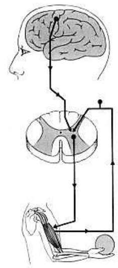
icSPORTS 2021 • 9th International Conference on Sport Sciences Research and Technology Support • Oct 29th 2021



Changes in Muscle Morphology, Neuromuscular Capacity and Tendon Function with Training:

Implications for Athletic Performance, Patient Rehabilitation and Aging Individuals

Per Aagaard
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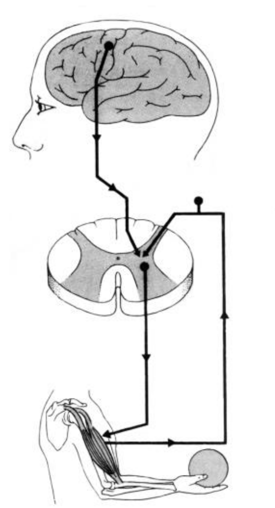
University of Southern Denmark

Effects of resistance training on…

- **Muscle size and structure**
  - anatomical CSA and volume
  - physiological fibre CSA
  - fibre type composition
  - muscle architecture
- **Tendon function**
  - CSA, stiffness, injury
- **Neuromuscular function**
  - explosive muscle strength
  - motor cortex, cerebellum
  - spinal cord circuitry



Drawing modified from Sale 1992

Effects of resistance training on…

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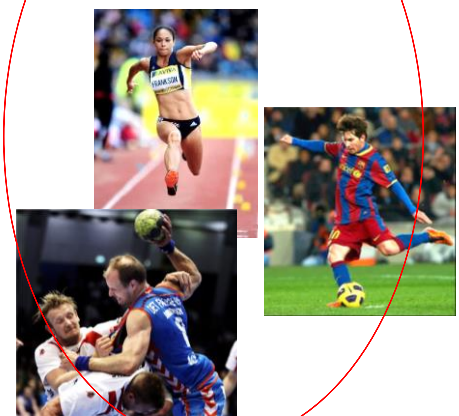
HUGE IMPLICATIONS FOR FUNCTIONAL PERFORMANCE!



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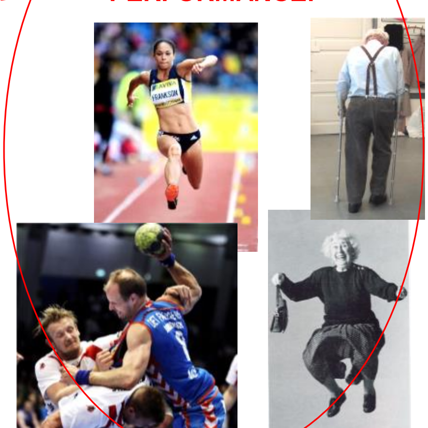
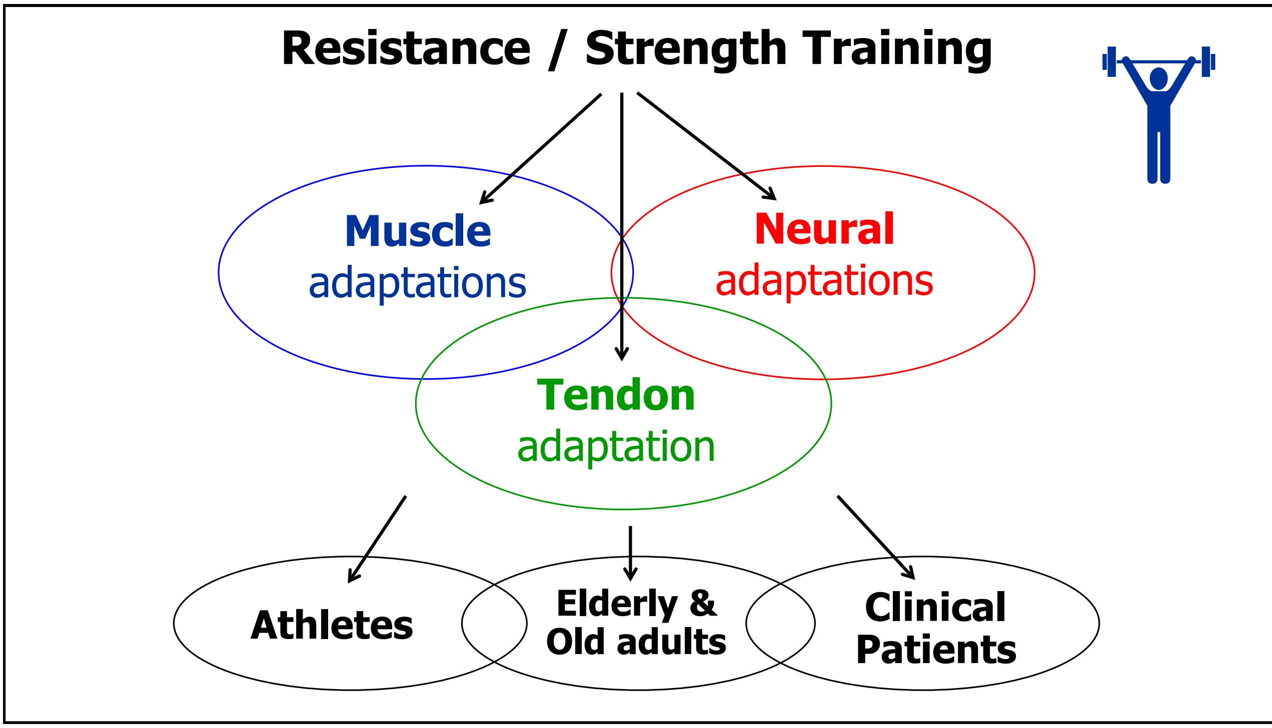
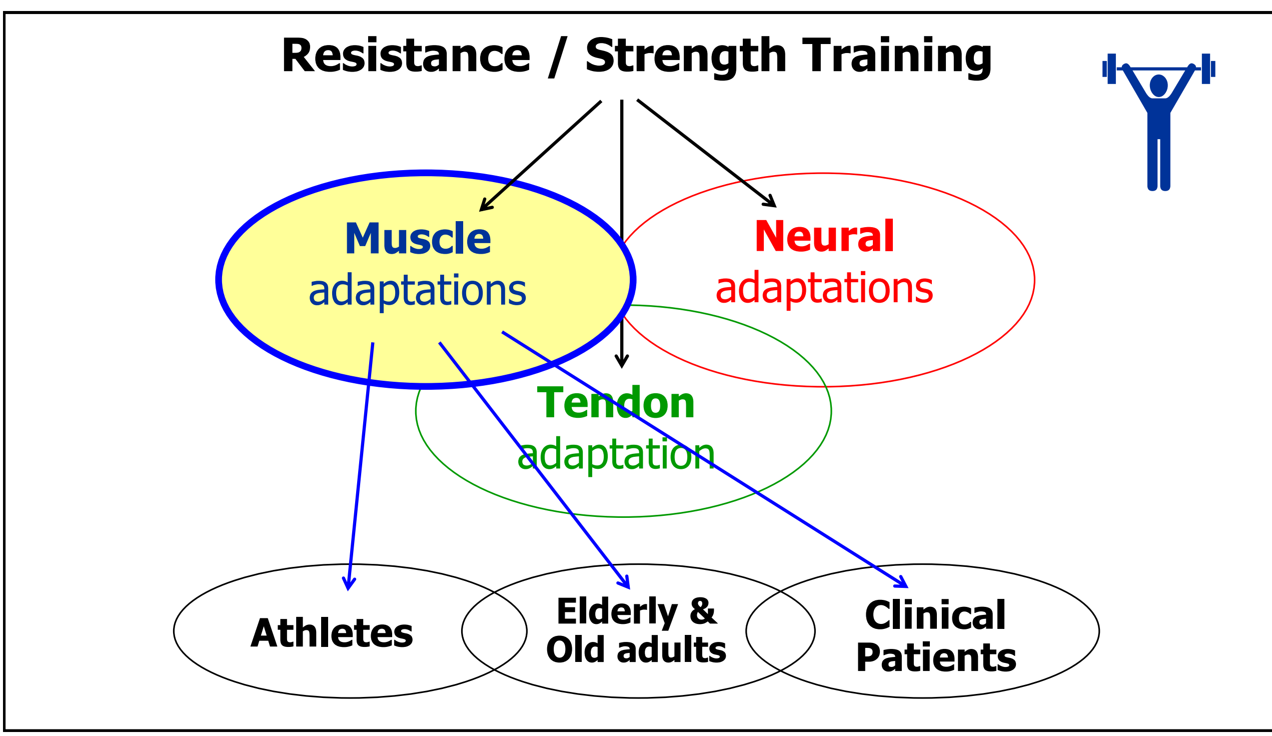



Resistance / Strength Training
Muscle
adaptations
Neural
adaptations
Tendon
adaptation
Athletes
Elderly &
Old adults
Clinical
Patients


Resistance / Strength Training
Muscle
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adaptation
Athletes
Elderly &
Old adults
Clinical
Patients

Use of Resistance Exercise to increase <u>muscle mass</u>
in Athletes, Clinical Patients and Elderly

<u>RATIONALE</u>

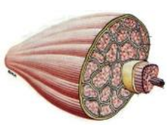
↑ Muscle Mass

⇓

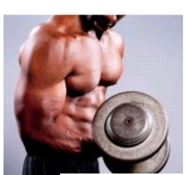
↑ Muscle force, power, explosive strength (RFD)

⇓

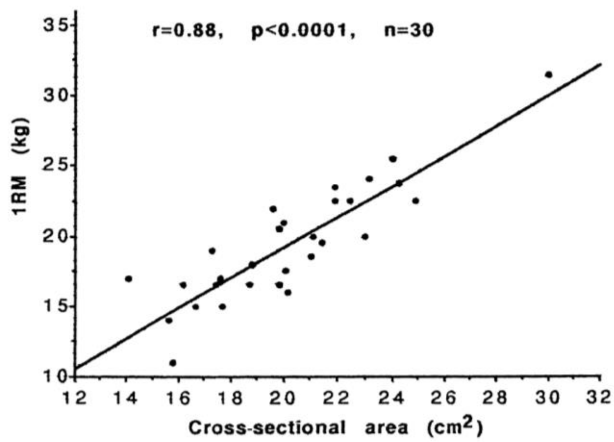
↑ Functional performance (acc, speed of movement, etc)



Close relationship exists between muscle <u>size</u> and maximal muscle <u>strength</u>

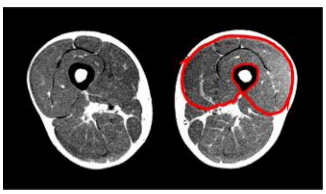


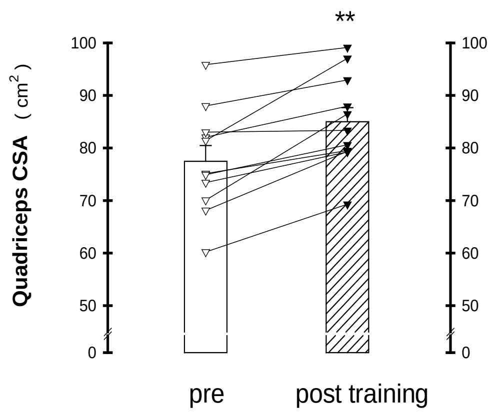
Elbow flexor 1RM STRENGTH



Moss, Jensen et al, Eur J Appl Physiol 1997
Elbow flexors, physical education students

Training-induced changes in anatomical muscle size

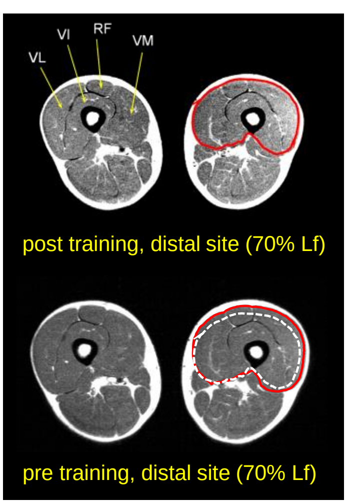


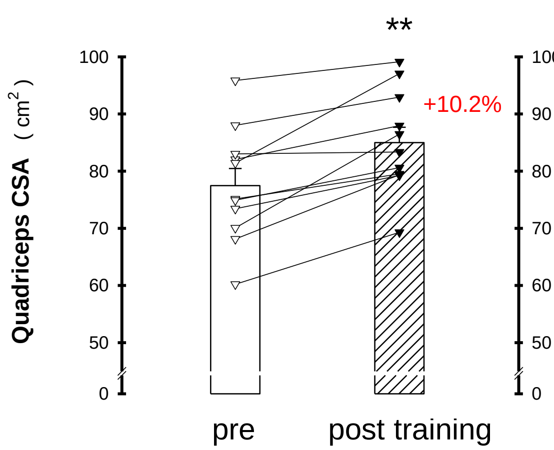


Changes in anatomical muscle CSA (MRI)

following 14 weeks of heavy-resistance strength training
- CSA obtained at 50% L_{femur}

** post > pre training
P < 0.001



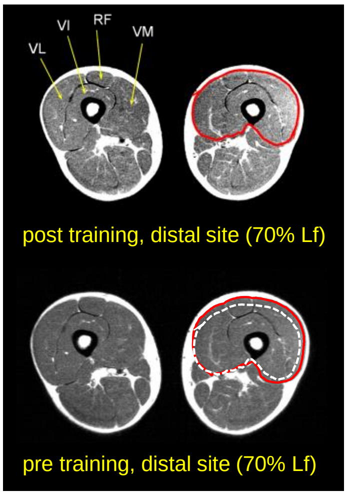


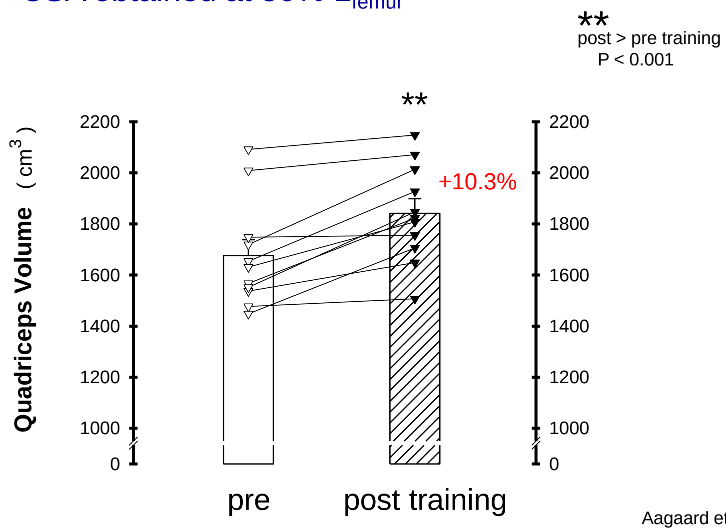
Aagaard et al.
J. Physiol. 2001

Changes in anatomical muscle Volume (MRI)

following 14 weeks of heavy-resistance strength training

- CSA obtained at 50% L_{femur}



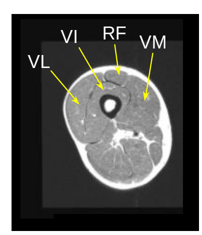


Aagaard et al.
J. Physiol. 2001

Increased anatomical muscle CSA and muscle volume in response to heavy-resistance strength training

Anatomical muscle CSA obtained by MRI or CT: 5-15% increases following few months of strength training

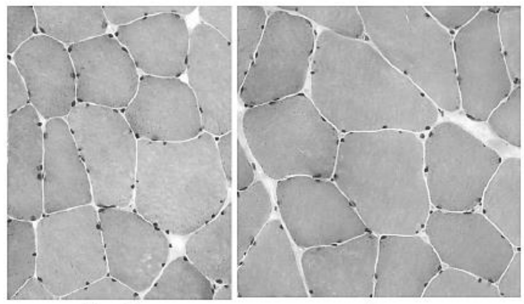
Aagaard 2001, Suetta 2004, Narici 1989, Häkkinen 1998, Häkkinen 2001, Peltonen 2018, Mikkola 2012, Erskine 2014



Total muscle volume: training induced increases similarly to that observed for anatomical CSA (5-15%)

Aagaard 2001, Reeves 2004, Erskine 2014, Van Roie 2013

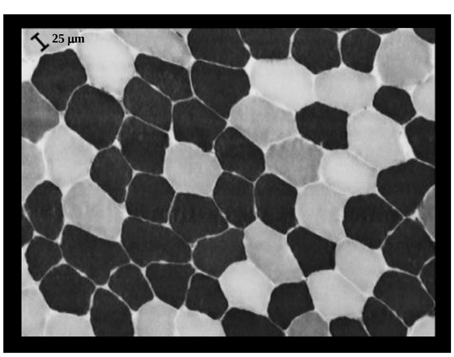
Training-induced changes in myofiber size



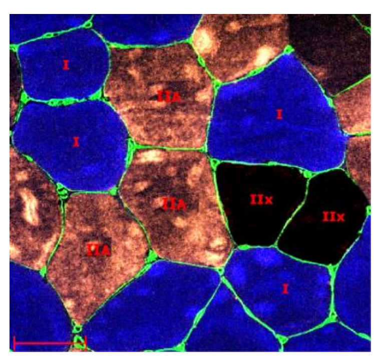
before after

Changes in myofiber CSA (biopsy analysis)

biopsy sampling, vastus lateralis
CSA of individual muscle fibres



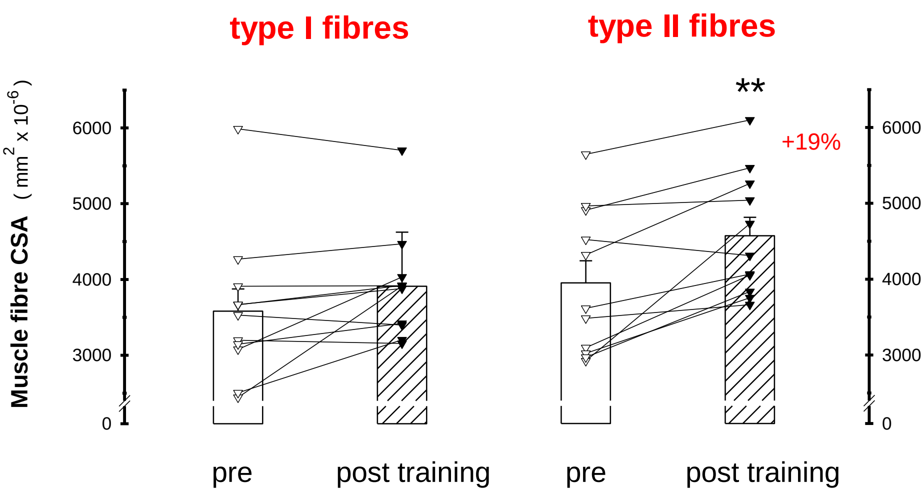
Jesper Andersen
ISMC, University of Copenhagen



Ulrik Frandsen
IOB, University of Southern Denmark

Changes in myofiber CSA (biopsy analysis)

following 14 weeks of heavy-resistance strength training



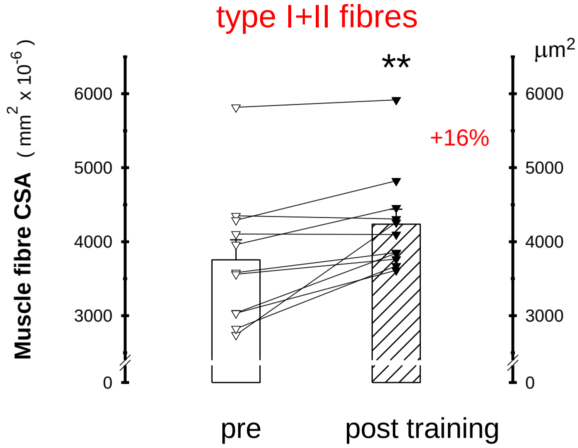
** post > pre training
P < 0.001

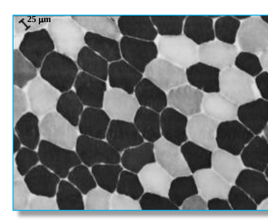
Aagaard et al.
J. Physiol. 2001

Changes in myofiber CSA (biopsy analysis)

following 14 weeks of heavy-resistance strength training

Average myofiber CSA
type I+II fibres





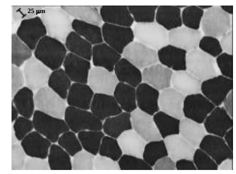
** post > pre training
P < 0.001

Aagaard et al.
J. Physiol. 2001

Increased myofiber CSA in response to heavy-resistance strength training

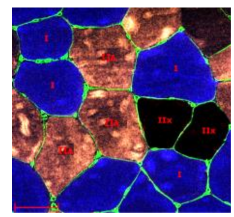
Preferential or greater increases in type II muscle fibre CSA (↑20-30% in 12 wks)

Kraemer 1995, Staron 1991, Aagaard 2001 , Kosek 2006, Suetta 2008, Jakobsen 2012, Andersen 2009, Farup 2014, Wang 2017, Snijders 2017



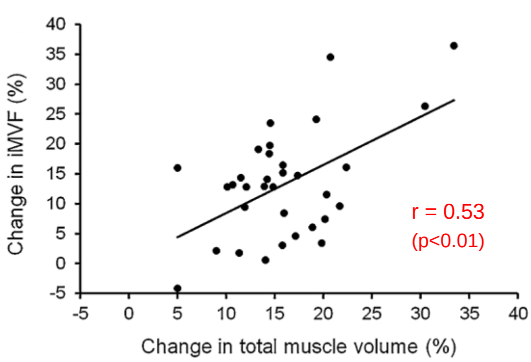
Comparable increases in type I and type II muscle fibre CSA (↑10-30% in 12 wks)

Kraemer 1995, Andersen 2005 (protein suppl), Vissing 2008, Pareja-Blanco 2017, Mobley 2018

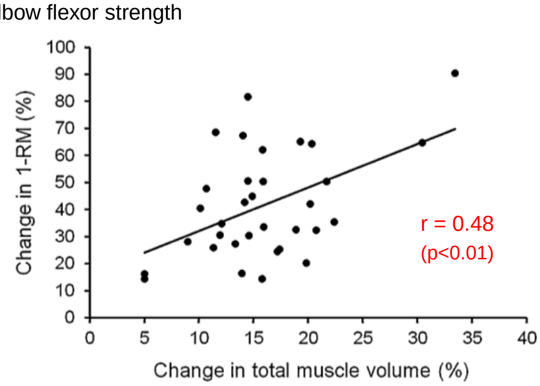


Gains in skeletal muscle size after resistance training contribute to the increase in maximal muscle strength

Δ isometric elbow flexor force

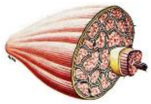


Δ 1-RM elbow flexor strength

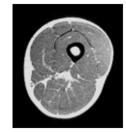


Young males (n=33)
12 wks elbow flexor RT, 3 sessions per wk, two exercises, 2-3 sets, 8-10 RM loads

Erskine, Folland et al 2014



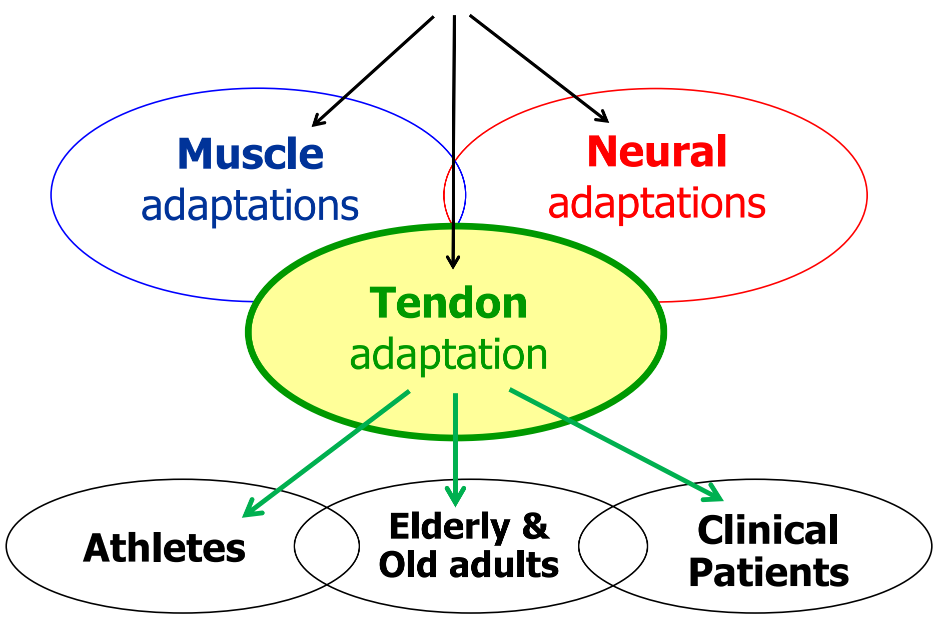
SUMMARY #1



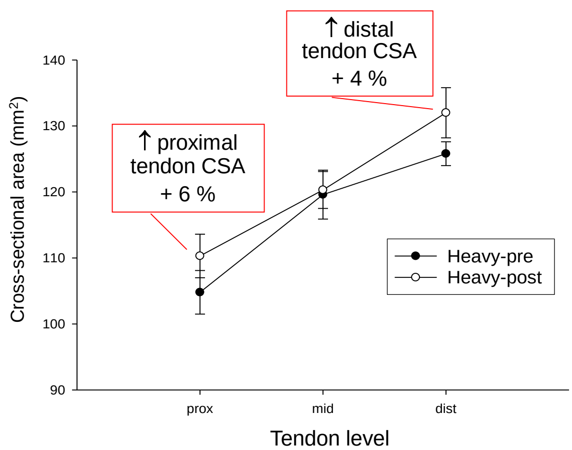
Adaptive changes in Muscles and Tendons in response to resistance training

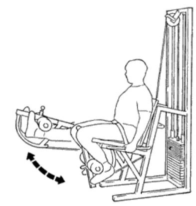
- increase in anatomical muscle cross-sectional area and volume (MRI, CT)
  Aagaard 2001, Suetta 2004, Narici 1989,1996, Häkkinen 1998, Higbie 1996
- increase in physiological muscle fibre area (muscle biopsy sampling)
  Aagaard 2001, McDonagh & Davies 1984, Hortobagyi 1996, Cribb 2006, Hather 1991
- increase in % IIA muscle fibres
  Andersen & Aagaard 2000, Hather 1991, Staron 1990, Andersen 1994, Kraemer 1995
- decrease in % IIX muscle fibres
  Andersen & Aagaard 2000, Andersen 1994, Staron 1990, Adams 1993, Kraemer 1995
- changes in muscle architecture: ↑ muscle fibre pennation angle
  Aagaard 2001, Reeves 2006, Suetta 2008, Duclay 2009
- ↑ tendon CSA, ↑ stiffness, ↓ tendon strain, ↑ type I collagen synthesis
  Kongsgaard 2007, Arampatzis 2007, Reeves 2003, Duclay 2009, Langberg 2007

Resistance / Strength Training

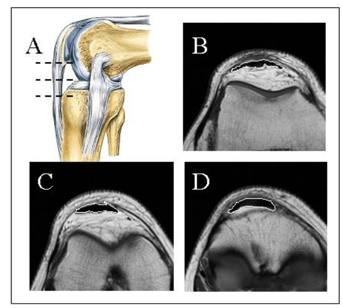


Effects of heavy-resistance strength training on patella tendon CSA



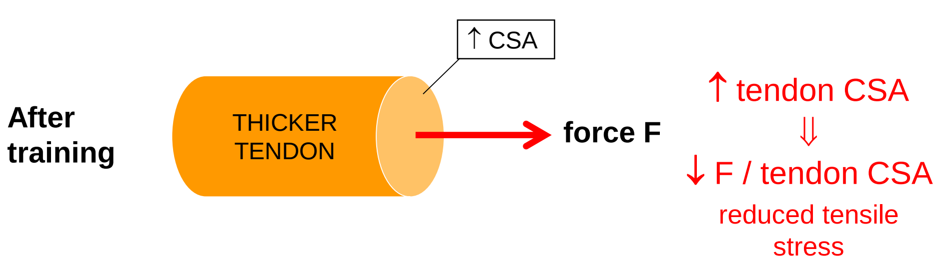


n=12 males (24.6±1.0 yr)
12 wks resistance training for the quadriceps muscle,
10 sets, 10 reps
Load intensity 70% of 1RM
3 sessions per week



Kongsgaard, Aagaard, Magnusson et al, Acta Physiol Scand 2007

Effects of heavy-resistance strength training on patella tendon CSA



Kongsgaard, Aagaard, Holm, Kjær, Magnusson et al, Acta Physiol Scand 2007

Effects of resistance training on human muscle **tendon** properties - summary #2

Resistance training results in <u>increased tendon stiffness</u>
Reeves 2003, Kongsgaard 2007, Arampatzis 2007, Seynnes 2009, Waugh Blazevich 2014

Resistance training may lead to <u>increased tendon CSA</u>
Kongsgaard 2007, Arampatzis 2007, Seynnes 2009, Farup 2014, Dalgaard 2019 (women), Eriksen 2019 (old adults: 62-70 yrs)

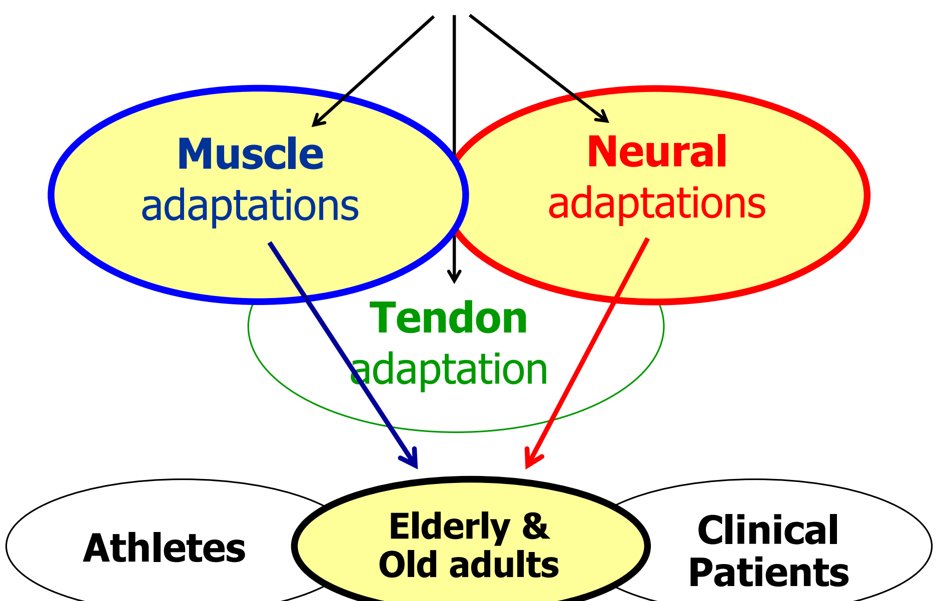
…although not demonstrated in all studies
Reeves 2003 (old adults: 74.3 ±3.5 yrs), Waugh Blazevich 2014 (children: 8.9 ±0.3 yrs), Bloomquist 2013

Resistance training results in <u>diminished tendon strain</u>
Reeves 2003, Kongsgaard 2007, Arampatzis 2007, Seynnes 2009, Urlando & Hawkins 2007, Carrol 2008

Resistance training may yield <u>increased Youngs Modulus</u>, indicating altered material properties
Reeves 2003 (old adults), Arampatzis 2007, Seynnes 2009, Waugh Blazevich 2014 (children)

…although not seen in all studies Kongsgaard 2007, 2009

Resistance / Strength Training

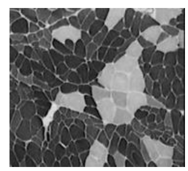


Heavy-resistance strength training induces muscle fiber growth also in very old individuals (85-97 yrs, mean age 89 ± 3 yrs)

≥85 year old discharged geriatric patients

12 weeks of resistance exercise

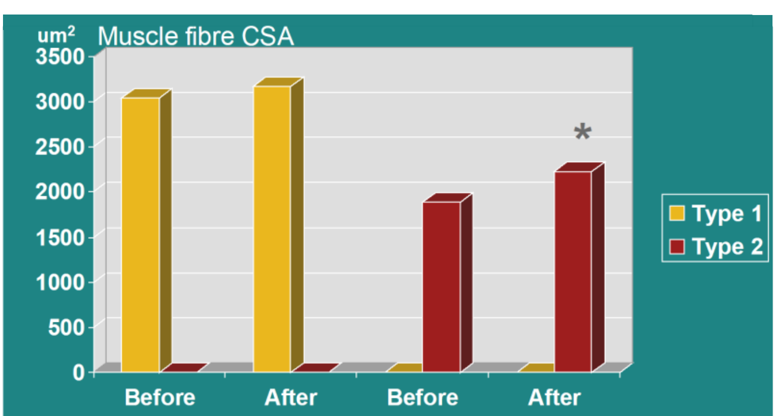
- isolated knee extensor exercise
- 3 session per week,
- 3 sets x 8 rep,
- training loads >70% 1 RM

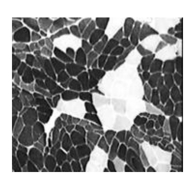


Kryger & Andersen,
Scand J Med Sci Sports 2007

Heavy-resistance strength training induces muscle fiber growth also in very old individuals (85-97 yrs, mean age 89 ± 3 yrs)

Loading 80% 1RM, 3/week, 12 weeks





Kryger & Andersen,
Scand J Med Sci Sports 2007

Heavy-resistance strength training induces muscle fiber growth also in very old individuals (85-97 yrs, mean age 89 ± 3 yrs)

≥85 year old discharged geriatric patients

<u>12 weeks of resistance exercise</u>
knee ext. 3 x weekly, 3 x 8 rep, >70% 1 RM

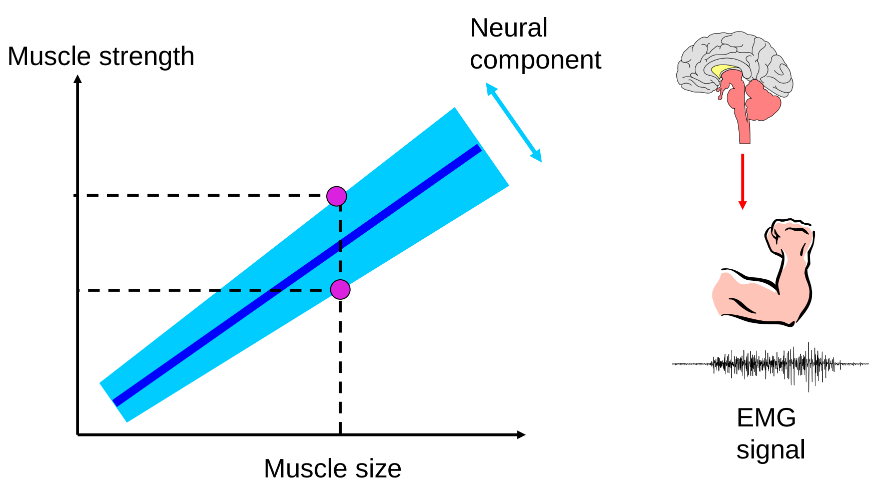
Results

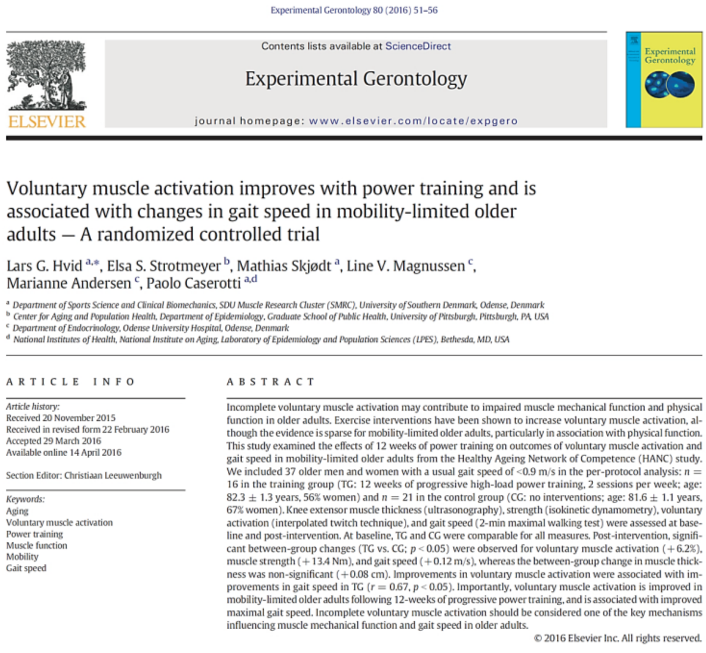
Type IIa fibre CSA	↑ 22% *
Quadriceps strength	↑ 40-45% *
Chair rising time (5 reps)	**30% faster** *
Maximal walking speed	**25% faster** *

* $p < 0.05$

Kryger & Andersen,
Scand J Med Sci Sports 2007

Maximal muscle strength
= Muscle size x Neural function





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ELSEVIER

Voluntary muscle activation improves with power training and is associated with changes in gait speed in mobility-limited older adults — A randomized controlled trial

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Gait speed

ABSTRACT

Incomplete voluntary muscle activation may contribute to impaired muscle mechanical function and physical function in older adults. Exercise interventions have been shown to increase voluntary muscle activation, although the evidence is sparse for mobility-limited older adults, particularly in association with physical function. This study examined the effects of 12 weeks of power training on outcomes of voluntary muscle activation and gait speed in mobility-limited older adults from the Healthy Ageing Network of Competence (HANC) study. We included 37 older men and women with a usual gait speed of <0.9 m/s in the per-protocol analysis: $n = 16$ in the training group (TG: 12 weeks of progressive high-load power training, 2 sessions per week; age: 82.3 ± 1.3 years, 56% women) and $n = 21$ in the control group (CG: no interventions; age: 81.6 ± 1.1 years, 67% women). Knee extensor muscle thickness (ultrasonography), strength (isokinetic dynamometry), voluntary activation (interpolated twitch technique), and gait speed (2-min maximal walking test) were assessed at baseline and post-intervention. At baseline, TG and CG were comparable for all measures. Post-intervention, significant between-group changes (TG vs. CG; $p < 0.05$) were observed for voluntary muscle activation (+6.2%), muscle strength (+13.4 Nm), and gait speed (+0.12 m/s), whereas the between-group change in muscle thickness was non-significant (+0.08 cm). Improvements in voluntary muscle activation were associated with improvements in gait speed in TG ($r = 0.67$, $p < 0.05$). Importantly, voluntary muscle activation is improved in mobility-limited older adults following 12-weeks of progressive power training, and is associated with improved maximal gait speed. Incomplete voluntary muscle activation should be considered one of the key mechanisms influencing muscle mechanical function and gait speed in older adults.

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Mobility-limited older individuals,

3 m habitual gait speed < 0.90 m/s

Age: 82 ± 1 yrs

TG: n=33
CG: n=32

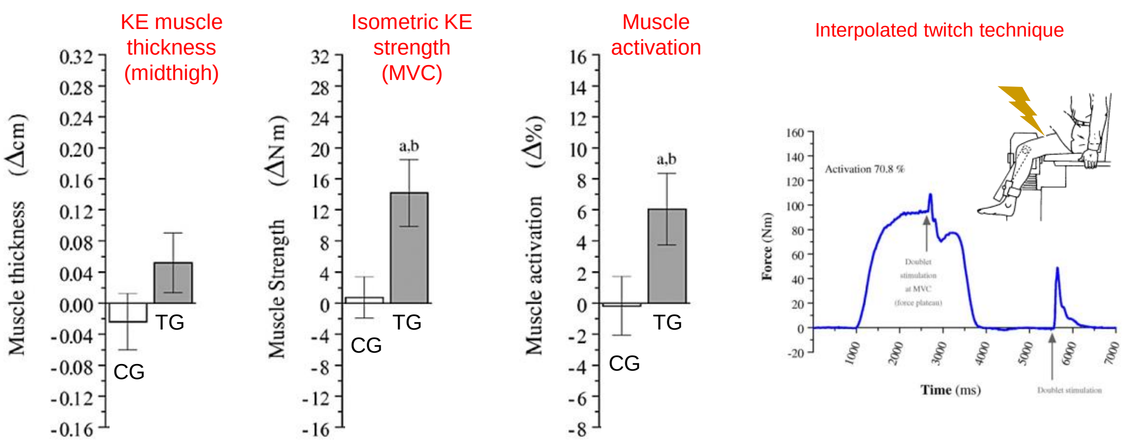
Heavy-load explosive-type resistance training
[Casseroti, Aagaard et al SJMSS 2008]

12 weeks
2 sessions/wk

LP, PF
3 sets, 10 reps →
3 sets, 8 reps
70-80% 1RM

Hvid, Caserotti et al, Exp Gerontol 2016

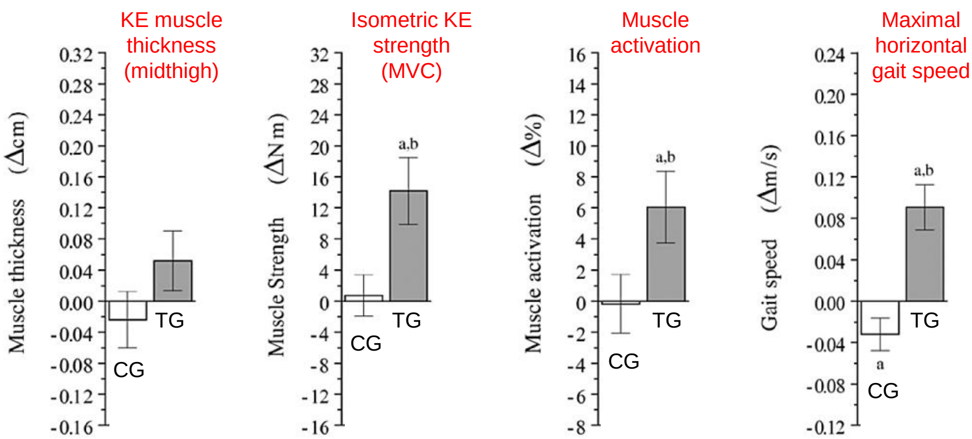
Heavy-resistance strength training induces gains in muscle activation in (very) old adults (mean age 82 ± 1 yrs)



a: within-group changes ($p < 0.05$);
b: between-group changes ($p < 0.05$).

Hvid, Caserotti et al, Exp Gerontol 2016A

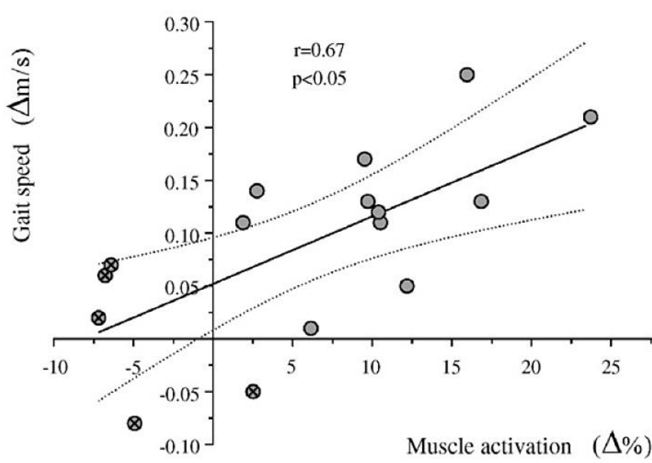
Heavy-resistance strength training induces gains in muscle activation in (very) old adults (mean age 82 ± 1 yrs)



a: within-group changes ($p < 0.05$);
b: between-group changes ($p < 0.05$).

Hvid, Caserotti et al,
Exp Gerontol 2016A

Training-induced gains in muscle activation are associated with corresponding changes in walking capacity (max gait speed)



$r^2 = 0.45$ ($p < 0.05$)

X-symbols: participants with voluntary muscle activation above 90% at baseline.

Hvid, Caserotti et al,
Exp Gerontol 2016A

Their conclusions...

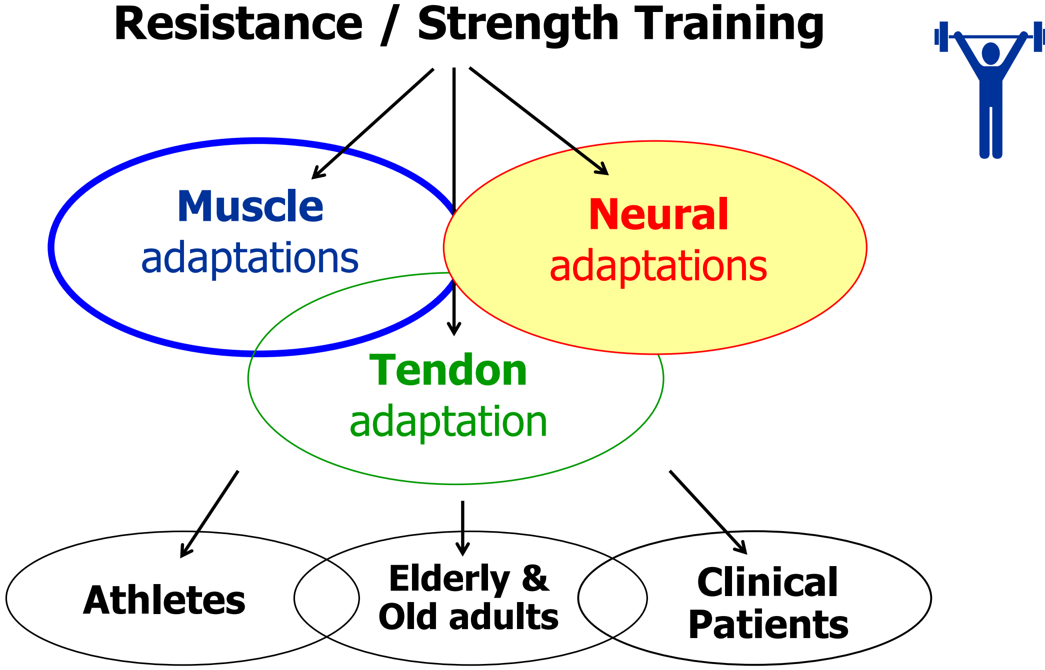
Voluntary muscle activation (VA) increased in mobility-limited older adults following 12-weeks of progressive power training.

The increase in VA was strongly associated with improvements in gait speed, particularly in old adults having low levels of voluntary muscle activation at baseline.

These results emphasize the effectiveness of a **power training** regime combining **high loads** and **explosive-type contractions**, to improve mechanical muscle function and functional capacity (e.g. gait speed) in older adults.

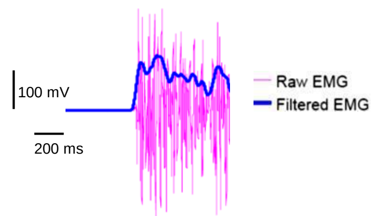
Hvid, Caserotti et al,
Exp Gerontol 2016A

Resistance / Strength Training

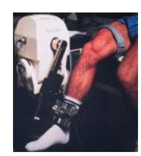


Neural adaptations in Rate of Force Development (RFD)

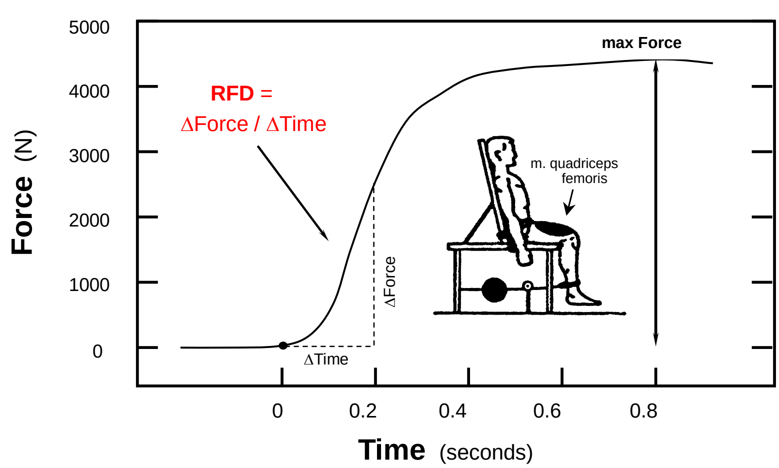
Effects of **resistance training** on maximal RFD
and neuromuscular activation / neural drive



Maximal Explosive Muscle Strength
'Rapid Force Capacity'



Rate of Force Development (RFD)



Aagaard et al, J Appl Physiol 2002

Ground contact times…

110 - 160 msec in long jump
180 - 220 msec in high jump
80 - 120 msec in sprint running

Zatsiorsky 1995

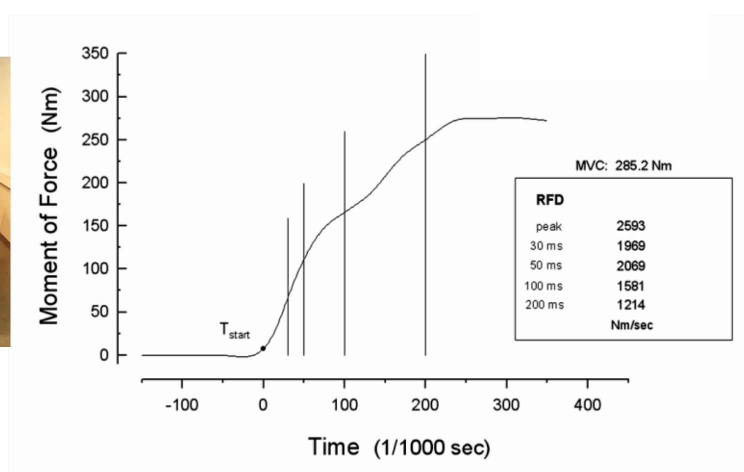
Time to reach peak force
in human skeletal muscle…

300 - 500 msec

Sukop & Nelson 1974, Thorstensson et al. 1976, Aagaard et al. 2002

RFD Contractile Rate of Force Development

Assessed during maximal isometric quadriceps contraction



Aagaard et al, J Appl Physiol 2002

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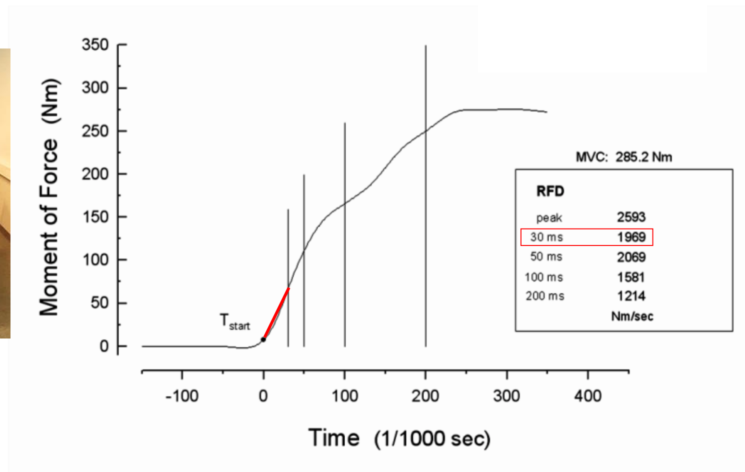

Aagaard et al, J Appl Physiol 2002

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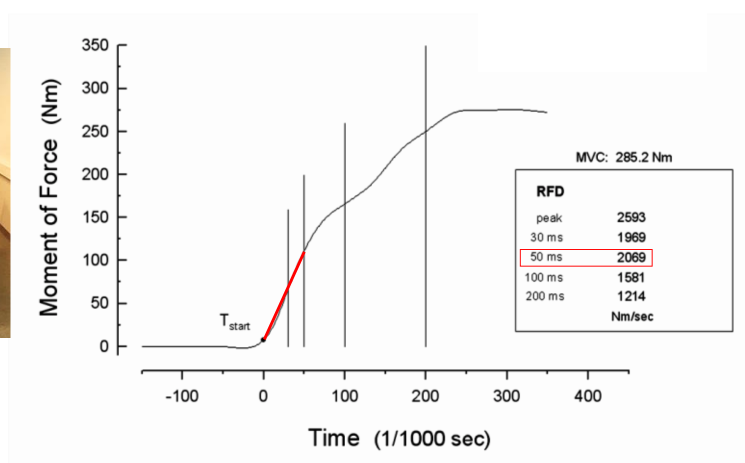
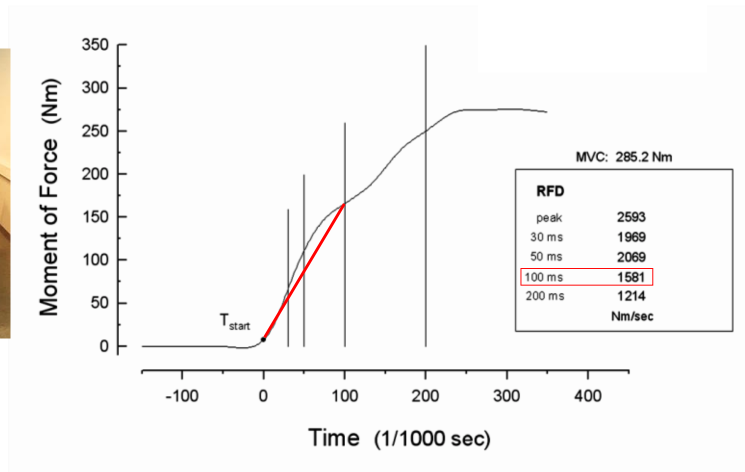


Aagaard et al, J Appl Physiol 2002

RFD Contractile Rate of Force Development

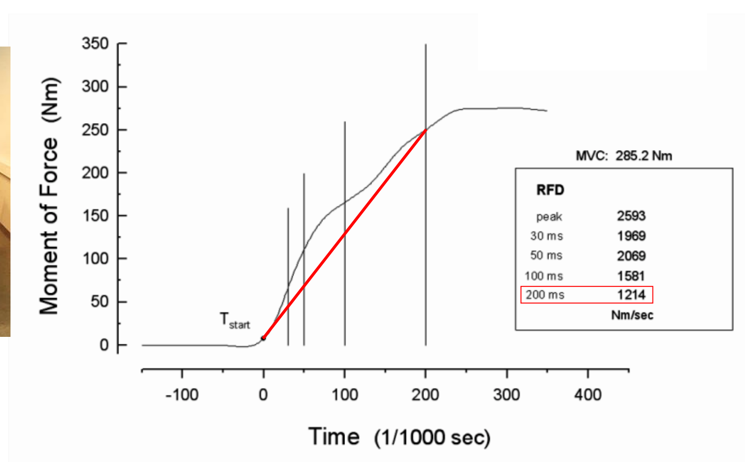
Assessed during maximal isometric quadriceps contraction



Aagaard et al, J Appl Physiol 2002

RFD Contractile Rate of Force Development

Assessed during maximal isometric quadriceps contraction

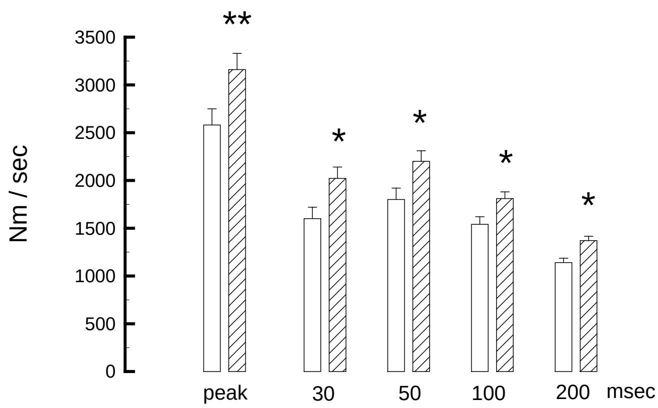


Aagaard et al, J Appl Physiol 2002

RFD Contractile Rate of Force Development

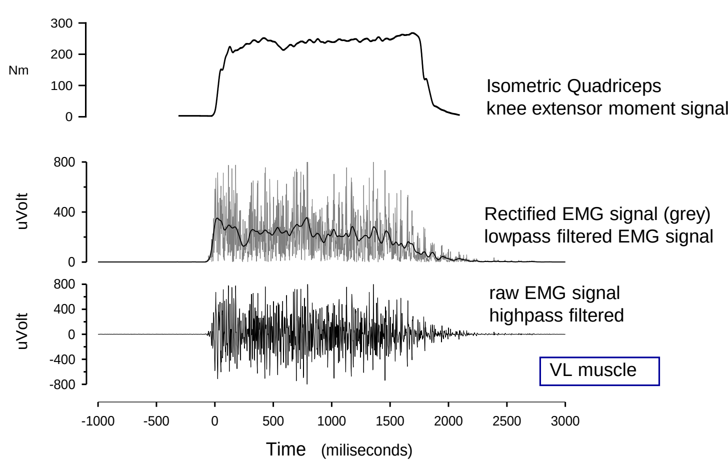
Assessed during maximal isometric quadriceps contraction

Pre and post 14 wks of heavy-resistance strength training



Aagaard et al, J Appl Physiol 2002

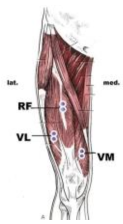
Training-induced changes in **neuromuscular activity** and RFD

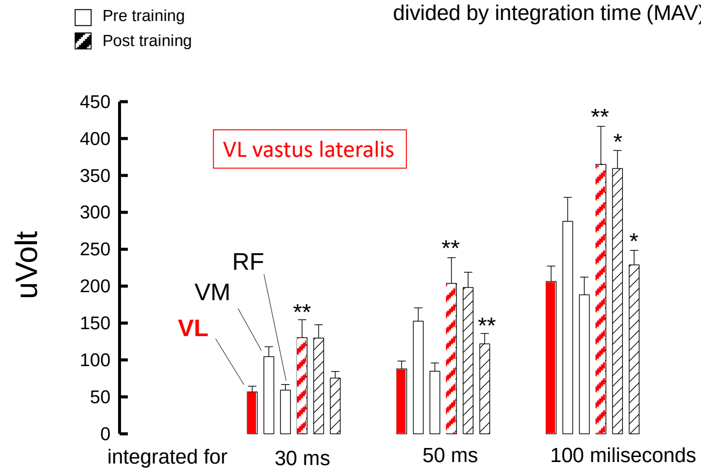


Aagaard et al, J Appl Physiol 2002

Adaptive changes in **neuromuscular activity** and RFD

quadriceps mean integrated EMG
divided by integration time (MAV)





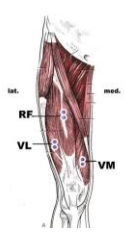
Pre to post training differences: * $p < 0.05$, ** $p < 0.01$

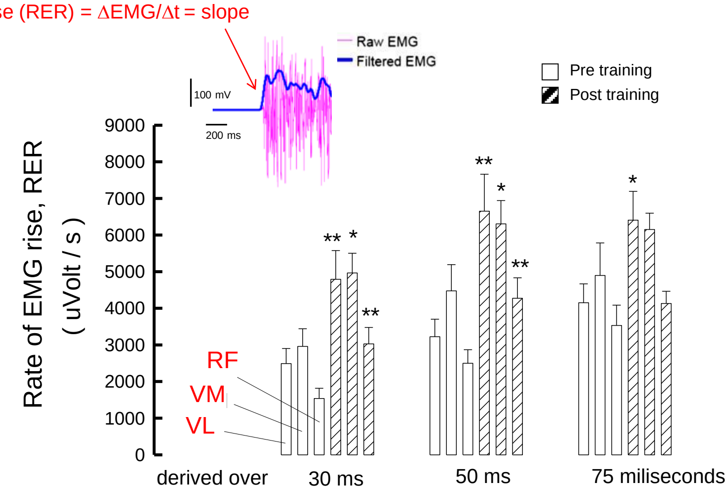
Aagaard et al, J Appl Physiol 2002

Adaptive changes in **neuromuscular activity** and RFD

Rate of EMG rise (ΔEMG/Δt)

Rate of EMG rise (RER) = ΔEMG/Δt = slope





Pre to post training differences: * $p < 0.05$, ** $p < 0.01$

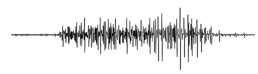
Aagaard et al, J Appl Physiol 2002

Training induced changes in
rapid force capacity **RFD**

Heavy-resistance strength training

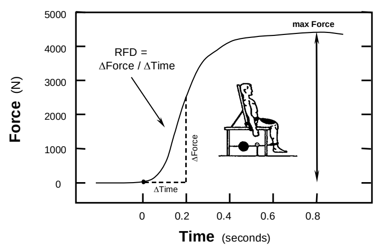
↓

Increased neuromuscular activity



↓ ...within initial 200 msec of contraction

Increased maximal Rate of Force Development (RFD)

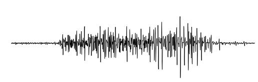


Training induced changes in
rapid force capacity **RFD**

Heavy-resistance strength training

↓

Increased neuromuscular activity



↓ ...within initial 200 msec of contraction

Increased maximal Rate of Force Development (RFD)

- Increased RFD and increased iEMG

  Häkkinen & Komi 1986, Häkkinen 1985, 1998, Van Cutsem 1998, Barry 2005
  Aagaard 2002, Suetta 2004, Del Balso & Cafarelli 2007, Vila-Chã 2010, Tillin Folland 2014

- Increased RFD and elevated rate of EMG rise

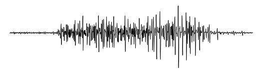
  Aagaard 2002, Barry 2005, Del Balso & Cafarelli 2007, Schmidtbleicher & Buerhle 1987

Training induced changes in
rapid force capacity **RFD**

Heavy-resistance strength training

↓

Increased neuromuscular activity



↓ ...within initial 200 msec of contraction

Increased maximal Rate of Force Development (RFD)

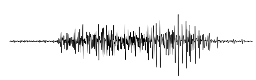
Functional consequences:
- enhanced acceleration
- faster movements
- elevated muscle force and muscle power during fast movements

Training induced changes in
rapid force capacity **RFD**

Heavy-resistance strength training

↓

Increased neuromuscular activity



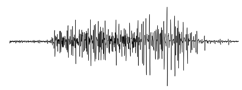
↓ ...within initial 200 msec of contraction

Increased maximal Rate of Force Development (RFD)

Functional consequences:
- enhanced acceleration
- faster movements
- elevated muscle force and muscle power during fast movements
- reduced risk of falls

Neural adaptations in Rate of Force Development (RFD)

Influence of explosive-type resistance training
on exercise induced gains in RFD



Neural adaptations in Rate of Force Development (RFD)

Influence of explosive-type muscle actions during training

Training-specific functional, neural, and hypertrophic adaptations to explosive- vs. sustained-contraction strength training

Thomas G. Balshaw,[1,2] Garry J. Massey,[1,2] Thomas M. Maden-Wilkinson,[2] Neale A. Tillin,[3] and Jonathan P. Folland[1,2]

Bojsen-Møller, Aagaard et al,
J Appl Physiol 2005

Male adults completed either sustained-contraction training (SCT, *n* = 16) or explosive-contraction strength training (ECT, *n* = 13) for 12 weeks (3 sessions per wk; 36 sessions in total)

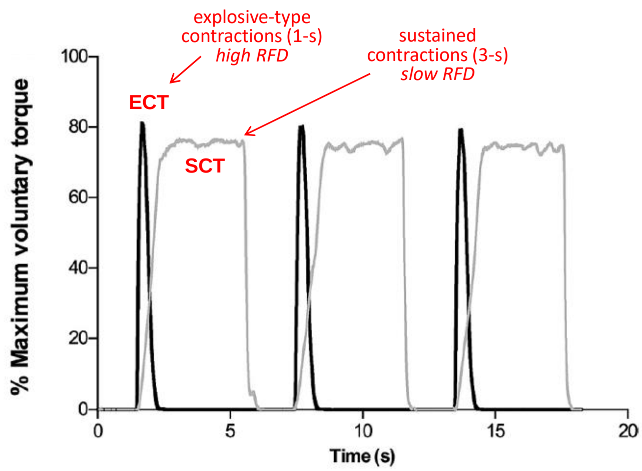
Isometric training, quadriceps femoris muscle.
Data recording + training: isometric strength testing chair
knee and hip angles of 95° and 110° flexion

ECT: contract as fast/hard as possible up to ≥ 80 % MVC ~1 s;
SCT: contract progressively (2-s ramp) up to 75 % MVC for 3 s
4 sets, 10 reps

Balshaw, Folland et al, J Appl Physiol 2016

Neural adaptations in Rate of Force Development (RFD)

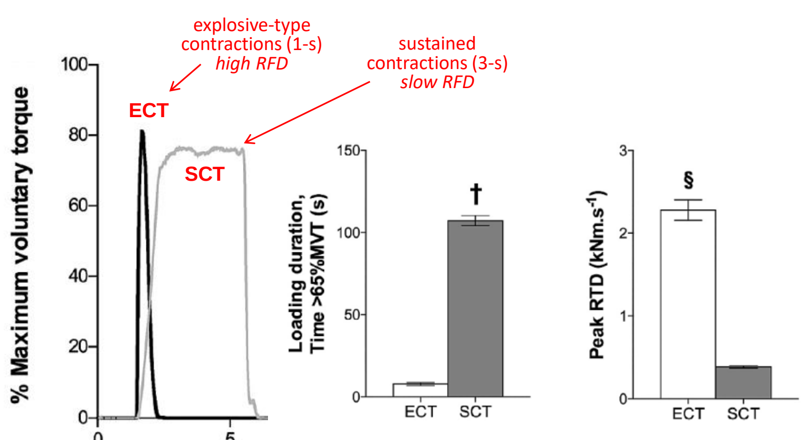
Influence of explosive-type muscle actions during training



Balshaw, Folland et al, J Appl Physiol 2016

Neural adaptations in Rate of Force Development (RFD)

Influence of explosive-type muscle actions during training

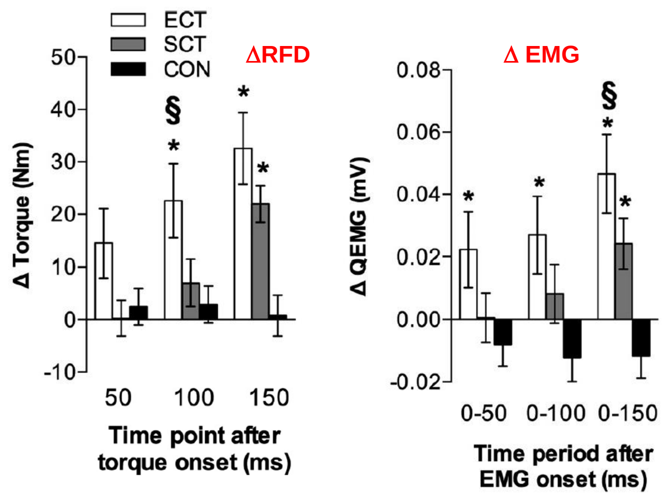


§,† SCT vs ECT (p<0.05)

Balshaw, Folland et al, J Appl Physiol 2016

Neural adaptations in Rate of Force Development (RFD)

Influence of explosive-type muscle actions during training



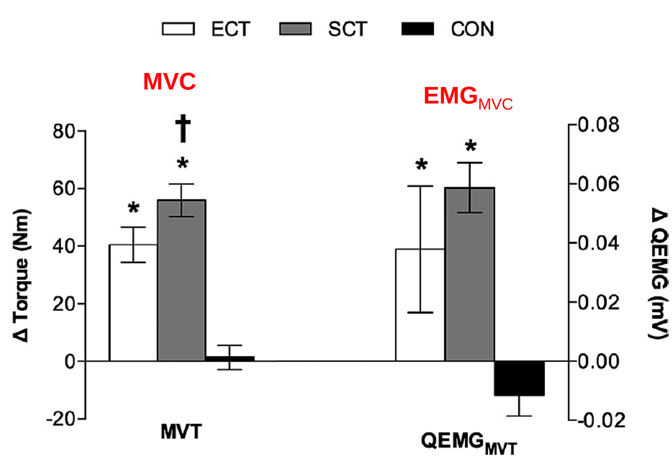
Training-induced changes in **quadriceps RFD** and **EMG_{RFD}**

§ SCT vs ECT (p<0.05)

Balshaw, Folland et al, J Appl Physiol 2016

Neural adaptations in Rate of Force Development (RFD)

Influence of explosive-type muscle actions during training



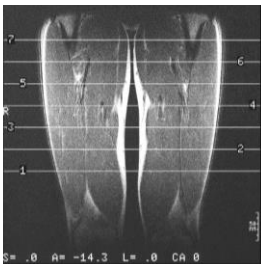
Training-induced changes in **quadriceps MVC** and **EMG_{MVC}**

† SCT vs ECT (p<0.05)

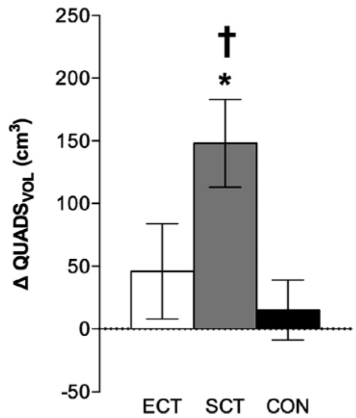
Balshaw, Folland et al, J Appl Physiol 2016

Neural adaptations in Rate of Force Development (RFD)

Influence of explosive-type muscle actions during training



Aagaard et al, J Physiol 2001



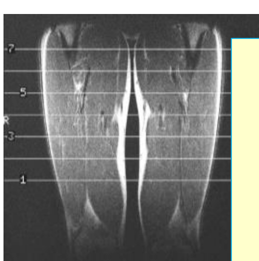
Training-induced changes in **quadriceps muscle volume**

† SCT vs ECT (p<0.05)

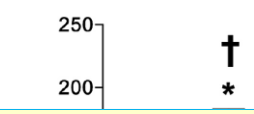
Balshaw, Folland et al, J Appl Physiol 2016

Neural adaptations in Rate of Force Development (RFD)

Influence of explosive-type muscle actions during training



Aagaard et al, J Physiol 2001



Explosive-type resistance training produced pronounced gains in both early-phase (100 ms) and late-phase (200 ms) RFD, while slow-type (i.e. non-explosive) training caused increases in late-phase RFD only.

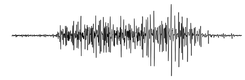
However, sustained slow-type resistance training led to greater gains in maximal isometric strength (MVC) and muscle volume

ning-induced hanges in **uadriceps scle volume**

† SCT vs ECT (p<0.05)

Balshaw, Folland et al, J Appl Physiol 2016

Muscular, neural and tendinous adaptations to resistance training



Take-home messages

- Resistance training leads to marked gains in **anatomical muscle size** and **myocellular fibre size**, respectively, resulting in corresponding gains in maximal muscle strength and RFD
- Resistance training leads to significant increases in **neuromuscular activation (neural drive)**, in turn also causing improvements in maximal strength, RFD and functional capacity, respectively
- Resistance training may also produce hypertrophy in **tendons**, in turn contributing to increase RFD and prevent tendon overuse injury
- These effects occur in both **young** and **old adults** incl. clinical patients

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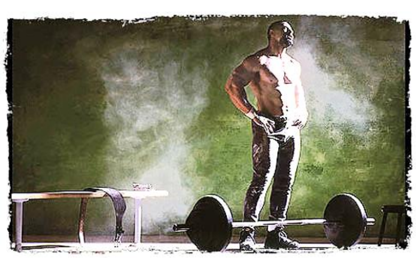
THANKS
for your attention!



University of Southern Denmark

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Lars L. Andersen
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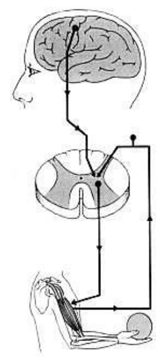
Emil Sundstrup



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