Changes in Muscle Morphology and Neuromuscular Capacity with Training

Implications for athletic performance, patient rehabilitation and aging individuals

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University of Southern Denmark

Strength Training - Muscular or Neural adaptation?
**Strength Training - Muscular or Neural adaptation?**

**Sometimes:** less focus on muscle adaptation (growth),
- more focus on neuromuscular adaptation

**But very often we wish to have BOTH!**
Effects of strength 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 strength training on...

- **Muscle size and structure**
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HUGE IMPLICATIONS FOR FUNCTIONAL PERFORMANCE!
Training-induced changes in anatomical muscle size

Effects of heavy-resistance strength training on muscle size and architecture

Heavy-resistance strength training

↓

Increases in...

- Anatomical muscle CSA and volume
  
  Higbie et al. 1996
  Narici et al. 1989, 1996
  Aagaard et al. 2001, Reeves 2003

- Physiological CSA of individual muscle fibres
  
  Hather et al. 1991
  Staron et al. 1994
  Aagaard et al. 2001
  Andersen & Aagaard 2000

- Muscle fibre pennation angle
  
  Kawakami et al. 1995
  Aagaard et al. 2001, Reeves et al. 2006
Muscle cross-sectional area (CSA)
Quadriceps muscle - Axial MRI (at 50% and 30% femur length)

Muscle cross-sectional area (CSA)
Quadriceps muscle - Axial MRI (at 30% femur length)
Pre and Post 14 wk heavy-resistance strength training
Changes in anatomical muscle CSA (MRI)
following 14 weeks of heavy-resistance strength training
- CSA obtained at 50% \(L_{\text{femur}}\)

Aagaard et al.
J. Physiol. 2001

Changes in anatomical muscle volume (MRI)
following 14 weeks of heavy-resistance strength training
- multiple axial CSA obtained at successive 0.1 \(L_{\text{femur}}\) steps

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 prolonged strength training


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


<table>
<thead>
<tr>
<th>Population</th>
<th>Training Duration (weeks)</th>
<th>ΔMVC (%)</th>
<th>ΔMVC/day (%)</th>
<th>ΔCSA (%)</th>
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<tbody>
<tr>
<td>Young adults</td>
<td>24</td>
<td>26.8</td>
<td>0.16</td>
<td>6.8</td>
<td>0.04</td>
<td>Häkkinen 1985</td>
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<td>0.18</td>
<td>19.0</td>
<td>0.11</td>
<td>Narici 1996</td>
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Percentage gain in muscle CSA and maximal muscle strength (MVC) induced by strength training

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<td>19.0</td>
<td>0.11</td>
<td>Ferri 2003</td>
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<tr>
<td>Elderly (65-81 yrs)</td>
<td>16</td>
<td>19.0</td>
<td>0.17</td>
<td>7.4</td>
<td>0.07</td>
<td>Frontera 1988</td>
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<tr>
<td>Elderly (60-72 yrs)</td>
<td>12</td>
<td>16.7</td>
<td>0.20</td>
<td>9.3</td>
<td>0.11</td>
<td>Häkkinen 1998</td>
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<td>Elderly (61 yrs)</td>
<td>10</td>
<td>17.0</td>
<td>0.25</td>
<td>9</td>
<td>0.12</td>
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<td>Elderly (85-97 yrs)</td>
<td>12</td>
<td>37</td>
<td>0.44</td>
<td>10</td>
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No or only minor increase in muscle size in response to low-resistance strength training

Mean CSA of all locations

Quadriceps Muscle Cross-sectional Area

Heavy: training loads 70% 1RM, Light: training loads 15% 1RM, 12 weeks, 36 sessions, isolated knee extension, matched for total work load

Holm, Aagaard et al, J Appl Physiol 2008
Effects of strength training on cellular muscle growth signaling

Exercise signals

IGF-1

PI3K

Akt

mTOR

IRS1

Intra cellular

Extracellular

MUSCLE CELL

P

P

p70S6K

↑ Protein synthesis

Changes in p70s6 kinase activation and myofibrillar protein synthesis rate with strength training

Holm et al, FASEB Exp Biol Meeting 2008
FASEB J 22, 963.2
Use of strength training to increase muscle mass and improve neuromuscular function in frail elderly post-operative patients

Use of strength training in the rehabilitation of elderly patients following hip replacement surgery [age 60-86 yrs]

Strength training (12 weeks)

- **Knee-extension**
- **Leg-press**

Wks 1-2: 3x10 (20 RM), Wks 3-4: 3x12 (15 RM), Wks 5-6: 4x10 (12 RM)

Wks 7-8: 5x8 (8 RM), Wks 9-10: 4x8 (8 RM), Wks 11-12: 3x8 (8 RM)

Suetta, Aagaard, Kjaer et al, J Appl Physiol 2004
Use of strength training in the rehabilitation of elderly patients following hip replacement surgery [age 60-86 yrs]

Changes in Muscle Cross Sectional Area (CT-scan)

Changes in Functional Performance (horizontal gait, sit-to-stand)

Suetta, Aagaard, Kjaer et al, JAGS 2004

Suetta, Aagaard, Kjaer et al, J Appl Physiol 2004
Training-induced changes in physiological muscle size (muscle fiber CSA)
**Muscle biopsy sampling**
- single muscle fibre size
- fibre types
- capillarization

**Changes in muscle fibre size (CSA)**
following 14 weeks of heavy-resistance strength training

<table>
<thead>
<tr>
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<th>type II fibres</th>
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<tr>
<td>pre</td>
<td></td>
<td></td>
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<tr>
<td>post</td>
<td></td>
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</table>

**Post training**
- **+19%**

**Post > pre training**
- **P < 0.001**

Aagaard et al.
J. Physiol. 2001
Increased single muscle fibre CSA in response to heavy-resistance strength training

Increased type I and type II muscle fibre CSA (15-25%)

Preferential or more pronounced increases in type II muscle fibre CSA

Changes in muscle fiber size with extreme training

Strength trained track and field athlete

Untrained age-matched young man

Unpublished data, Andersen, Aagaard, Suetta, Kjaer
Reductions in muscle fiber size with aging
Age-related loss in muscle mass (sarcopenia)

Young subject
Old subject

VL muscle
Jesper L. Andersen, CMRC

Reductions in muscle fiber size with aging
Age-related loss in muscle mass (sarcopenia)

60-yr old woman  80-yr old woman

Caserotti, Aagaard et al 2008

Parise & Yarasheski,
Curr Opin Clin Nutr Metab Care, 2000
Heavy-resistance strength training leads to muscle fiber hypertrophy in the very old

Age 89.2 yrs, range 85-97 (n=11), 12 weeks training, 3 t/week

Muscle strength and muscle mass can be markedly increased by strength training in elderly

80+ year old discharged geriatric patients
12 weeks of resistance exercise
tong ext. 3 x weekly, 3 x 8 rep, >70% 1 RM

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

* p < 0.05

Kryger & Andersen,
Training-induced changes in neural function

Contractile Rate of Force Development (RFD)

\[ \text{RFD} = \frac{\Delta \text{Force}}{\Delta \text{Time}} \]
Ground contact times…

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

Luhtanen & Komi 1979, Dapena & Chung 1988,
Zatsiorsky 1995, Kuitunen et al. 2002

Time to reach peak force production in human skeletal muscle…

300 - 500 msec

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

Maximal Explosive Muscle Strength

Rate of Force Development (RFD)
during maximal isometric muscle contraction

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

Aagaard et al.
J. Appl. Physiol. 2002
Pre and post 14 wks of heavy-resistance strength training

**RFD** Contractile Rate of Force Development
Assessed during maximal isometric quadriceps contraction

Pre training
Post training
MVC post 339 Nm
MVC pre 291 Nm

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

Aagaard et al., J. Appl. Physiol. 2002
Neuromuscular drive and explosive muscle strength
Maximal isometric quadriceps contraction, static knee extension

Aagaard et al., J. Appl. Physiol. 2002

Neuromuscular activity and ‘explosive’ muscle strength
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

Pre training
Post training
Neuromuscular activity and ‘explosive’ muscle strength
quadiceps 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

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Training induced changes in explosive muscle strength RFD

Heavy-resistance strength training

Increased neuromuscular activity
...within initial 200 msec of contraction

Increased maximal Rate of Force Development
Heavy-resistance strength training

Increased neuromuscular activity
...within initial 200 msec of contraction

**Increased maximal Rate of Force Development**

- Increased RFD and increased iEMG

- Increased RFD and elevated rate of EMG rise

**Functional consequences:**
- enhanced acceleration
- faster movements
- elevated muscle force and muscle power during fast movements
- reduced risk of falls
Increased maximal motorneuron firing rates following period of strength training

![Graph](image1)

Post > Pre, P < 0.001

Motor Unit firing rate (Hz)

Interspike intervals

I. II. III.

* * *

- data adapted from Van Cutsem et al., J Physiol 1998

Supramaximal motorneuron firing rates increases the maximal Rate of Force Development

![Graph](image2)

Muscle Force

10 N

Not affecting maximal force generation

Slim rate

400 Hz

200 Hz

120 Hz

80 Hz

De Haan, Exp Physiol 1998 (rat GM, in situ)
Supramaximal motorneuron firing rates increases the maximal Rate of Force Development

However, greatly affecting max Rate of Force Development

\[ \frac{\Delta \text{Force}}{\Delta \text{time}} \]

Strength training induce changes in maximal motorneuron firing frequency in young and old individuals

Strength training ↓

\[ \uparrow \text{motor neuron firing rate} \]
(at 100% MVC) in both young and old subjects

Kamen et al. 1998 (young, old), Patten et al. 1999 (young, old), 2001 (young)
Van Cutsen et al. 1998 (young), Kamen & Knight 2004 (young, old)
Christie & kamen 2010 (young, old)
Strength training induce changes in maximal motorneuron firing frequency in young and old individuals

**Strength training**

\[
\uparrow \quad \downarrow
\]

\[
\uparrow \text{motor neuron firing rate (at 100\% MVC) in both young and old subjects}
\]

Kamen et al. 1998 (young, old),
Patten et al. 1999 (young, old), 2001 (young)
Van Cutsem et al. 1998 (young), Kamen & Knight 2004 (young, old)
Christie & kamen 2010 (young, old)

Furthermore, after strength training maximal motor neuron firing rate did not differ between old and young subjects

Patten et al. 1999, Kamen & Knight 2004, Christie & Kamen 2010

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**RFD  Contractile Rate of Force Development**

Elderly subjects (60-86 years) - hip replacement patients (n=9)

pre and post 12 wks unilateral strength training - Affected Limb

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

Suetta, Aagaard et al.
J. Appl. Physiol. 2004
Heavy-resistance strength training

Concurrent increases in
maximal RFD and neuromuscular activity (iEMG)
also in elderly individuals

Häkkinen & Häkkinen 1995 (age 50, 70 yrs, gender F, M)
Häkkinen et al. 1998 (age 40, 60 yrs, gender F, M)
Häkkinen et al. 2001 (age 63 yrs, gender F)
Suetta et al. 2004 (post hip replacement surgery, 60-86 yrs)
Barry et al. 2005 (age 60-79 yrs, gender F+M)

Strength training in the elderly: enhanced explosive muscle strength (RFD) may result in improved functional performance
Strength training in the elderly: enhanced explosive muscle strength (RFD) may result in improved functional performance

Elderly subjects (60-86 years), hip replacement patients (n=9), 12 wks resistance training

Training-induced changes in maximum walking speed vs RFD

Suetta C, 5th International Conference on Strength Training, 2006
Training-induced changes in neural function:
Evoked spinal motorneuron responses (H reflex, V wave)

The H-reflex: electric stimulus is applied to Ia afferent axons
⇒ evoked efferent motoneuron response (H-reflex)

Aagaard et al., J Appl Physiol 92, 2002
Data acquisition and processing
Signal sampling: 10,000 Hz
Digitizer A/D-converter
Plantar flexor moment of force

Aagaard et al.
J Appl Physiol 92, 2002

The H-reflex
Hoffmann reflex

Increased H-reflex amplitude indicates altered spinal circuitry state:
- ↑ excitability of spinal motoneurons and/or
- ↓ presynaptic inhibition of Ia afferents
- ↓ postsynaptic inhibition of spinal motoneurons

Aagaard et al.
J Appl Physiol 92, 2002
Increased V-wave amplitude indicates:
- ↑ descending supraspinal motor drive
- ↑ spinal motoneuron excitability
- ↑ magnitude of efferent neural motor drive to muscle fibers
**Increased V-wave and H-reflex amplitudes recorded during maximal contraction (MVC)**

pre and post 14 wks of strength training

![Graph showing peak-to-peak amplitude normalized to M_max for V-wave and H-reflex.](image)

Soleus muscle
Aagaard et al, J. Appl. Physiol. 2002

* P < 0.05
** P < 0.01

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**V-wave responses in MS patients**

Increased V-wave amplitude observed following 3 wks (15 sessions) of heavy-resistance strength training

![Graph showing V/M_max for strength training group and control group.](image)

Fimland et al, J Neurophysiol 2009

Maximal plantarflexor strength

* Post > pre (P<0.05)
Training-induced changes in neural function

Heavy-resistance strength training

↓

Elevated V-wave and H-reflex responses in maximal and submaximal muscle contraction

Strength training may induce neural adaptation at both supraspinal and spinal levels:

- Increased descending motor drive from higher CNS centres
- Increased motoneuron excitability and/or decreased presynaptic inhibition of excitatory Ia afferents, decreased postsynaptic inhibition of motoneurons

Aagaard et al, JAP 2002
Duclay et al, MSSE 2008
Del Balso & Cafarelli, JAP 2007
Finland et al, EJAP JNP 2009
Sale et al, MSSE 1983

Resistance training ⇒ improved neuromuscular function

Enhanced descending motor drive from higher CNS centres

Brain
motor cortex
cerebellum

Nerve impulses ↑

Increased spinal motoneuron excitability

Spinal
cord
efferent
motor neurons

Muscle

Nerve impulses ↑

Resistance training ⇒ improved neuromuscular function

Enhanced descending motor drive from higher CNS centres

Increased spinal motoneuron excitability

↑ maximal muscle strength
↑ rapid force capacity
↑ maximal muscle power
↑ eccentric muscle strength

Nerve impulses ↑

Training induced changes in muscle stem cell activity

Satellite cells in human skeletal muscle

Satellite cells = dormant myogenic cells situated between the basal lamina and the muscle cell membrane

Vierck et al., Cell Biol. Int. 24, 2000

NCAM/D56 antibody staining haematoxylin counterstaining
We propose that the exercise-induced expansion of satellite cell pool is a powerful non-pharmacological tool that should be considered in preventive, therapeutic and rehabilitative strategies aiming to improve skeletal muscle function. Furthermore, we propose that the exercise-driven renewal of the satellite cell reserve pool in skeletal muscles is an important mechanism for the survival of stem cells.

Fig. Modified from MacKey et al, Scand J Med Sci Sports 2007

**EFFECTS OF AGING and STRENGTH TRAINING ON SATELLITE CELL ACTIVATION**

Satellite cell number before and after 12 wks resistance training
(13 males, 16 females, mean age 76 yrs)

Low-resistance strength training with partial blood-flow occlusion (BFR exercise)

NOS signaling and VGF factors in muscle hypertrophy: effects on muscle mechanical performance and size in young individuals, lower limb surgical patients and aging individuals

ACSM Annual Meeting, Denver June 2010

Rapid Increases in Myogenic Satellite Cells Expressing Pax-7 with Blood Flow Restricted Low-intensity Resistance Training

Janus L. Nielsen, Per Aspgaard, Rune D. Borch, Tobias Hjærslev, Mathias Vreimosen, Nita-Helle Bredberg, University of Southern Denmark, Odense, Denmark, Odense University Hospital, Odense, Denmark, and The Danish School of Sport Sciences, Odense, Denmark

Abstract

The adaptive mechanisms underlying the well-documented effect of low-intensity resistance exercise (LIRE) with blood flow restriction (BFR) to enhance muscle strength and muscle mass in humans are not fully understood. Although the influence of Klotho1/2 signaling and a stimulating effect on protein synthesis have been demonstrated, the potential role of myogenic satellite cell activity has not been examined. In the present study, BFR RE was hypothesized to activate myogenic satellite cells (SCs) expressing Pax-7. To examine the effect of short-term low-intensity RE with BFR on the activation of Pax-7 SCs in relation to muscle cell growth and myosin distribution. METH/DES. 15 young men (23 ± 2 yrs) completed 7 sessions of BFR with exercise restricted to a 10-second interval (20 cm height) using concentric/contraction exercises (100 crowing coughs; middle). Muscle biopsies were obtained (L) at baseline (time) and day 3 post 2 days training. SC expressing Pax-7, myosin density, and muscle fiber area were assessed by immunohistochemistry.

RESULTS: Type II and I fiber area increased with BFR training from 4591 ± 992.6 to 5767 ± 1041.4 µm², and from 4227 ± 796.1 to 4642 ± 709.5 µm² (p<0.02). SC and myosin counts did not differ between type I and II muscle fibers and all increased after BFR training (1:0.1 ± 0.02 of the control). Likewise, Pax-7 SC per muscle fiber increased 3.4 ± 0.5 (p=0.002) vs. 0.09 ± 0.01 of the control. Myosin number per muscle fiber increased (2.3 ± 0.2 to 3.9 ± 0.8) (p=0.02). Numerical data not change with training (1:0.1 ± 0.02 of the control). Taken muscle fiber CSA was similar to the Pax7 positive SC per muscle fiber area and post training (4:4 ± 0.2 (p=0.02). CONCLUSION: Five days of sessions of low-resistance training using BFR led to increased muscle fiber hypertrophy (+37 to +40%) that was accompanied by highly concentrated satellite cell activation and myosin accumulation. Further, Pax-7 SC number was positively related to myofiber size and post training. Thus the associated hypertrophy response with BFR at least in part seems to rely on an amplified myogenic satellite cell activation.
Rapid Increases in Myogenic Satellite Cells Expressing Pax-7 with Blood Flow Restricted Low-Intensity Resistance Training

Jacob L. Nielsen1, Per Aagaard1, Rune D. Bøth1, Tobias Rypdal2, Mathias Werber2

1Sports Science Institute, 2University of Southern Denmark, Odense, Denmark

Number of Pax7 positive satellite cells per muscle fiber

<table>
<thead>
<tr>
<th></th>
<th>PRE</th>
<th>DAY 8</th>
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<tr>
<td></td>
<td>0.101 ± 0.027</td>
<td>0.383 ± 0.066</td>
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Ulrik Frandsen, IOB-SDU, 2009

Muscle Fiber Area

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ACSM Annual Meeting, Denver June 2010
Rapid Increases in Myogenic Satellite Cells Expressing Pax-7 with Blood Flow Restricted Low-Intensity Resistance Training

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Muscle Fiber Area

Potentially allows accelerated rehabilitation following ACL reconstruction

Similarly allows accelerated rehabilitation in non-reconstructed ACL injured subjects
SUMMARY
Adaptive changes in muscle morphology induced by strength training

- increase in anatomical muscle cross-sectional area and volume (MRI, CT)
- increase in physiological muscle fibre area (muscle biopsy sampling)
  McDonagh & Davies 1984, Aagaard 2001
- increase in % IIA muscle fibres
- decrease in % IIX muscle fibres
  (increase in % IIX muscle fibres)
  Andersen 1994, Andersen & Aagaard 2000; strength training → detraining
- changes in muscle architecture: ↑ muscle fibre pennation angle
- ↑ CSA, ↑ tendon stiffness, ↓ tendon strain, ↑ type I collagen synthesis

SUMMARY
Neuromuscular adaptation with strength training

- ↑ Neuromuscular activity in muscle fibres during MVC (↑ iEMG)
- ↑ Rate of EMG rise (RER) ⇒ ↑ Rate of Force development (RFD)
- ↓ Motoneuron inhibition during eccentric contraction ⇒ ↑ ECC strength
  Aagaard et al 2000, Andersen et al 2005
- Increased excitability of spinal motoneurons (↑ H-reflex, V-wave)
- Increased cortico-spinal excitability (↑ MEP evoked by TMS)
  Orms & Cafarelli 2007
- ↑ Maximal motoneuron firing frequency
- Motoneuron firing: ↑ incidence of discharge ‘doublets’ ⇒ ↑ RFD
  Van Cutsem et al 1998
- More synchronized activation of synergist muscle pairs
  Montani 1993
Strength training leads to significant changes in muscle size & structure and neuromuscular capacity …in turn leading to huge functional benefits

Acknowledgements

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Lars Hvid  Henning Langberg
Niels Ørtenblad  Mads Kongsgaard
Philip Hansen  Christian Couppé