Changes in Muscle Morphology, Neuromuscular Capacity and Tendon Function with Training: Implications for Athletic Performance, Patient Rehabilitation and Aging Individuals

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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
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HUGE IMPLICATIONS FOR FUNCTIONAL PERFORMANCE!
Use of Resistance Exercise to increase muscle mass in Athletes, Clinical Patients and Elderly

**RATIONALE**

- ↑ Muscle Mass
- ↑ Muscle force, power, explosive strength (RFD)
- ↑ Functional performance (acc, speed of movement, etc)

Close relationship exists between muscle size and maximal muscle strength

Elbow flexor 1RM STRENGTH

\[ r = 0.88, \quad p < 0.0001, \quad n = 30 \]

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% $L_{\text{femur}}$

**Post Training**

**Pre**

Quadriceps CSA (cm²)

Fig. 6
Aagaard et al., *A mechanism for increased contractile strength of human pennate muscle...*

Changes in anatomical muscle CSA (MRI)

post training, distal site (70% Lf)

pre training, distal site (70% Lf)

**Post Training**

**Pre**

Quadriceps CSA (cm²)

Fig. 6
Aagaard et al., *A mechanism for increased contractile strength of human pennate muscle...*

+10.2%

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

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


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

Training-induced changes in myofiber size

Changes in myofiber CSA (biopsy analysis)

biopsy sampling, vastus lateralis
CSA of individual muscle fibres

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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)


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


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

\[ r = 0.53 \quad (p<0.01) \]

\[ r = 0.48 \quad (p<0.01) \]
SUMMARY #1

Adaptive changes in **Muscles and Tendons** in response to resistance training

- increase in anatomical muscle cross-sectional area and volume (MRI, CT)

- increase in physiological muscle fibre area (muscle biopsy sampling)

- increase in % IIA muscle fibres

- decrease in % IIX muscle fibres

- changes in muscle architecture: ↑ muscle fibre pennation angle

- ↑ tendon CSA, ↑ stiffness, ↓ tendon strain, ↑ type I collagen synthesis
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

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

Resistance training results in **increased tendon stiffness**

Resistance training may lead to **increased tendon CSA**

…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 **diminished tendon strain**

Resistance training may yield increased Youngs Modulus, indicating altered material properties

…although not seen in all studies Kongsgaard 2007, 2009

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**Resistance / Strength Training**

- **Muscle adaptations**
- **Neural adaptations**
- **Tendon adaptation**

- **Athletes**
- **Elderly & Old adults**
- **Clinical Patients**
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


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

Muscle fibre CSA

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
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

Maximal muscle strength = Muscle size x Neural function

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EMG signal

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Maximal muscle strength

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Muscle strength

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Neural component

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Muscle size

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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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ARTICLE INFO

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 mobility aging network of competencies (MANCoSE) study. We included 37 older men and women with a normal gait speed of ≥0.90 m/s in the pre-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 ± 1.5 years, 67% women). Knee extensor muscle thickness (sonomorphographic) and muscle activation (interpolated twitch technique) and gait speed were assessed at baseline and post-intervention. No differences or significant between-group changes (TG vs. CG, p > 0.05) were observed for voluntary muscle activation (–0.2%, muscle thickness; +1.4%, and gait speed; −0.02 m/s), whereas the between-group change in muscle thickness was non-significant (−0.02 m/s). Improvements in voluntary muscle activation were associated with improvements in muscle thickness (r = 0.33, p = 0.042) and gait speed (r = −0.31, p = 0.051). These findings support the hypothesis that improving voluntary muscle activation could improve mobility-limited older adults following 12 weeks of progressive power training, and are associated with improved muscle thickness and gait speed. Improvements in 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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Heavy-resistance strength training induces gains in muscle activation in (very) old adults (mean age 82 ± 1 yrs)

KE muscle thickness (mid-thigh) Isometric KE strength (MVC) Muscle activation

Interpolated twitch technique

a: within-group changes (p < 0.05); b: between-group changes (p < 0.05).
Heavy-resistance strength training induces gains in muscle activation in (very) old adults (mean age 82 ± 1 yrs)

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

X-symbols: participants with voluntary muscle activation above 90% at baseline.
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
Neural adaptations in **Rate of Force Development (RFD)**

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

![Graph showing rate of force development](image)

Maximal Explosive Muscle Strength

‘Rapid Force Capacity’

**Rate of Force Development (RFD)**

\[
RFD = \frac{\Delta \text{Force}}{\Delta \text{Time}}
\]

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
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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

Pre and post 14 wks of heavy-resistance strength training

Aagaard et al., J Appl Physiol 2002

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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**

/pre 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** ($\Delta EMG/\Delta t$)

Rate of EMG rise (RER) = $\Delta EMG/\Delta t = \text{slope}$

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

\[ \downarrow \]

Increased neuromuscular activity

\[ \downarrow \]

**Increased maximal Rate of Force Development (RFD)**

- Increased RFD and increased iEMG

- Increased RFD and elevated rate of EMG rise
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

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

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

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

Influence of explosive-type muscle actions during training

Training-induced changes in quadriceps RFD and EMG

Balshaw, Folland et al, J Appl Physiol 2016

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

**Graph**
- **Δ QUADS vol. (cm³)**
- **ECT**
- **SCT**
- **CON**

† SCT vs ECT (p<0.05)

*Balshaw, Folland et al, J Appl Physiol 2016*

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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.
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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