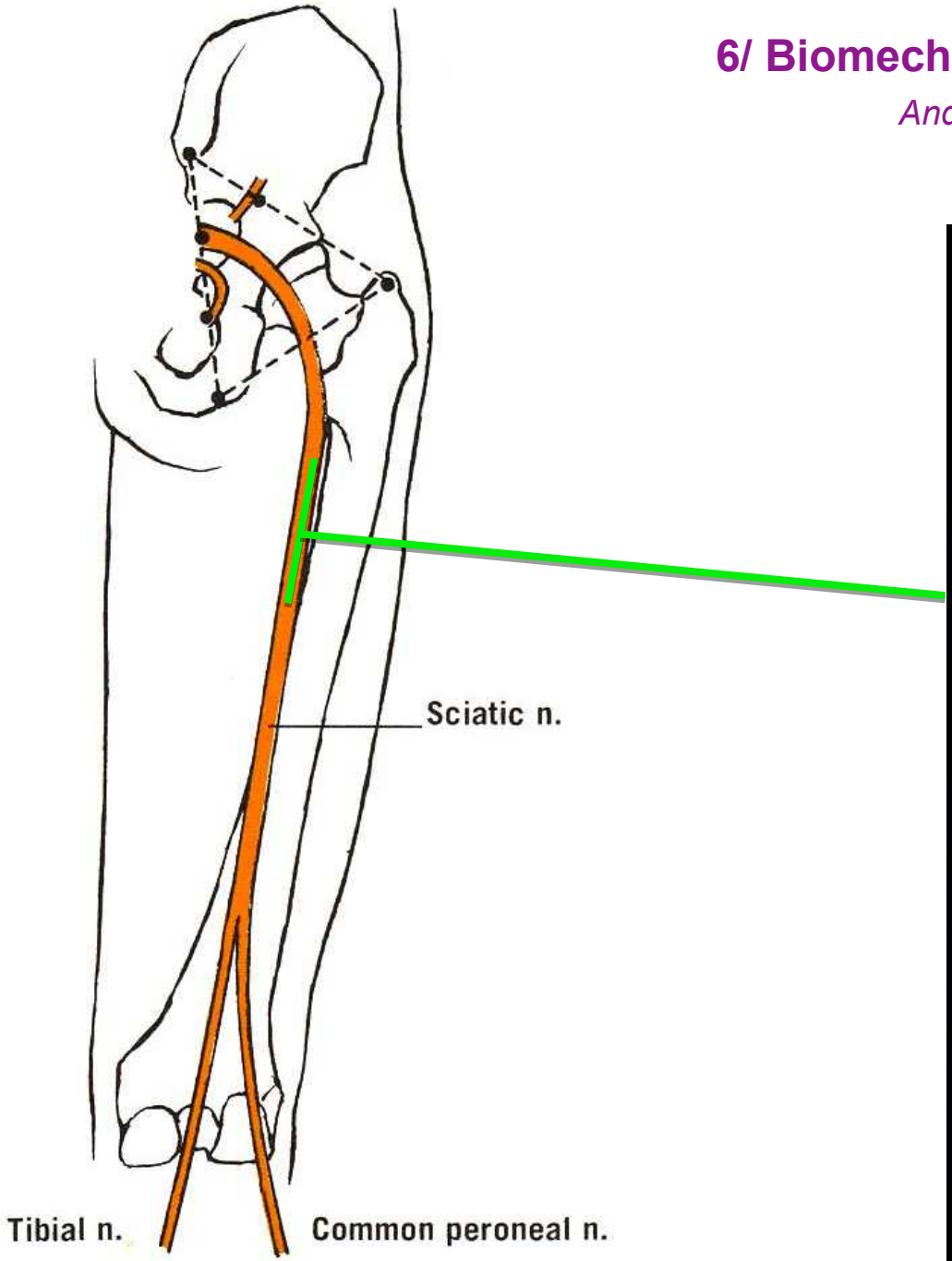
- **Muscles do not limit the maximal ROM**
- **A structure that crosses both hip and ankle limits the maximal ROM**
- **Nerve?**

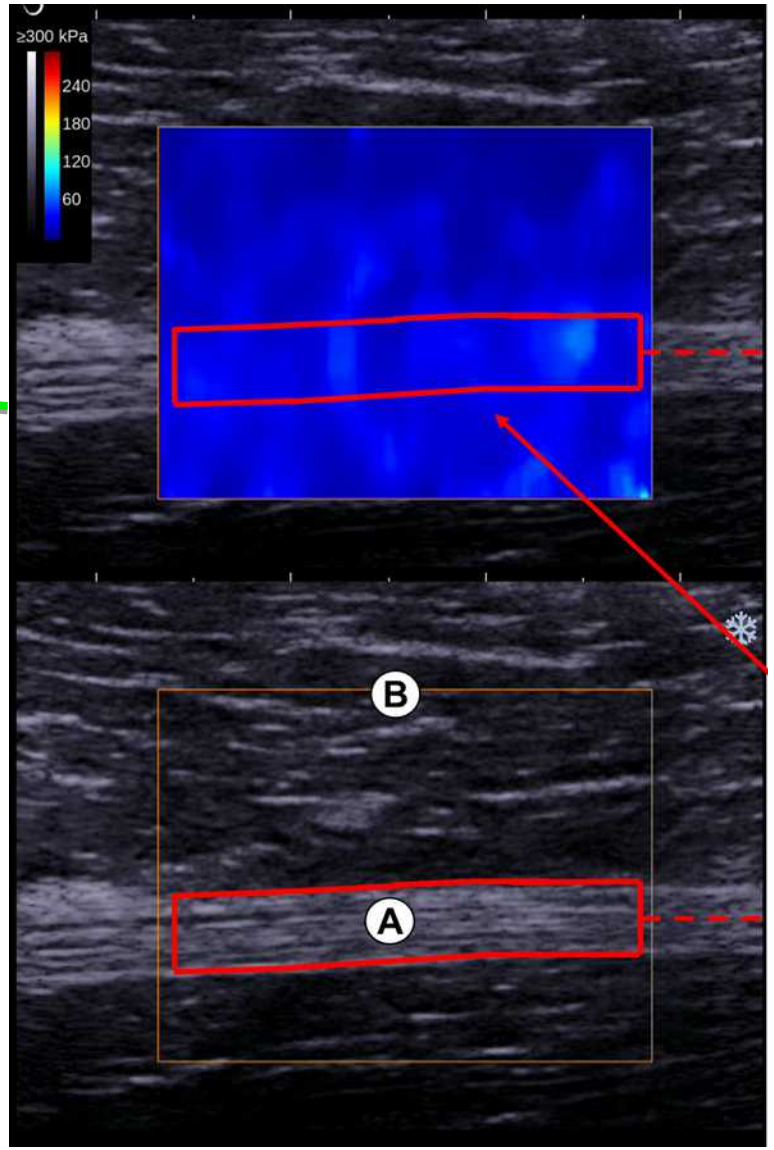


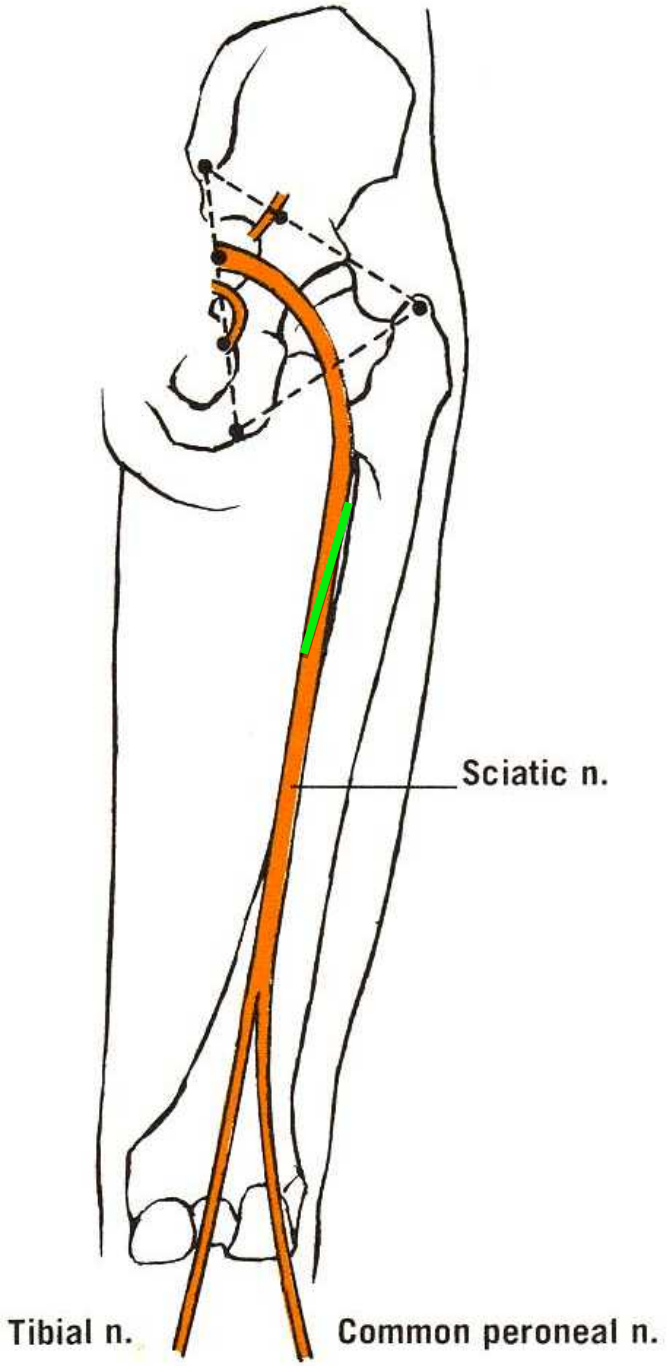


6/ Biomechanics of nerves

Andrade, Freitas, Hug, Ates, Coppieters & Nordez. To be submitted







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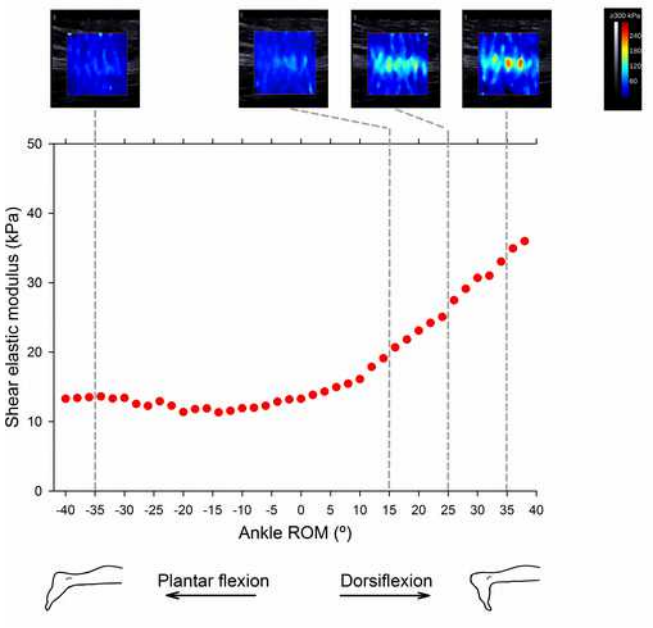


CV < 10.3 %

- **Reliable measurement of nerve stiffness**
- **Role in maximal ROM limitation?**
- **Biomechanics of nerves => fascias**

Conclusions

1/ Measurement of passive muscle shear elastic modulus DURING stretching

=> Estimation of the passive force-length relationship

2/ Measurements of hamstrings during stretching

3/ Measurement during static stretching

} **=> Non homogeneous**

4/ Effects of eccentric exercise

=> Homogeneous effect
=> Increase in shear elastic modulus indicator of the amount of damage ?

5/ Effect of hip angle on ankle ROM

=> Non muscular tissues could limit the maximal ROM

6/ Measurements on the nerve

=> Nerve biomechanics
=> role in the limitation of the maximal ROM ?

1- Elastography methods

Institut Langevin
ONDES ET IMAGES

Supersonic Shear Imaging

Aixplorer

SUPERSONIC imagine

Muscle-tendon biomechanics

“Dynamic” measurements

2- Passive muscle

Estimation of passive muscle tension

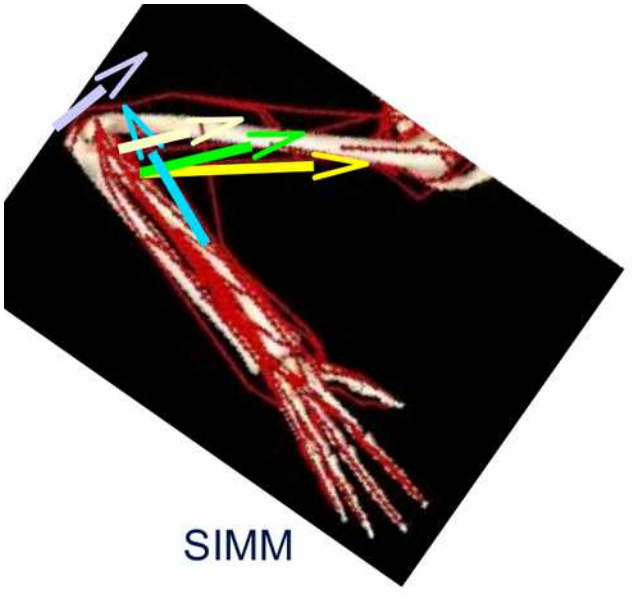
3- Muscle contraction

Estimation of individual muscle force

Estimation of muscle force

- **Muscle redundancy** Several muscles produce the net torque at joint *e.g., Zajac et al., 2003*

↳ No experimental method to measure muscle force in vivo



Estimation of muscle force

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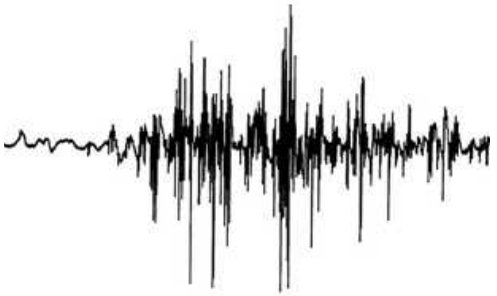
- **Electromyography (EMG)**

  "Electrical manifestation of the neuromuscular activation associated with a contracting muscle"

  Basmajan and De Luca, 1985



  ↳ Muscle activation levels, synergies ≠ muscle force

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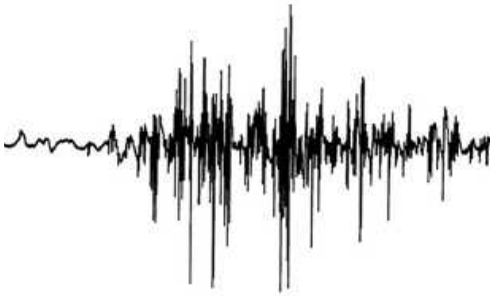

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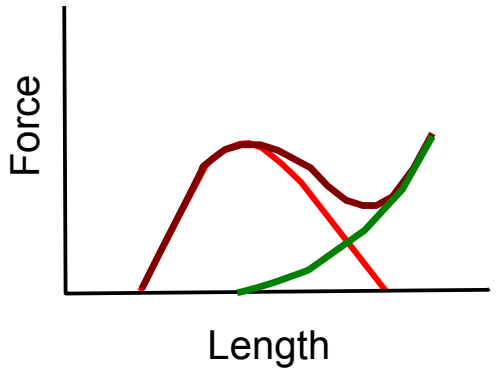

EMG-force relationship altered

- Muscle length
- Passive force
- Contraction velocity
- Fatigue

Estimation of muscle force

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  ↪ No experimental method to measure muscle force in vivo

- **Electromyography (EMG)**

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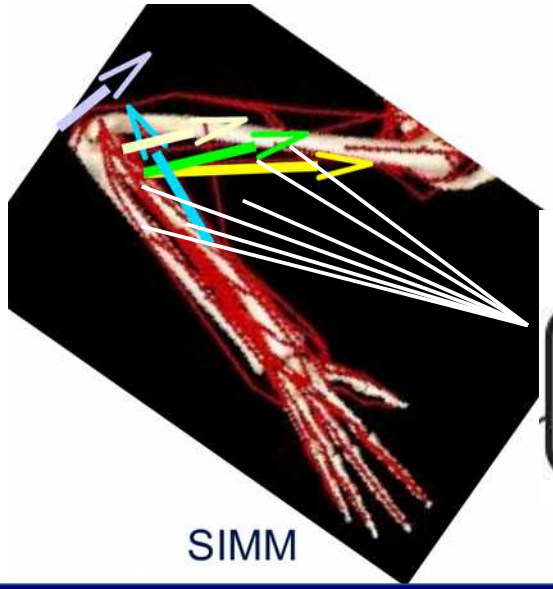
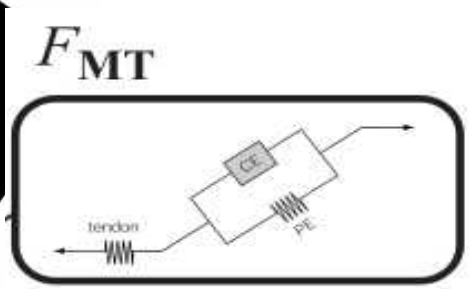
- **Neuromusculoskeletal models**

  e.g., Buchanan et al., 2004; Lloyd and Bezier, 2003; Erdemir et al., 2007





No validation

Erdemir et al., 2007

↪ Can SSI provide an estimation of individual muscle force ?

1/ Relationship between shear elastic modulus and force

Bouillard, Nordez, Hug. PloS One, 2011

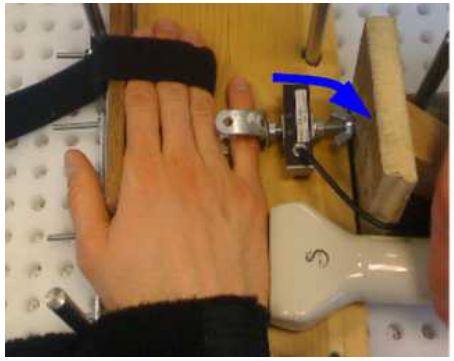
- *Abductor digiti minimi* (ADM) : little finger abduction (fusiform)

(e.g., Chao, 1989)

- *First digitorum interrosseous* (FDI) : index abduction (pennate)

(e.g., Infantolino and Challis, 2010)

10 subjects



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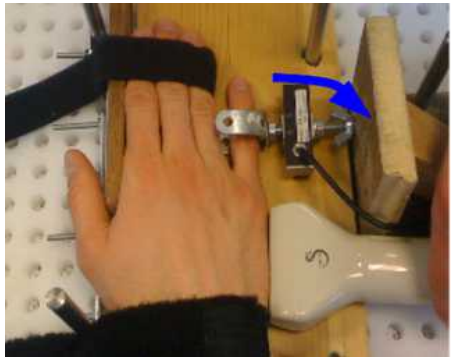
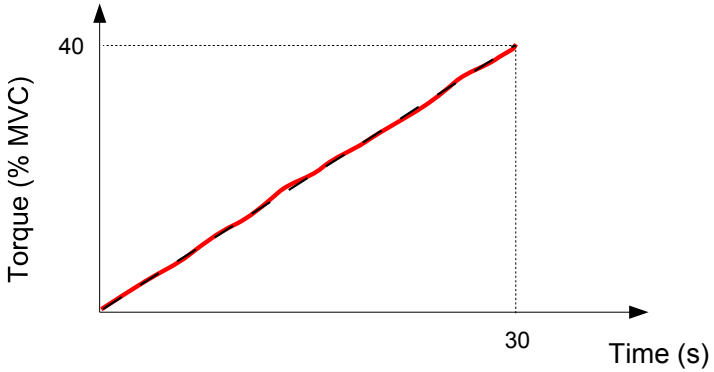
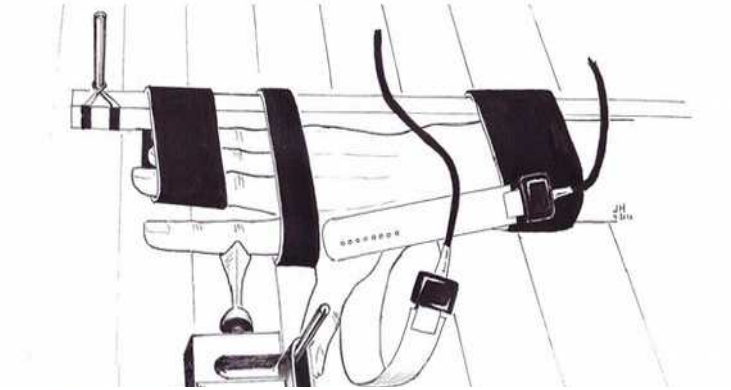
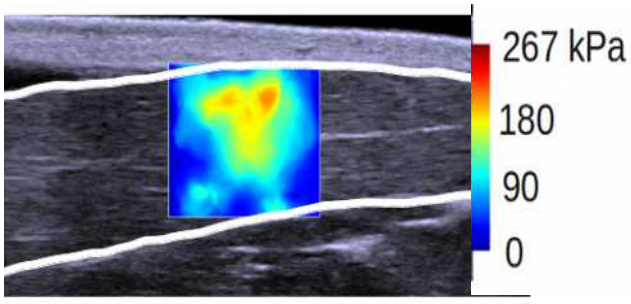




EMG session (vectors)



SSI session (1Hz)



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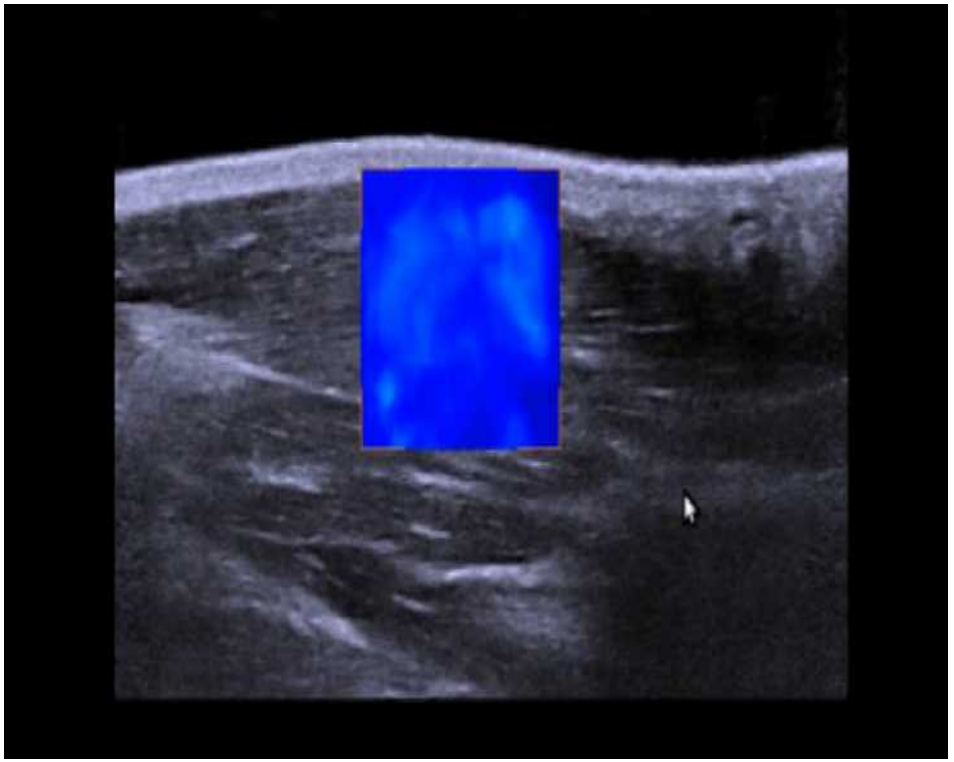
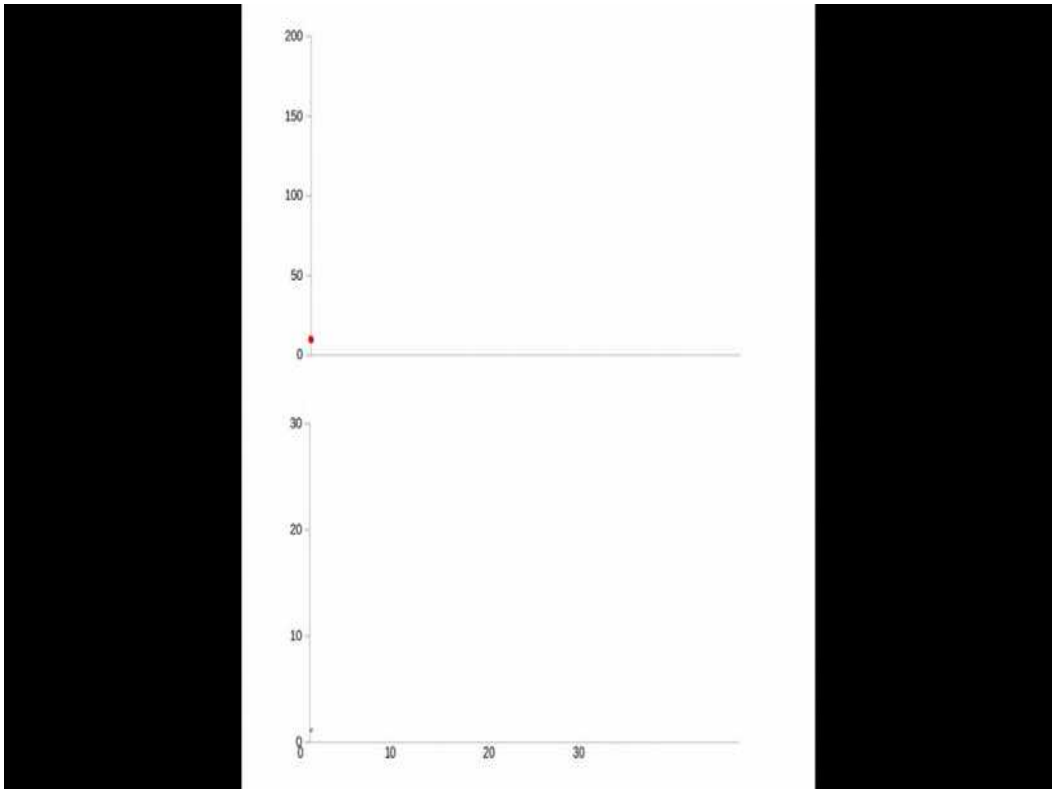


Velocity x 1.5

● **Shear elastic modulus**

— Torque



Time (s)

1/ Relationship between shear elastic modulus and force

Bouillard, Nordez, Hug. PloS One, 2011

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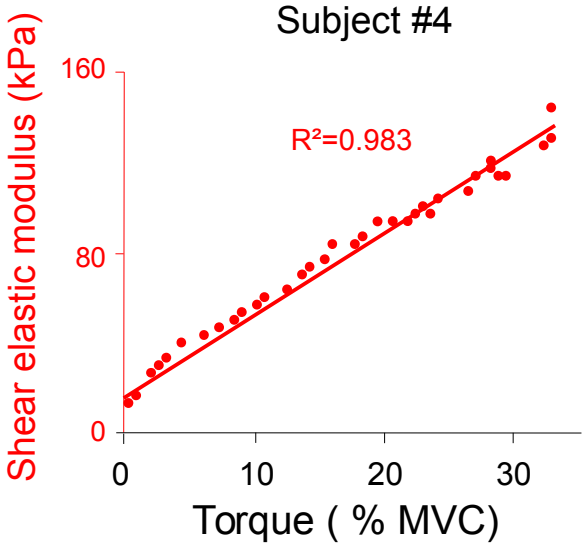
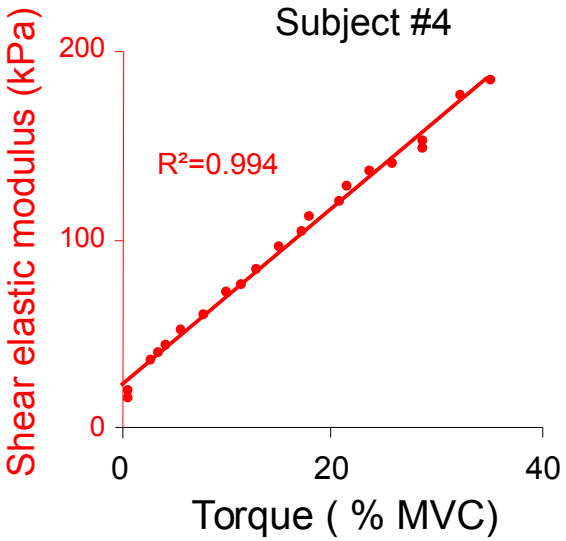


SSI: $R^2 = 0.981$ (0.951-0.997)

- *First digitorum interrosseous* (FDI)



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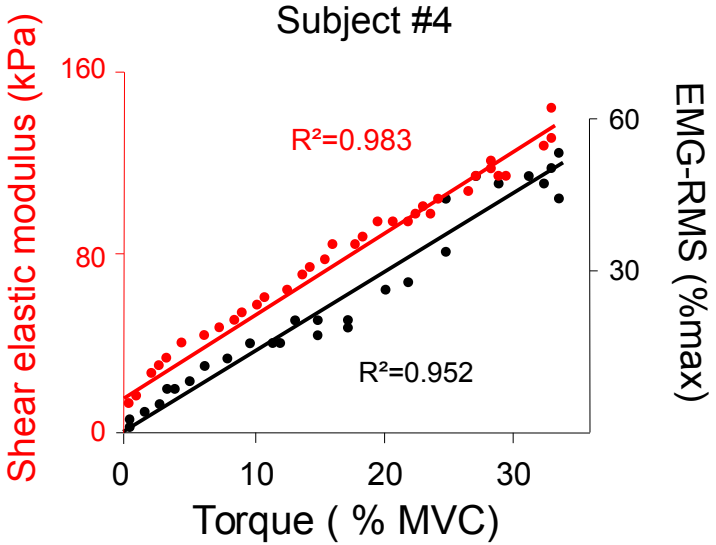

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EMG: R^2 = 0.948 (0.847-0.992)

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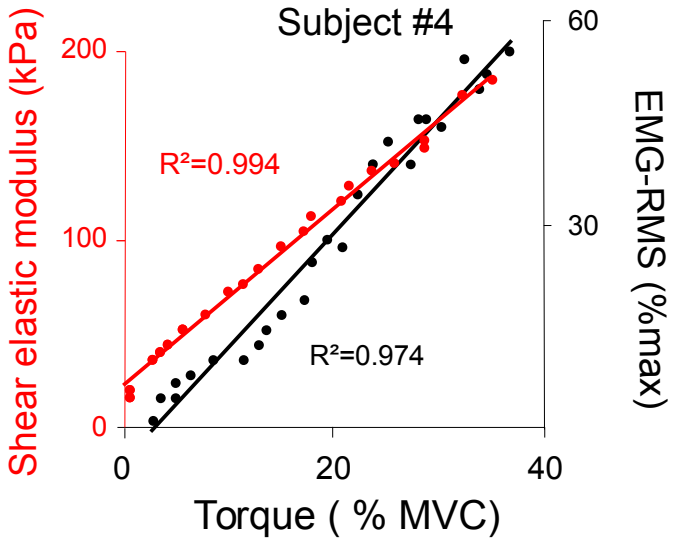

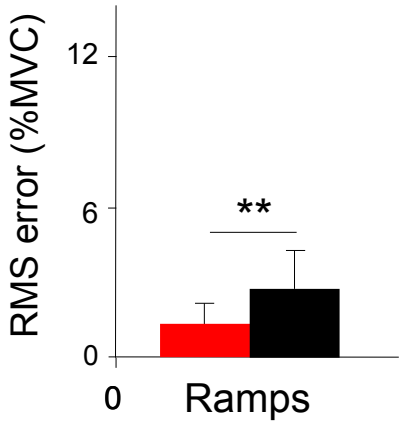

- **SSI significantly better than sEMG**

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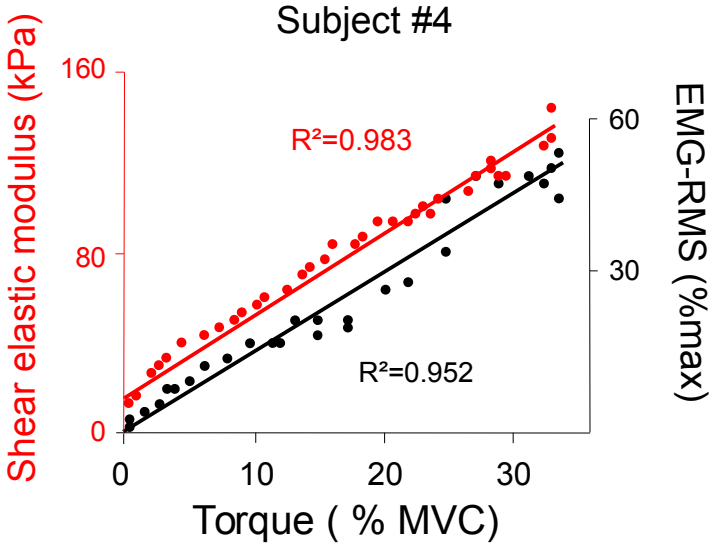

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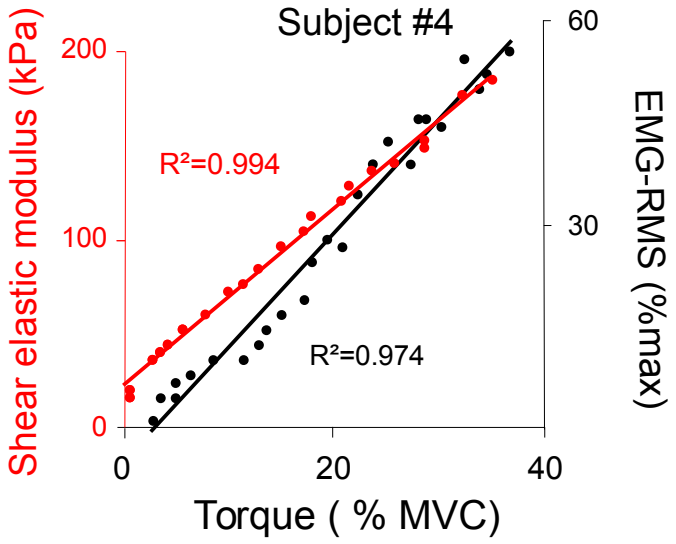
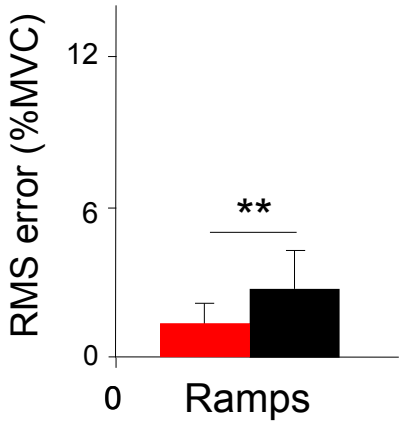
No differences between muscles

- *First digitorum interrosseous* (FDI)





- SSI significantly better than sEMG
- **No effect of pennation**

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Bouillard, Nordez, Hug. PloS One, 2011

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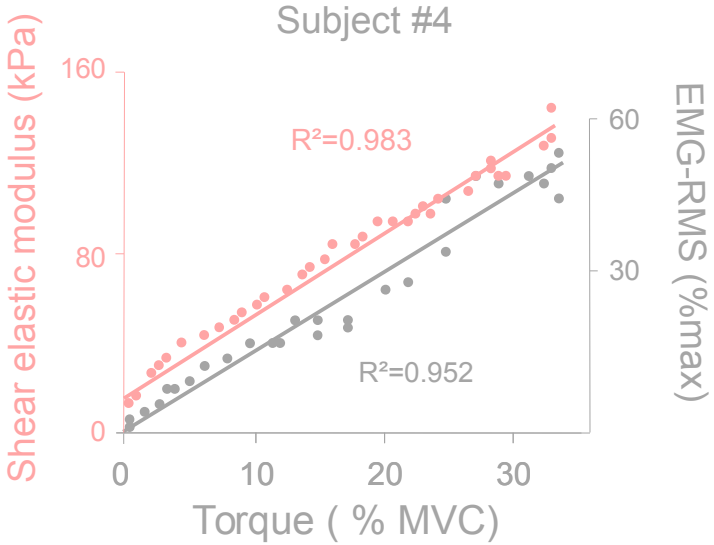

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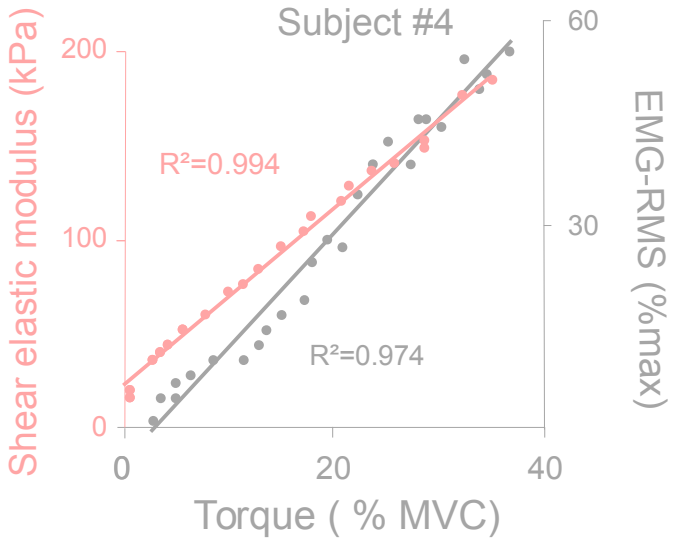

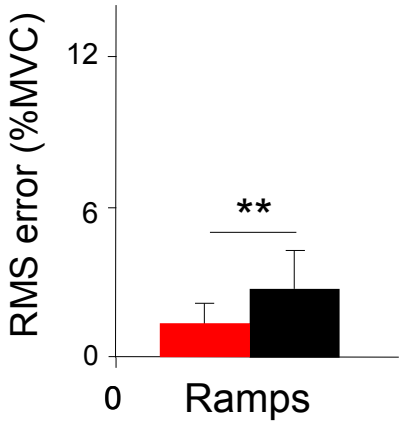

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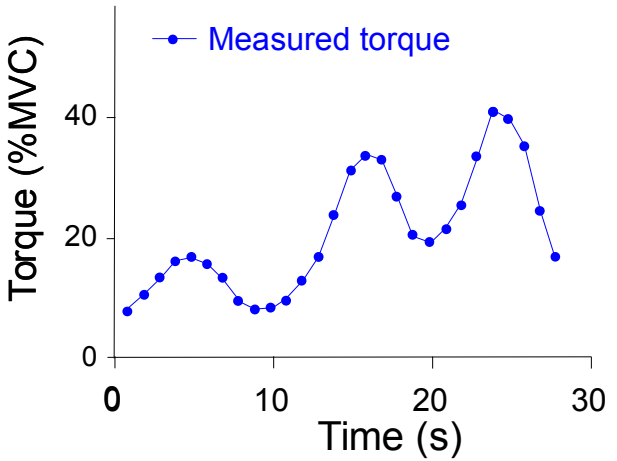

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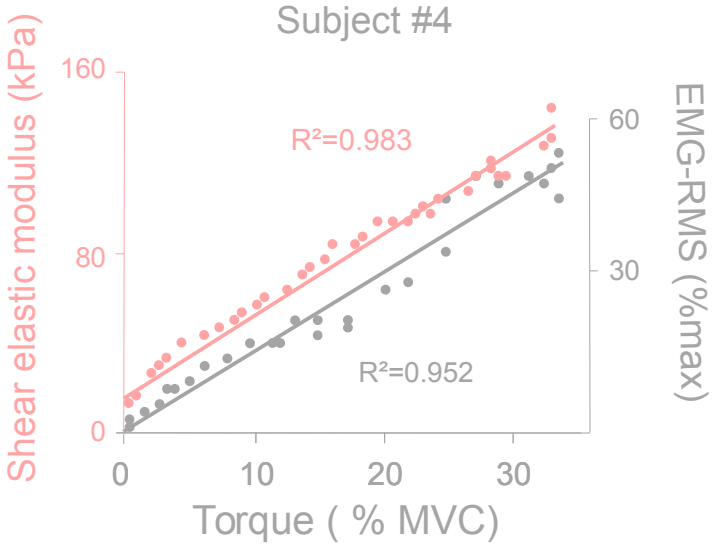

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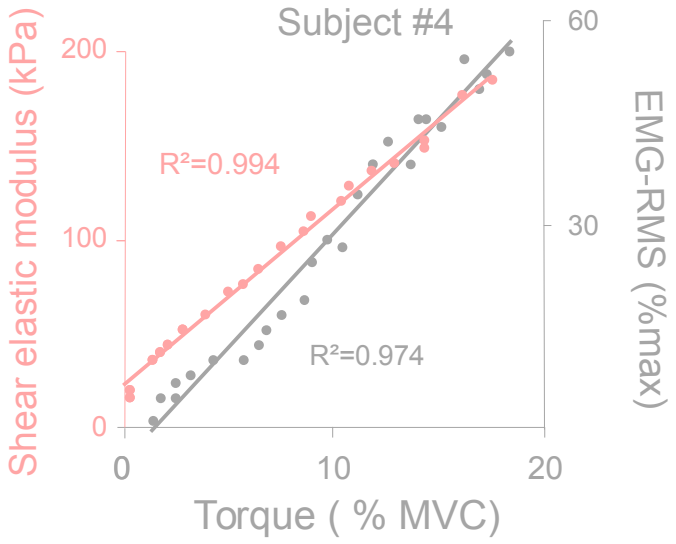
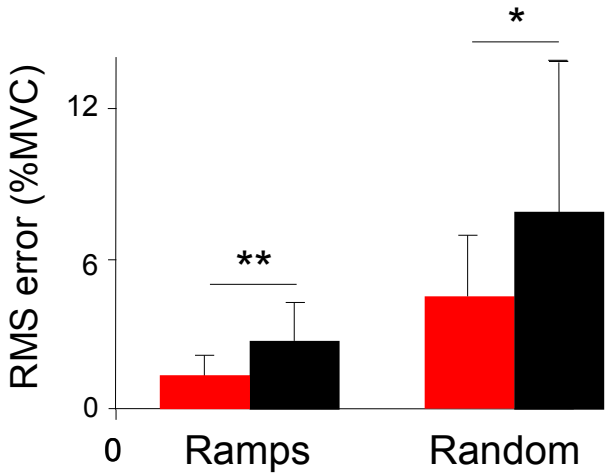
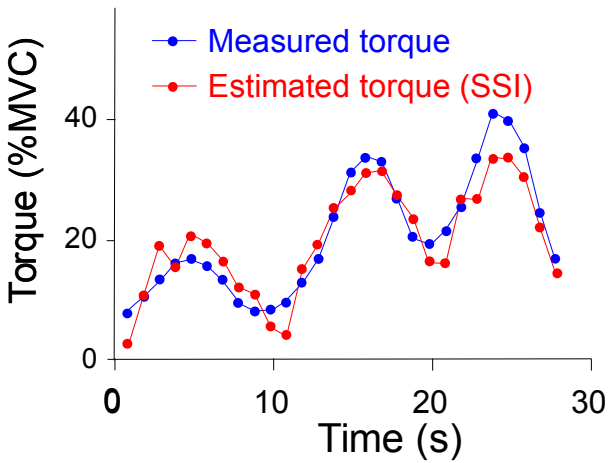




- SSI significantly better than sEMG
- No effect of pennation
- **Possible to estimate muscle force during random changes**



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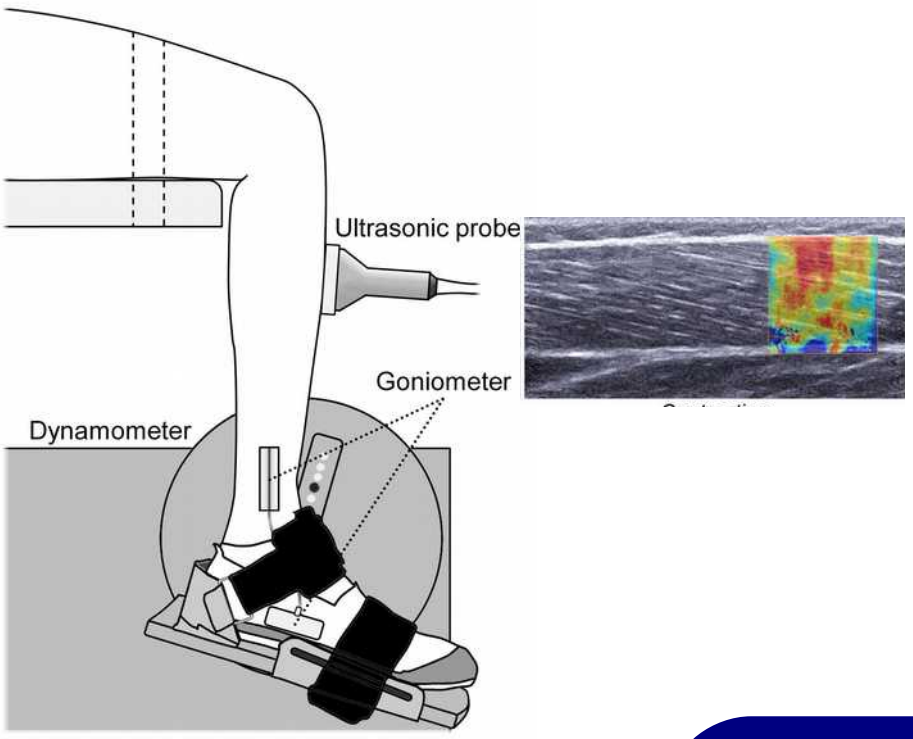


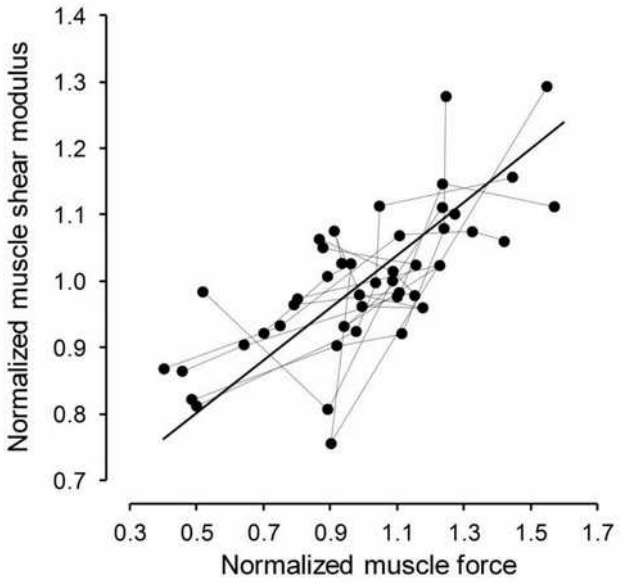
Articles in PresS. J Appl Physiol (May 29, 2014). doi:10.1152/japplphysiol.01058.2013

Length–force characteristics of in vivo human muscle reflected by supersonic shear imaging

Kazushige Sasaki[1,2], Sho Toyama[2], and Naokata Ishii[2]

[1]*Faculty of Human Sciences and Design, Japan Women's University*

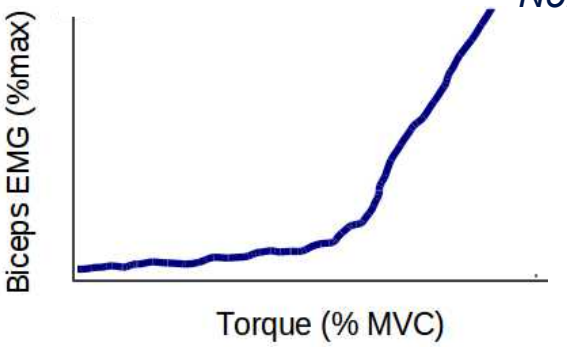
[2]*Department of Life Sciences, Graduate School of Arts and Sciences, University of Tokyo*



- SSI significantly better than sEMG
- No effect of pennation
- Possible to estimate muscle force during random changes
- **Force-length**

2/ Coordination between elbow flexors

Nordez & Hug. J Appl Physiol, 2010



In accordance with the literature concerning the *biceps brachii*

(e.g., Gennisson et al., 2005 ; Lawrence and De Luca, 1983)

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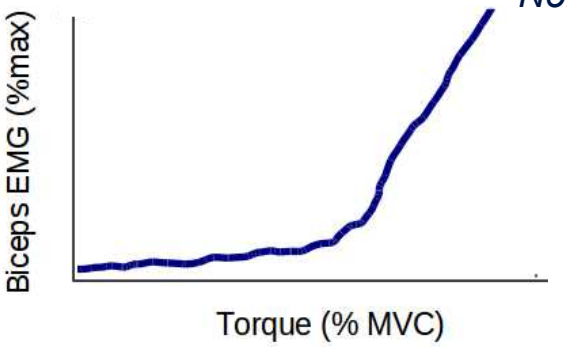
Nordez & Hug. J Appl Physiol, 2010



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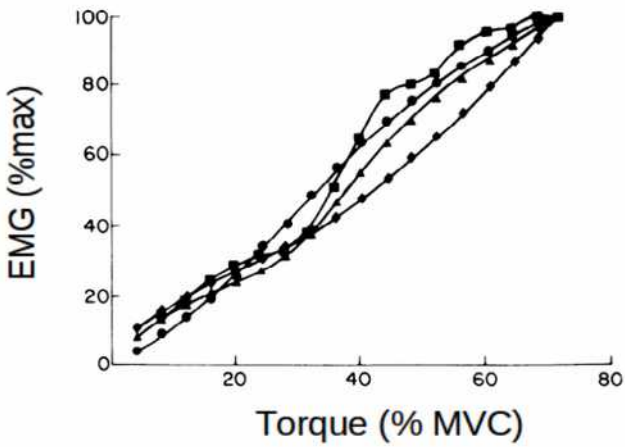

Different results for smaller muscles

(e.g., *first digitorum interrosseus*, *Lawrence and De Luca, 1983*)

Hypothesis: linked to the biceps recruitment strategy of motor units

(e.g., De Luca, 1997 ; Lawrence and De Luca, 1983)

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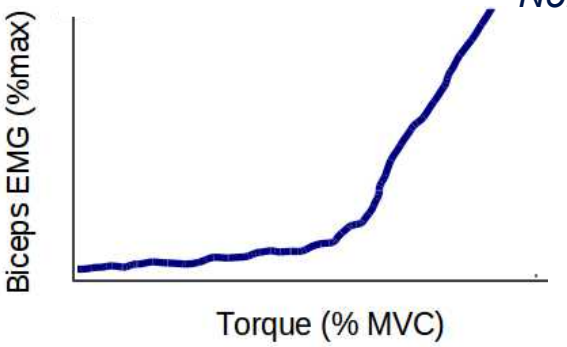
Nordez & Hug. J Appl Physiol, 2010



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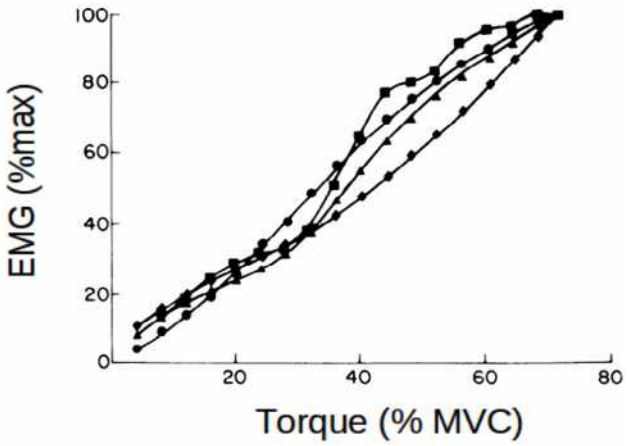

Different results for smaller muscles

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Hypothesis: linked to the biceps recruitment strategy of motor units

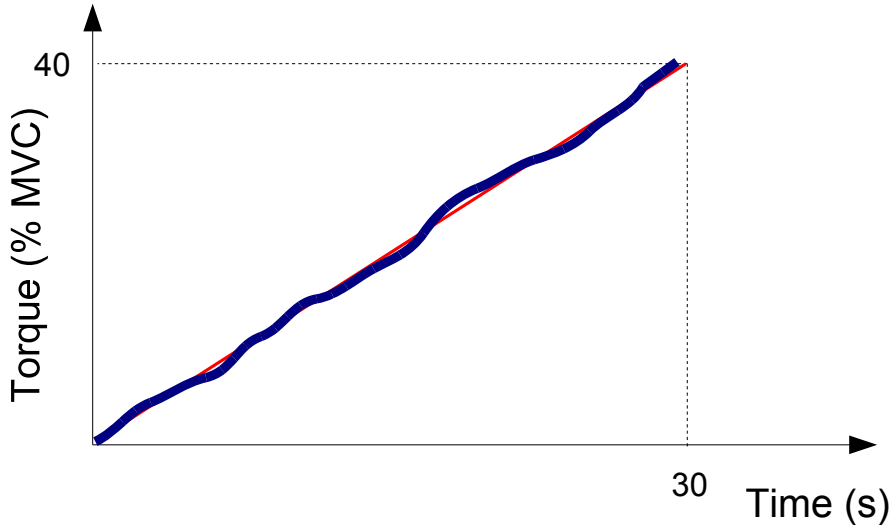
(e.g., De Luca, 1997 ; Lawrence and De Luca, 1983)

Alternative hypothesis: explained by the muscle redundancy (contributions of *brachioradialis* and *brachialis*)

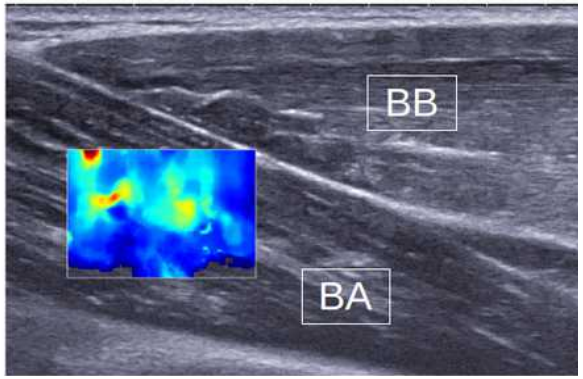
2/ Coordination between elbow flexors

10 healthy subjects

Bouillard, Nordez, Hodges, Cornu & Hug. J Biomech, 2012



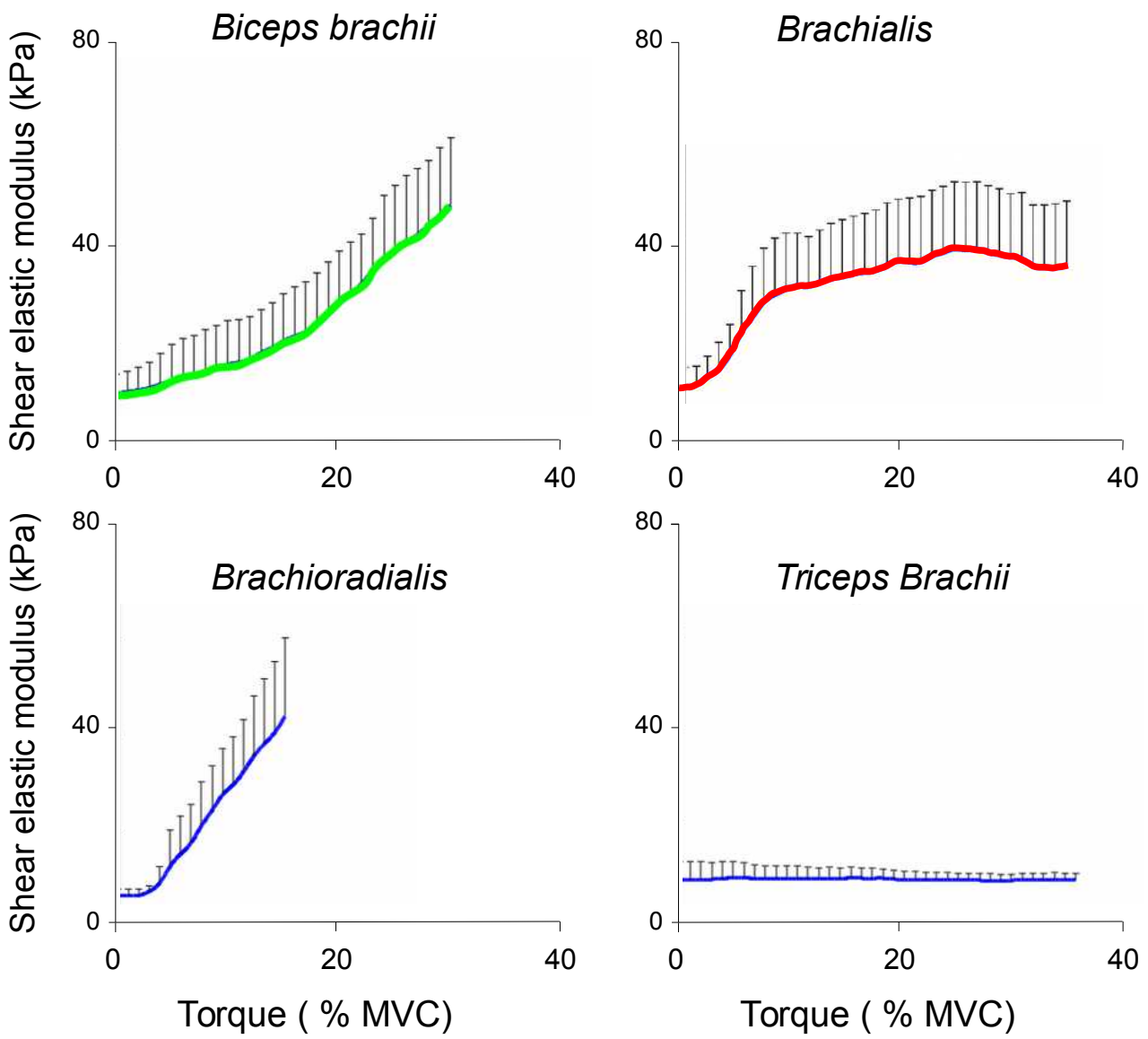
Measurements performed successively (1 Hz)



- *Biceps brachii* (BB)
- *Brachioradialis* (BR)
- *Triceps brachii (TB)*
- *Brachialis (BA)*

2/ Coordination between elbow flexors

Bouillard, Nordez, Hodges, Cornu & Hug. J Biomech, 2012



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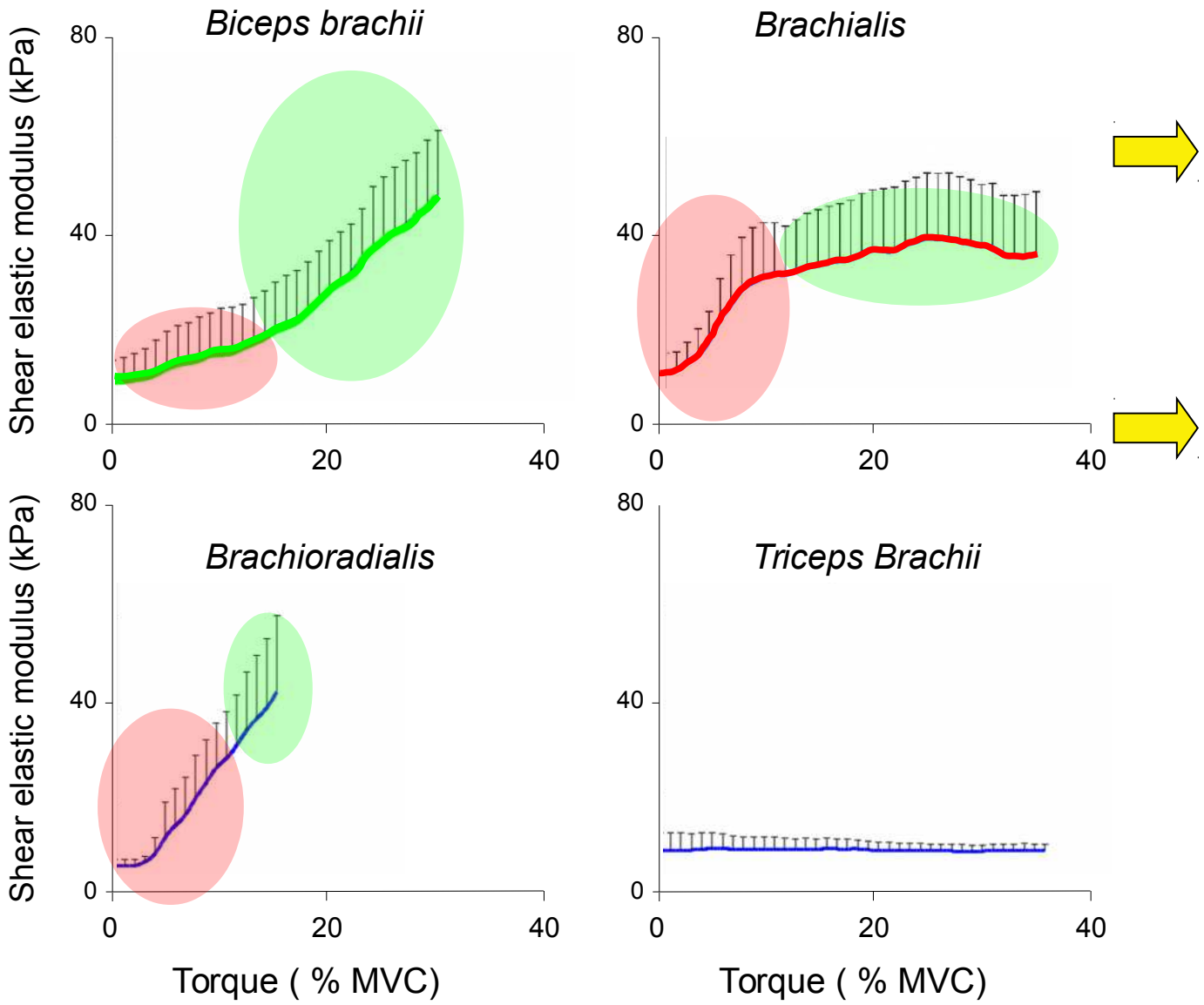


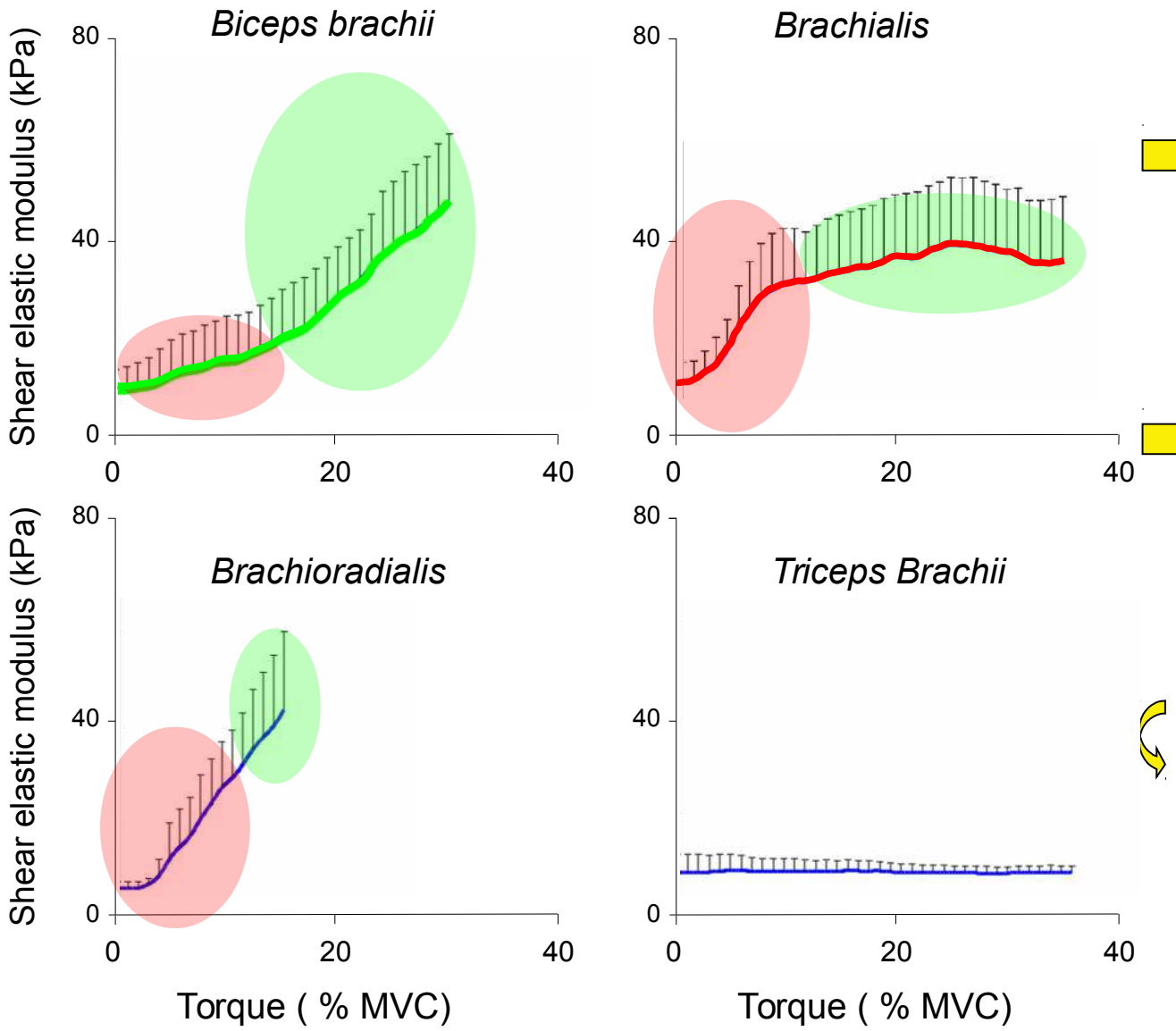
1st phase: torque mainly produced by *brachialis* and *brachioradialis*

2nd phase: *Biceps brachii* "replace" the *brachialis*

10 healthy subjects

2/ Coordination between elbow flexors

Bouillard, Nordez, Hodges, Cornu & Hug. J Biomech, 2012



1st phase: torque mainly produced by *brachialis* and *brachioradialis*

2nd phase: *Biceps brachii* "replace" the *brachialis*

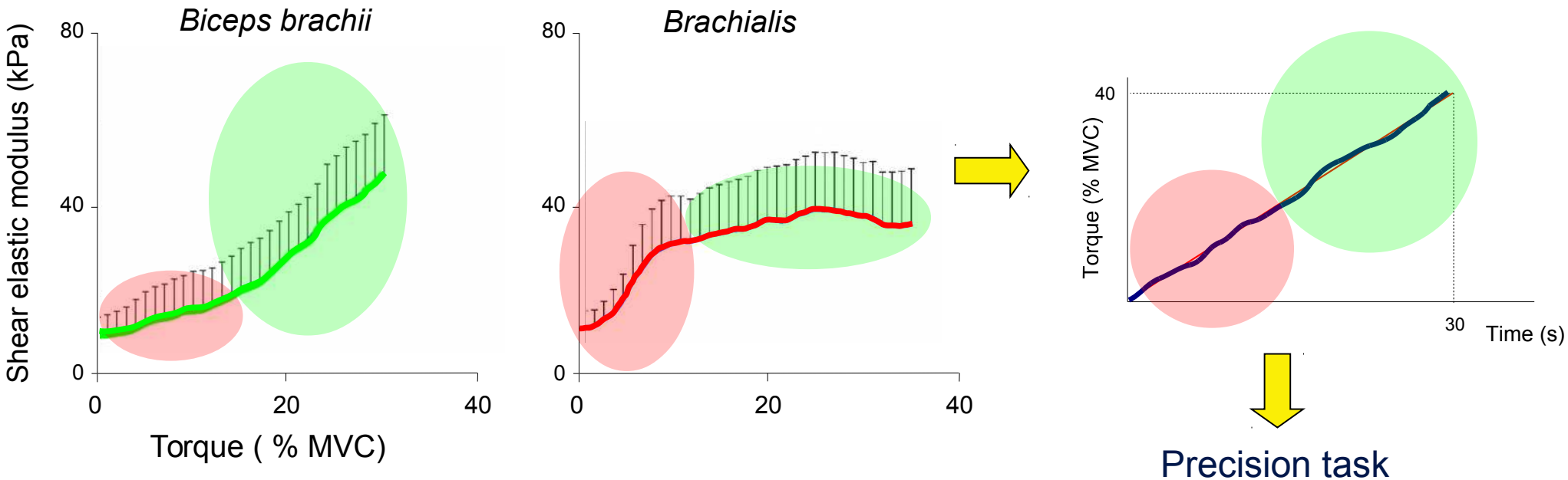
Changes in the load sharing between muscles

Alternative hypothesis to the muscle recruitment strategy

10 healthy subjects

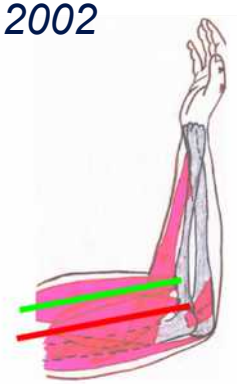
2/ Coordination between elbow flexors

Bouillard, Nordez, Hodges, Cornu & Hug. J Biomech, 2012



Moment arm about 2 times longer for the *Biceps* vs. *Brachialis*

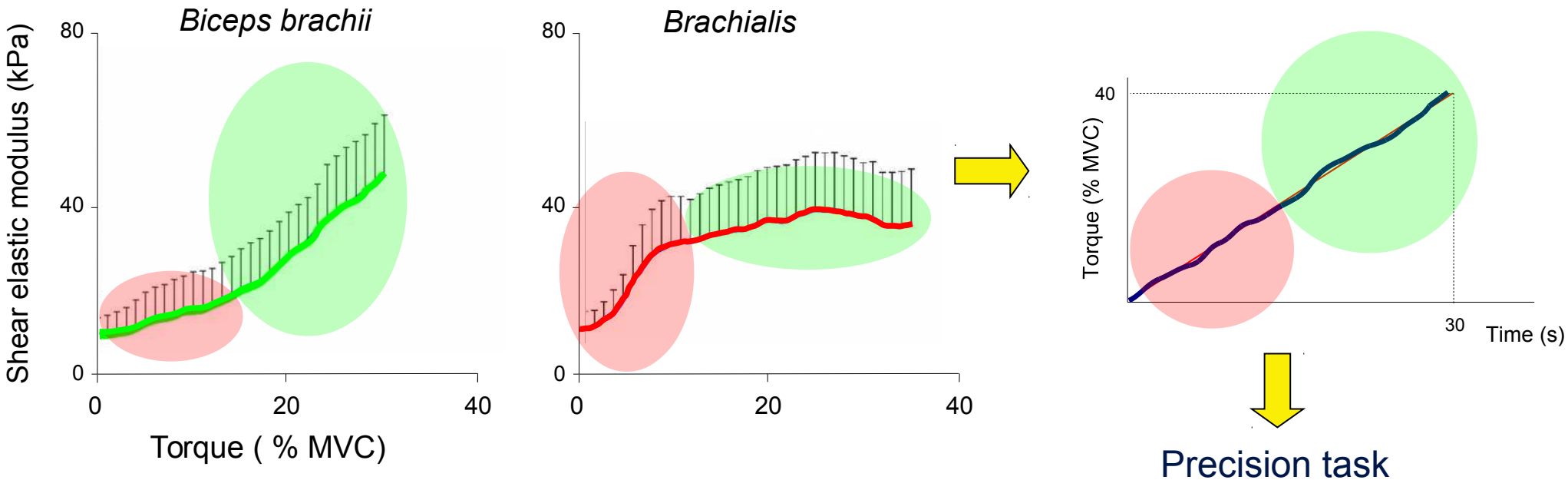
Murray et al., 2002



- *Brachialis* at the beginning of the ramp (low torque – precision)
- *Biceps Brachii* at the end of the ramp (high torque)

2/ Coordination between elbow flexors

Bouillard, Nordez, Hodges, Cornu & Hug. J Biomech, 2012

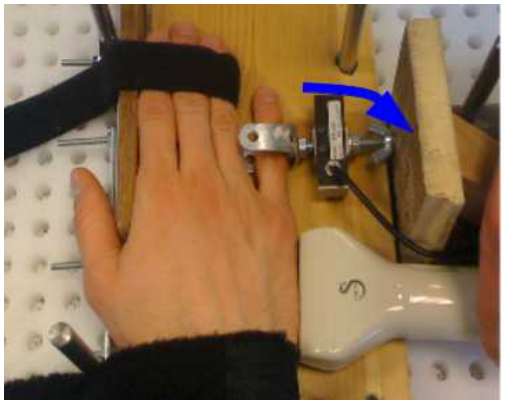


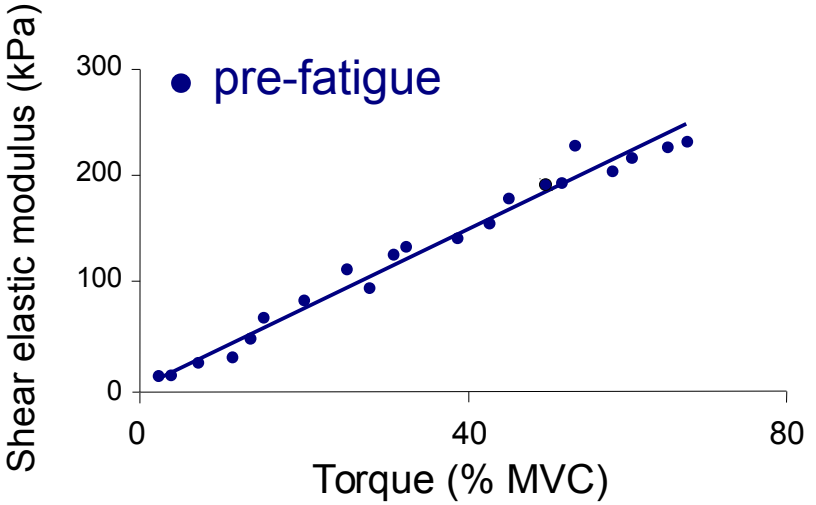
When submaximal contractions are performed with several synergistic muscles

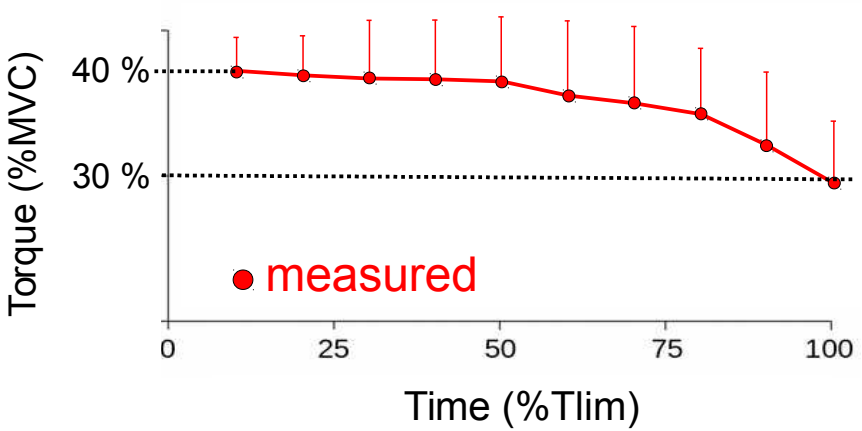
Do they have the same activation level ?

3/ Feasibility of the estimation during fatiguing contractions

Bouillard, Hug, Guével & Nordez. J Appl Physiol, 2013



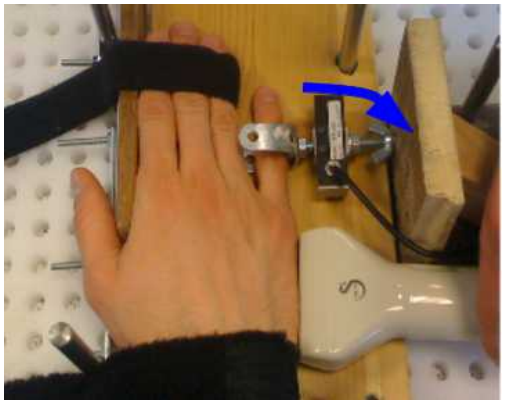


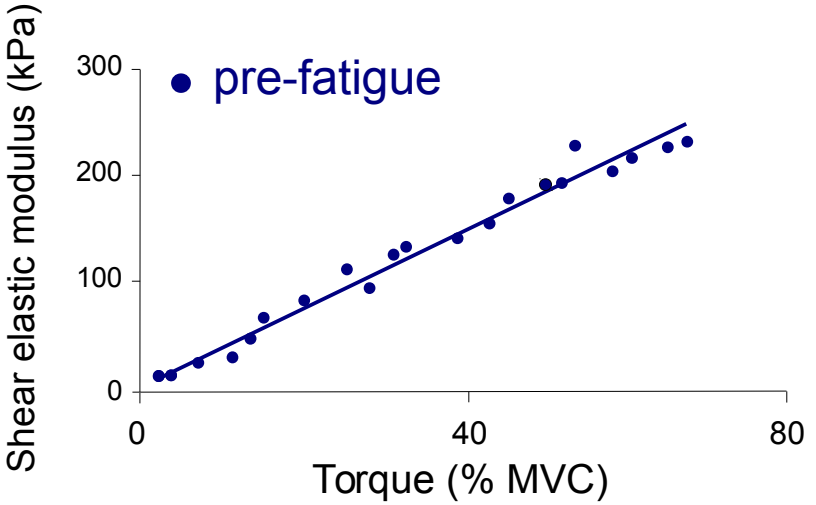


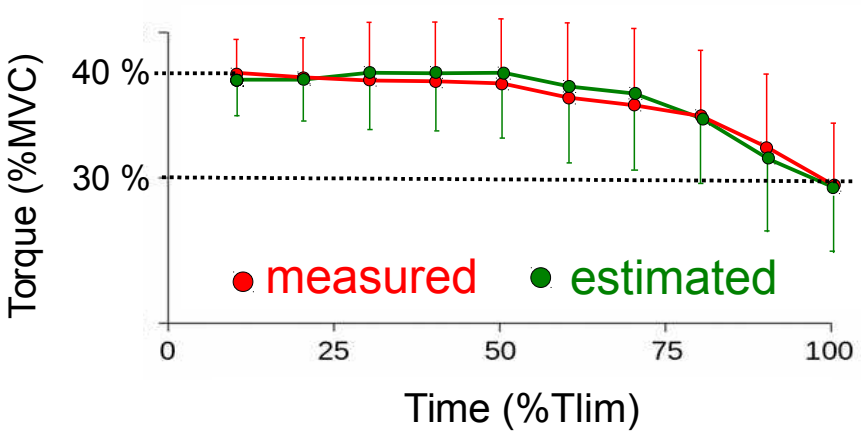
12 healthy subjects

3/ Feasibility of the estimation during fatiguing contractions

Bouillard, Hug, Guével & Nordez. J Appl Physiol, 2013







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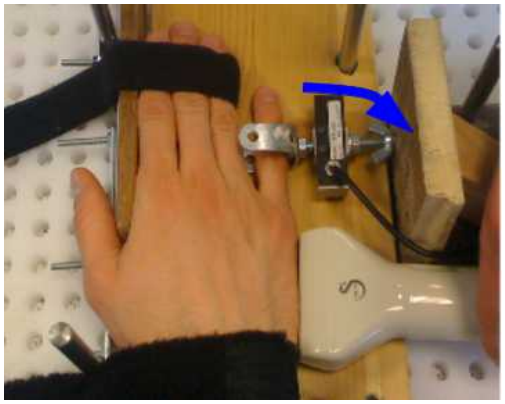
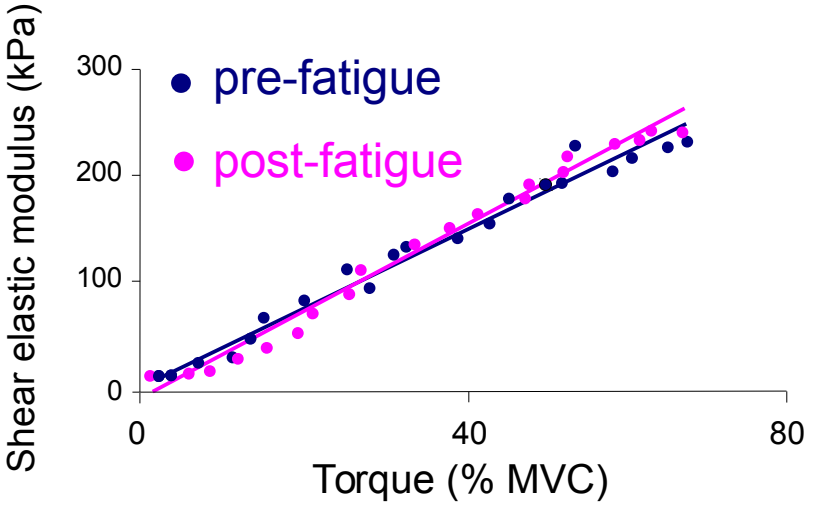
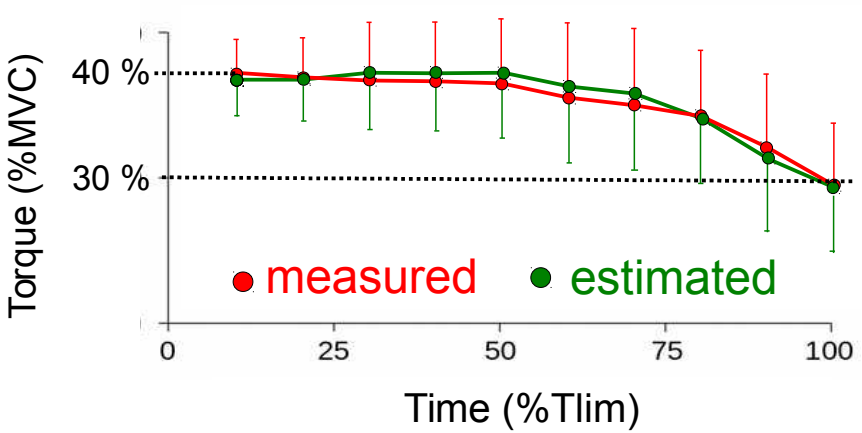






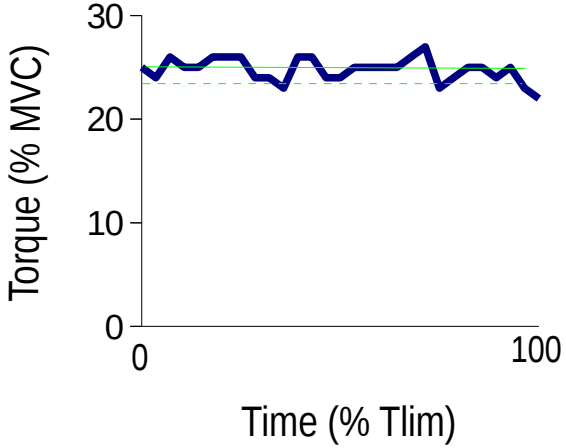
12 healthy subjects

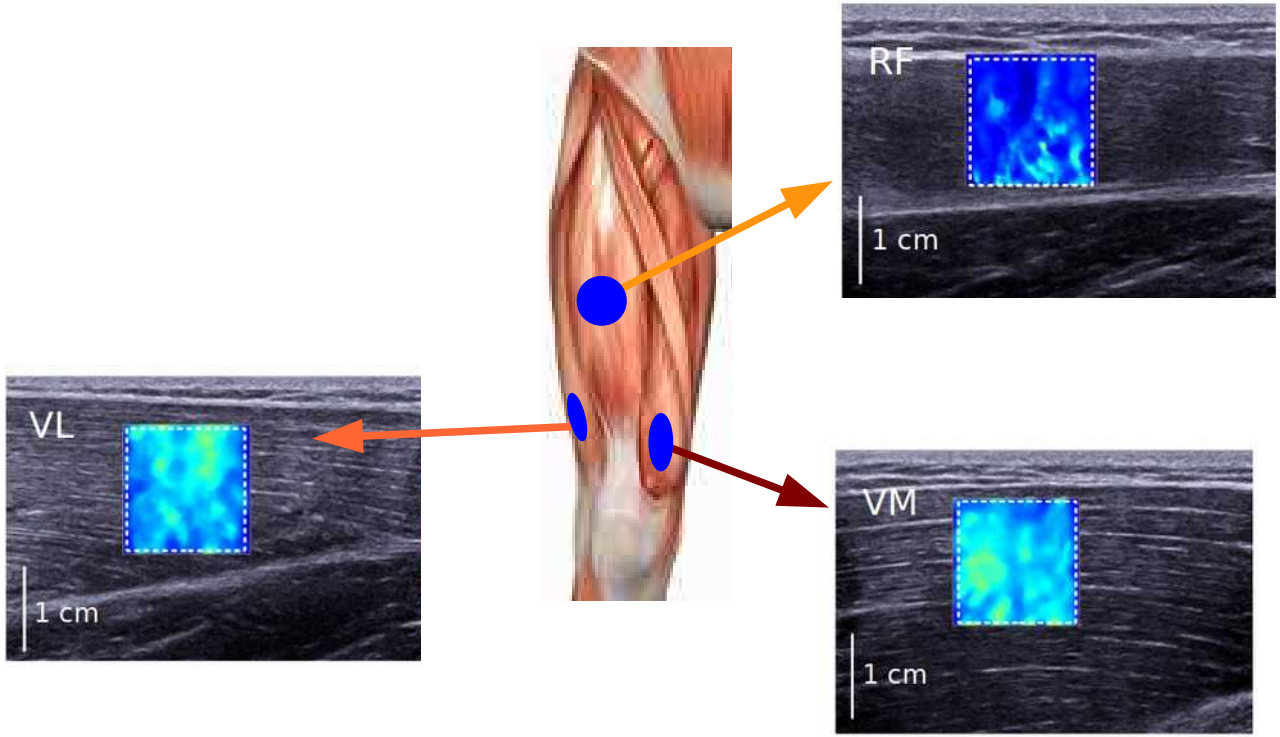
Fatigue does not influence the ability to estimate muscle force

4/ Changes in the load sharing during a fatiguing contraction

Bouillard, Hug, Guével & Nordez. J Appl Physiol, 2013

8 healthy subjects



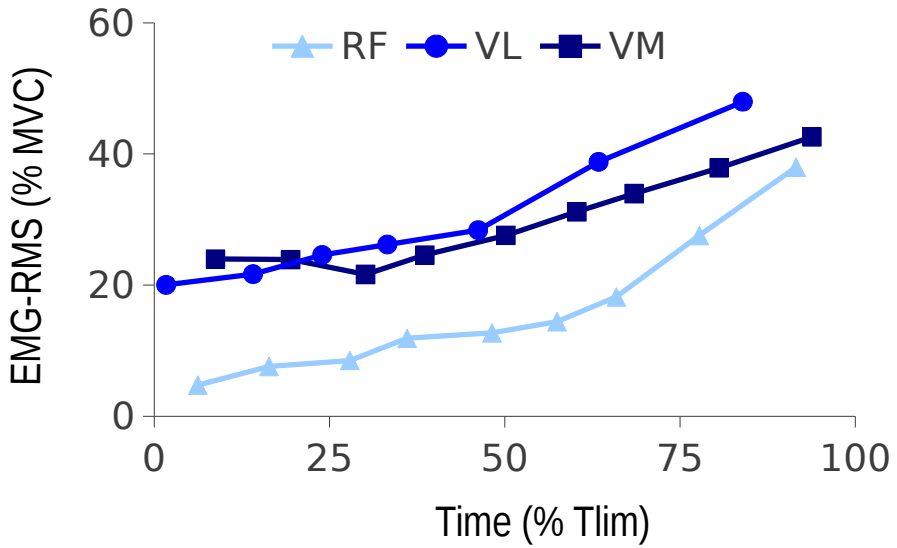


Alternative measurements on each muscle

4/ Changes in the load sharing during a fatiguing contraction

Bouillard, Hug, Guével & Nordez. J Appl Physiol, 2013

Typical example

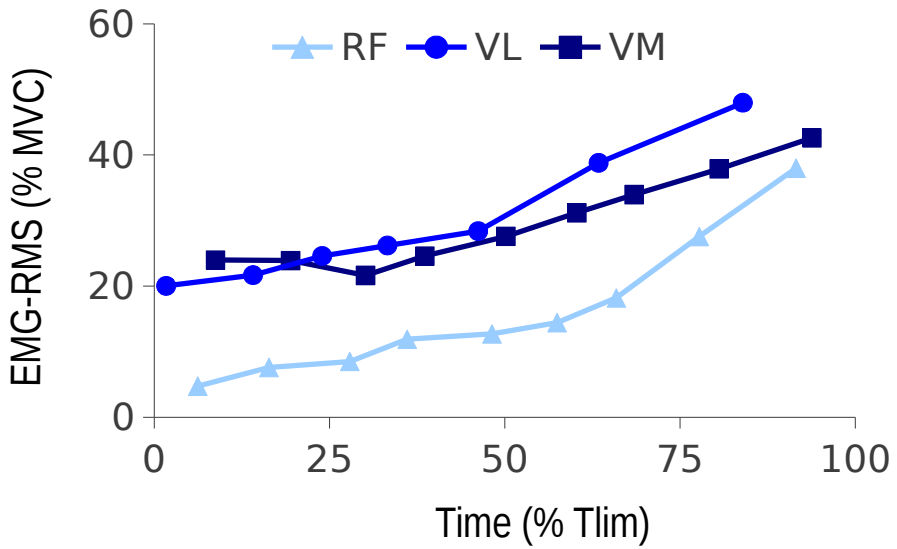


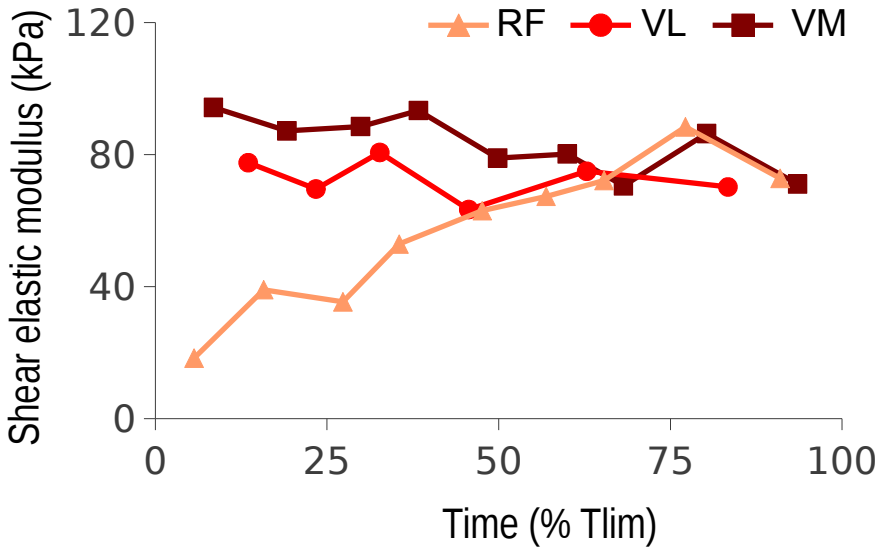
↑ EMG activity level

4/ Changes in the load sharing during a fatiguing contraction

Bouillard, Hug, Guével & Nordez. J Appl Physiol, 2013

Typical example





↑ EMG activity level

Opposite changes (4/8 subjects)

Change in the load sharing

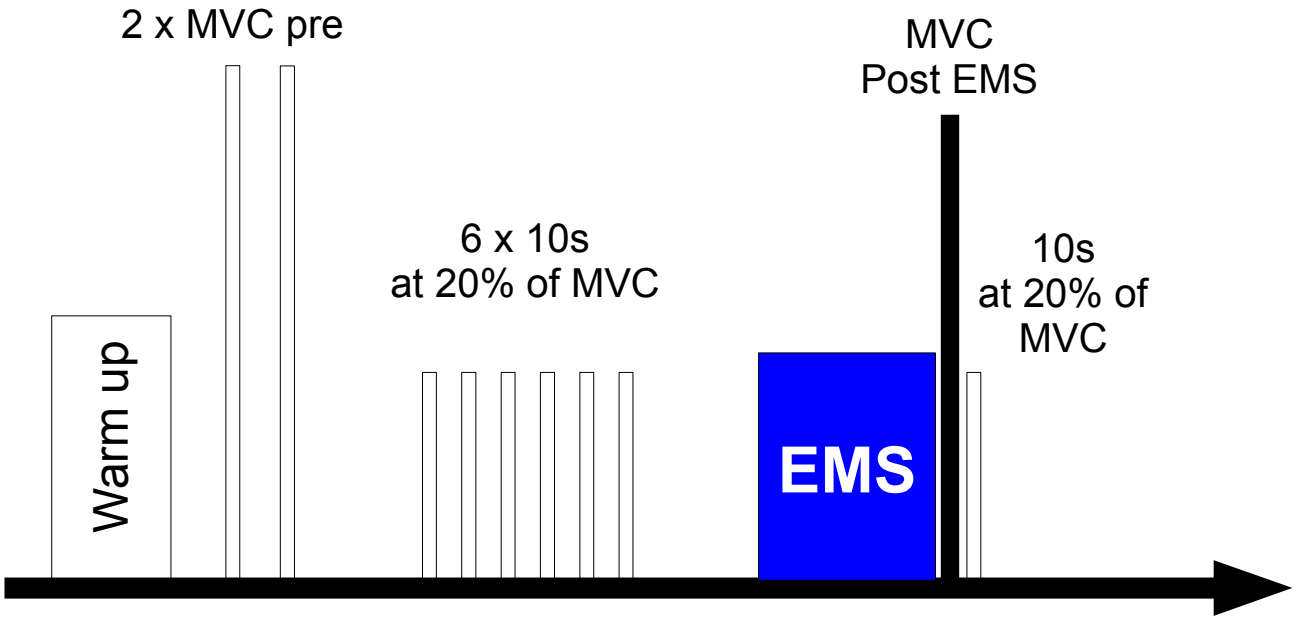
High inter-individual variability

5/ Effects of VL pre-fatigue (EMS)

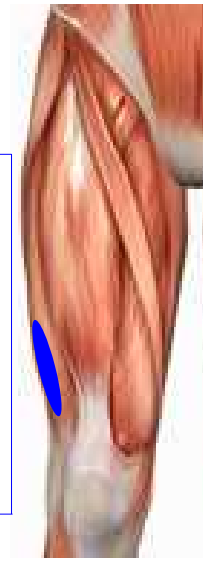
Bouillard, Jubeau, Nordez & Hug. J Neurophysiol, 2014

Does the load sharing depend on localized muscle fatigue ?

16 healthy subjects



EMS :
Vastus Lateralis
5 min
3 sec / 2sec
50 Hz / 500 µs
20 % de MVC



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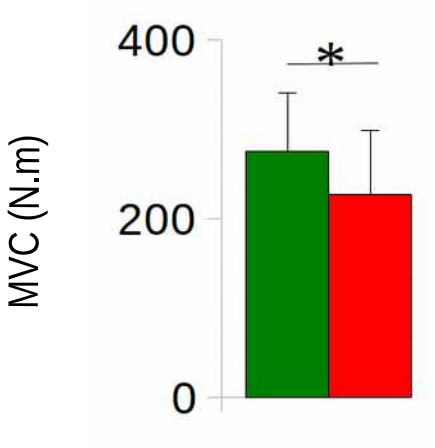
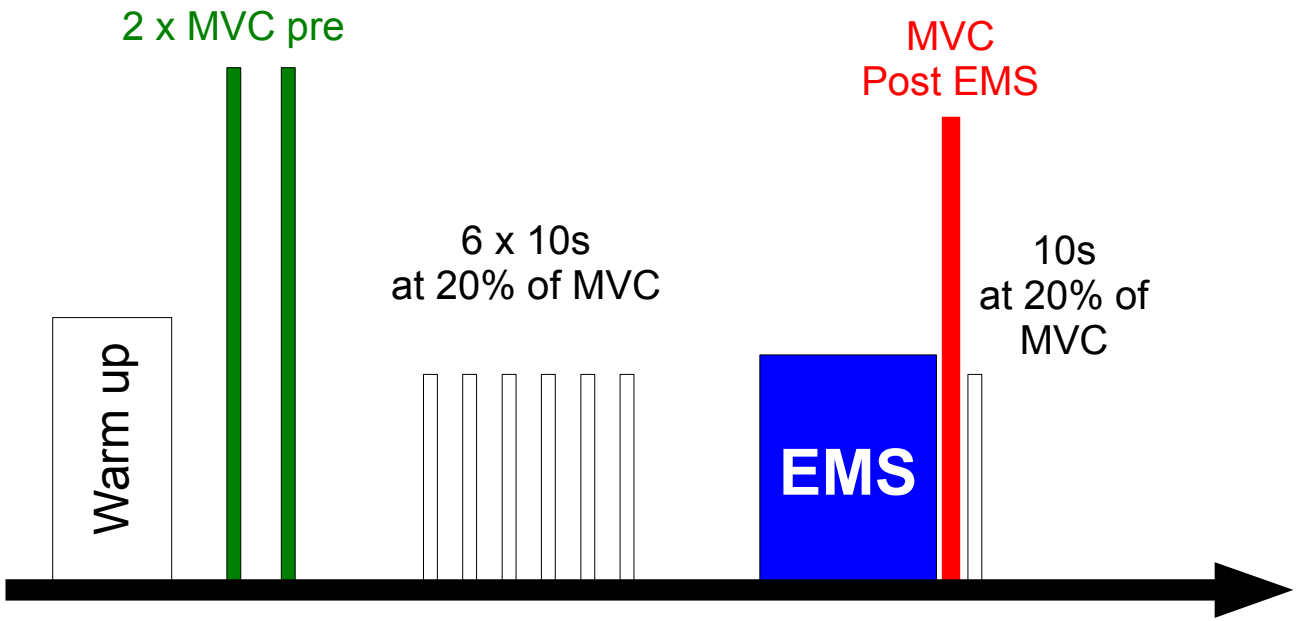


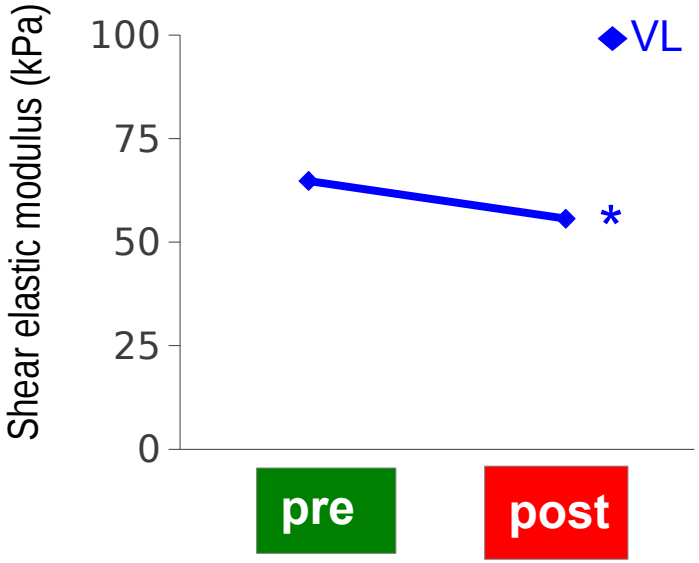
MVC pre
MVC post EMS

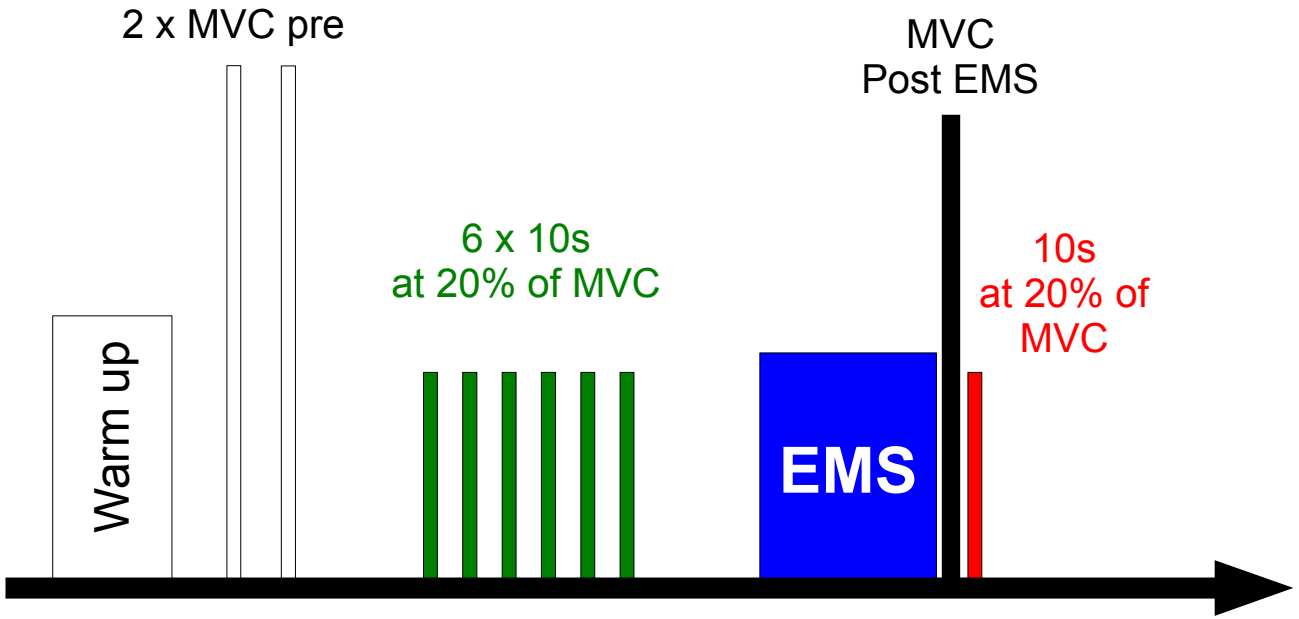


- **EMS induced fatigue**

5/ Effects of VL pre-fatigue (EMS)

Bouillard, Jubeau, Nordez & Hug. J Neurophysiol, 2014

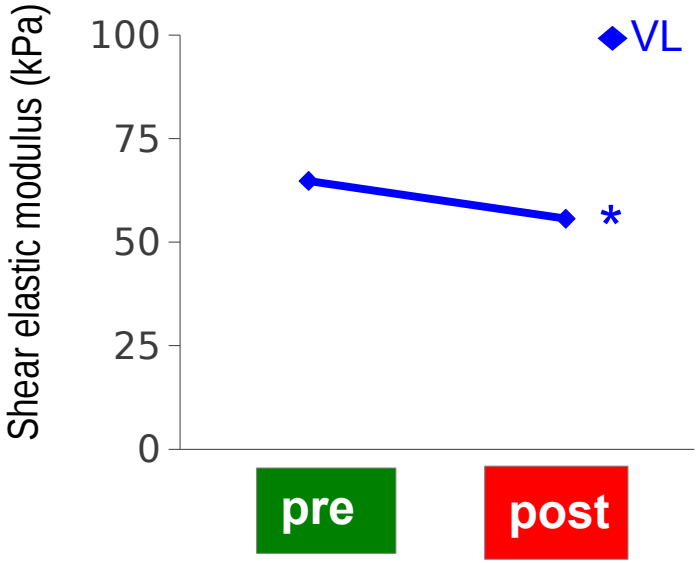




- EMS induced fatigue
- **Decrease VL force after EMS**

5/ Effects of VL pre-fatigue (EMS)

Bouillard, Jubeau, Nordez & Hug. J Neurophysiol, 2014



- **Decrease in muscle force of VL after EMS**

↳ Optimal motor control

(Prilutski and Zatsiorski, 2002)

Is it possible to control one muscle independently?

- EMS induced fatigue
- **Decrease VL force after EMS**

5/ Effects of VL pre-fatigue (EMS)

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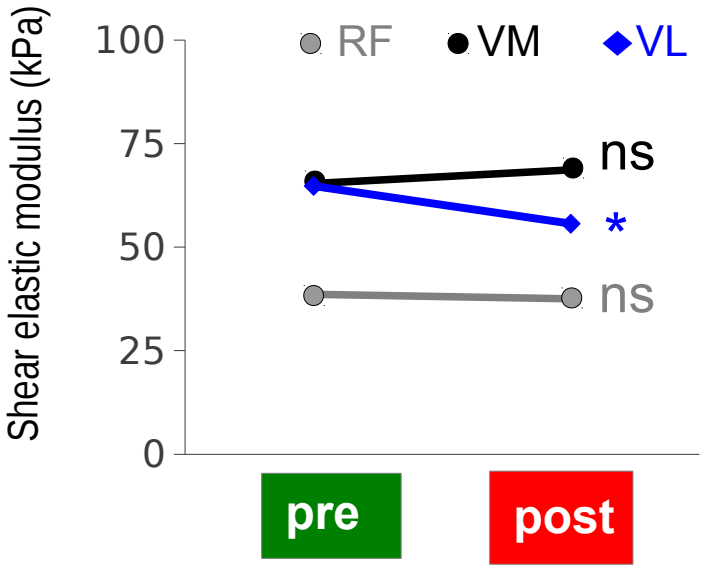

- **Decrease in muscle force of VL after EMS**

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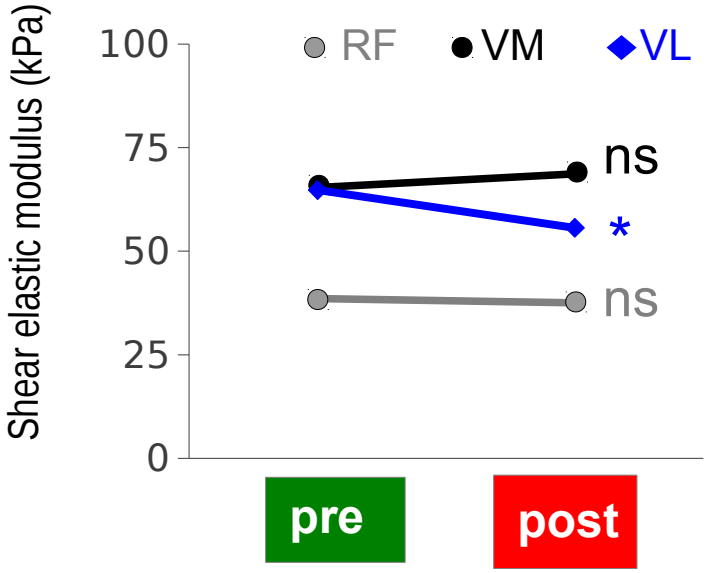
Is it possible to control one muscle independently?

- EMS induced fatigue
- **Decrease VL force after EMS**
- **No systematic compensations**

5/ Effects of VL pre-fatigue (EMS)

Bouillard, Jubeau, Nordez & Hug. J Neurophysiol, 2014



VI?

	RF	VM
#1	11.9	12.4
#2	14.0	-19.8
#3	5.7	5.8
#4	6.9	16.8
#5	-8.2	-5.6
#6	6.9	8.3
#7	-5.4	16.7
#8	-5.3	
#9	-13.4	6.8
#10	-7.8	-14.7
#11	12.0	-6.8
#12	4.2	
#13	-42.9	
#14	6.9	7.4
#15		9.4

VI?

Increase Decrease

No change (in kPa)

- **Decrease in muscle force of VL after EMS**

Optimal motor control

(Prilutski and Zatsiorski, 2002)

Is it possible to control one muscle independently?

- EMS induced fatigue
- **Decrease VL force after EMS**
- **No systematic compensations**

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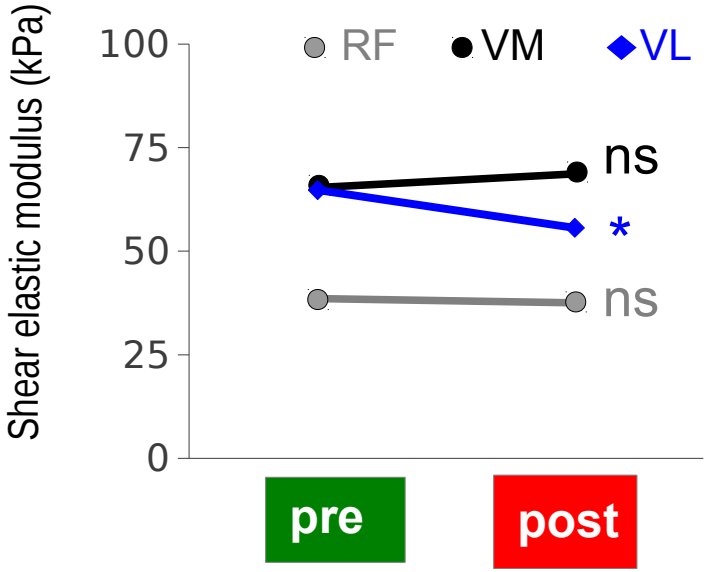

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Increase Decrease

No change (in kPa)

- **Decrease in muscle force of VL after EMS**

  Optimal motor control

  (Prilutski and Zatsiorski, 2002)

  Is it possible to control one muscle independently?

- **High inter individual variability**

  Same cost function for each subject ?

  (Loeb, 2012)

- EMS induced fatigue
- **Decrease VL force after EMS**
- **No systematic compensations**

Conclusions

1/ Measurement of muscle shear elastic modulus during isometric contraction

=> Estimation of the active force-length relationship

2/ Analysis of the load sharing during elbow flexion

=> Change in the load sharing during incremental elbow flexion

3/ Estimation of muscle force during fatiguing isometric contraction

=> Accurate estimation of the change in muscle force

4/ Analysis of the load sharing during fatiguing knee extension

=> High inter individual variability
=> Decrease in muscle force in the pre-fatigated muscle

Conclusions

Limitations

- **Not an actual force estimation (in N) => change in muscle force**

Conclusions

Limitations

- Not an actual force estimation (in N)
- **Sampling frequency** 1 Hz => isometric contractions

Collaborations:

J Bercoff *(Supersonic Imagine)*

M Tanter - JL Gennisson *(Institut Langevin)*

1Hz => 4Hz **Study of "slow" dynamic contractions**

Not an intrinsic limitation (measurements last 50ms)

Conclusions

Limitations

- Not an actual force estimation (in N)
- Sampling frequency
- **Number of probe / price** Only one muscle

Several machines (~100 k€)?

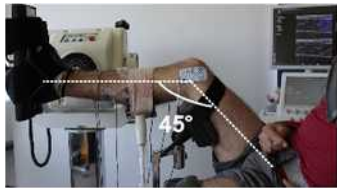
Smaller sensors on the same machine?

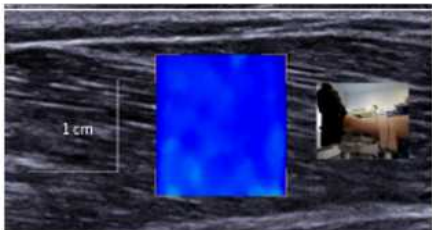
Conclusion

Local mechanical properties of muscles and tendons using elastography

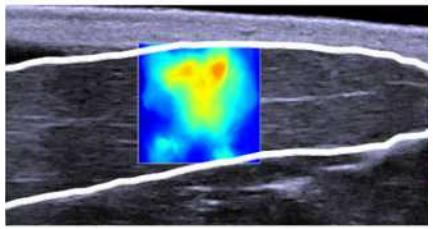
- **Fundamental applications**

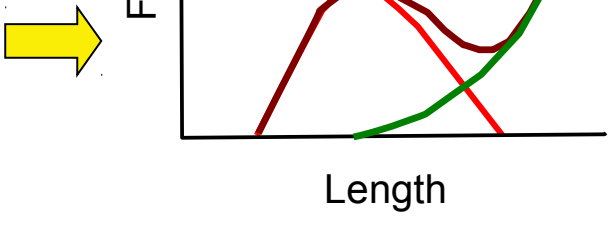
Estimation of passive muscle tension

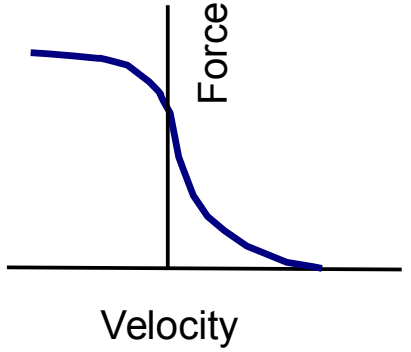




Estimation of individual muscle force







- **Sports applications** (*e.g.*, stretching, coordination, fatigue, damage...)
- **Clinical applications** (*e.g.*, myopathies, neuropaties, spasticity...)
- **Industrial applications** (coll. Supersonic Imagine)

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Thanks !

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l'Europe s'engage en Pays de la Loire

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RSPDL
RECHERCHE & SPORT EN PAYS DE LA LOIRE