The architectural determinants of skeletal muscle function, and how they can be used to optimize our rehabilitation protocols

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Marjorie A. King Research to Reality Presentation
January 10, 2016

http://www.mc.uky.edu/muscle/
Return to Play?

Clinical Translational

“bench to bedside”

1. See a problem clinically
2. Delve into the literature
3. Design a model
4. Translate to human
Muscle Strain Injury

- Account for 70% of cases in sports med Garrett, 1990

- During a 16 year period collegiate athletes suffered 21,784 muscle-tendon strains of the lower extremity (LE) Agel et al., 2007

- Re-injury rates: AFL 34% Brockett et al., 2004

- After 1 year of return to sports, re-injury rate was 70% Sherry and Best, 2004
Cyclists vs Runners

Adapted from Herzog et al., MSSE 1991
Chicken or Egg?

Athletes select sports that fit their muscle function

OR

Muscle can adapt to performance demands of the sport
When you hear ‘muscle’ think sarcomere

Purves et al., Life: The Science of Biology, 4th Edition
Sarcomere structure

Alternating light/dark bands

**Dark:**

A band – myosin containing force producing cross bridges

**Light**

I band - actin only

**Z-disk** – anchor for actin
Sarcomere structure

Arranged in parallel

Arranged in series

Sarcomere number is predictive of function
Architectural Parameters

Physiologic Cross-Sectional Area (PCSA)
  - Isometric force generation
Advantages?

• Parallel Sarcomere Number
  – Influences PCSA
    • Increased isometric force

$$\text{PCSA} \approx F_i$$
Architectural Parameters

Physiologic Cross-Sectional Area (PCSA)
- force generation

FL/ML ratio
- fibre velocity
- fibre extensibility
Advantages?

- Serial Sarcomere Number
  - Dynamic
  - Contractile velocity (concentric)

\[ L_F \approx V \]
Advantages?

• Serial Sarcomere Number
  – Dynamic
    • Contractile velocity
  – Static
    • Flatter appearance of Force-Length Relationship (FLR)
    • Increased extensibility (eccentric)
The FLR

Force [Normalized] vs. Sarcomere Length [µm]

- **Plateau**
- **Ascending**
- **Descending**

Sarcomere Lengths:
- 1.27 µm
- 2.00 µm
- 2.25 µm
- 3.65 µm
Example:

Muscle:

Sarcomere number: 5000

Optimal length for sarcomere force production: 2.0µm (2×10^{-6} m)

At what length does the muscle produce optimal force?

10 mm
Muscle:

Sarcomere number: 5000

Optimal length for sarcomere force production: 2.0µm (2x10^{-6}m)

At what length does the muscle produce optimal force?

What if you add 1000 sarcomeres in series?

12mm
Muscle fibre architecture

• Fibre arrangement within muscle is a major determinant of
  1. functional properties
  2. contractile properties

Fibre arrangement is the greatest determinant of muscle function!
Muscle Architecture

- **tendon**
- **aponeurosis**

Diagram showing different types of muscle architecture:
- Parallel
- Unipennate
- Bipennate
- Unipennate with non-uniform fibre lengths
- Multipennate
Based on architecture, what is the major (primary) function of each muscle? velocity or force?
Muscle Architecture

In general,

Hamstrings & dorsiflexors:
- high FL/ML ratio
- low PCSA

Functionally designed for:
- high excursions
- high velocities

Quads & plantarflexors:
- low FL/ML ratio
- high PCSA

Functionally designed for:
- force production
Can we influence these properties?

Tabary et al. 1976

High correlation between joint angle and sarcomere number

Passive stretch = increased serial sarcomere number

McComas, 1996
Williams et al., 1986

4 days immobilization and stimulation

11% increase in length (~2000 sarcomeres in series)
What happens during immobilization?

Alteration of muscle architecture = atrophy

1. Loss of sarcomeres in series
2. Loss of sarcomeres in parallel
Exercise Effect on Sarcomere Number

- Force [Normalized]
- Muscle Length [Normalized]

- Plateau
- Ascending
- Descending
FLR Post Chronic Exercise (short)

Tibiotarsal Joint Angle [degrees]
Joint Moment [Nm]

$R^2 = 0.98$

$R^2 = 0.99$

$2.3 \pm 1.7^\circ$
FLR post chronic exercise (long)

R² = 0.99

9.6 ± 1.9°
Increase in Isometric Torque

Tibiotarsal Joint Angle [degrees]

% Increase in Joint Torque

Butterfield and Herzog *Pflugers Archiv*, 2006
Summary of Results

• Muscle sarcomere number adapts to eccentric exercise rapidly

• We can influence the magnitude of the adaptation by altering working range
Butterfield et al., *J Appl Physiol*, 2005
Butterfield et al., *J Appl Physiol*, 2005
Vastus Intermedius

Butterfield et al., *J Appl Physiol*, 2005
Vastus Lateralis

Butterfield et al., *J Appl Physiol*, 2005
Summary of Results

• Muscle responds to exercise by altering sarcomere number
  – Exercise specific
  – Optimizes function for demands
  – Greater starting length during eccentric results in greater sarcomere number addition
So what?

Clinical Translation - Strength

LeStayo et al., Clin Orthop Rel Res 2009
Table 2. Mean (± standard deviation [SD]) and probability values for muscle size, strength, and mobility outcomes for the eccentric and traditional resistance exercise groups.

<table>
<thead>
<tr>
<th></th>
<th>Eccentric</th>
<th>Traditional</th>
<th>Interaction Group x time F score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre Mean (SD)</td>
<td>Post Mean (SD)</td>
<td></td>
</tr>
<tr>
<td>Quadriceps volume (cm³)</td>
<td>979.4 (255)</td>
<td>1091.4 (270)</td>
<td>8.85</td>
</tr>
<tr>
<td></td>
<td>*p &lt; 0.001</td>
<td></td>
<td>1074.5 (374)</td>
</tr>
<tr>
<td>Knee extension strength (N/m)</td>
<td>102.3 (32)</td>
<td>117.2 (31)</td>
<td>3.37</td>
</tr>
<tr>
<td></td>
<td>*p = 0.005</td>
<td>(p = 0.08)</td>
<td>113.3 (42)</td>
</tr>
<tr>
<td>Timed up and go (s)</td>
<td>8.5 (2.7)</td>
<td>6.6 (1.1)</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>*p = 0.01</td>
<td>(p = 0.27)</td>
<td>7.7 (1.7)</td>
</tr>
<tr>
<td>Six-minute walk (m)</td>
<td>525.3 (117)</td>
<td>575.9 (95)</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>*p = 0.048</td>
<td>(p = 0.88)</td>
<td>523.2 (142)</td>
</tr>
<tr>
<td>Stair ascent (s)</td>
<td>7.4 (1.8)</td>
<td>5.6 (1.0)</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>*p = 0.001</td>
<td>(p = 0.26)</td>
<td>7.8 (3.8)</td>
</tr>
<tr>
<td>Stair descent (s)</td>
<td>6.4 (2.0)</td>
<td>4.9 (1.0)</td>
<td>4.76</td>
</tr>
<tr>
<td></td>
<td>*p = 0.001</td>
<td>(p = 0.047)</td>
<td>7.0 (4.0)</td>
</tr>
</tbody>
</table>

* Significant within group pre- to posttraining changes; †significant between group pre- to posttraining changes.
Clinical Translation - CAR

L Lepley et al., 2015 Knee
## Quadriceps central activation ratio (CAR [mean (SD)])

<table>
<thead>
<tr>
<th>Group</th>
<th>Pre-operative</th>
<th>12-Weeks</th>
<th>RTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>N&amp;E (n = 8)</td>
<td>95.7(3.5)</td>
<td>94.8(4.2)</td>
<td>97.6(2.8)</td>
</tr>
<tr>
<td>N-only (n = 10)</td>
<td>97.4(3.0)</td>
<td>91.4(8.4)</td>
<td>91.8(4.6)</td>
</tr>
<tr>
<td>E-only (n = 8)</td>
<td>95.9(4.5)</td>
<td>95.0(3.8)</td>
<td>98.1(1.2)</td>
</tr>
<tr>
<td>STND (n = 10)</td>
<td>94.9 ± (5.3)</td>
<td>91.7(6.4)</td>
<td>91.8(9.0)</td>
</tr>
<tr>
<td>Healthy (n = 10)</td>
<td>–</td>
<td>–</td>
<td>96.6(2.8)</td>
</tr>
</tbody>
</table>

Abbreviation: CAR, central activation ratio

* P < 0.05, compared to N-only and STND for Pre-to-RTP.
† P = 0.04, compared to STND for Pre-to-RTP.
‡ P < 0.05, compared to N-only.
Clinical Translation

• Length dependence and exercise specific adaptations
  – Be aware of muscle architecture and function
    • Quads vs hamstrings
    • Be aware of demands of sport
Eccentric exercise

1. Follow guidelines for any strength and conditioning program with respect to progression
Eccentric exercise

1. Follow guidelines for any strength and conditioning program with respect to progression

2. Keep in mind, that peak eccentric force can be up to 2x peak isometric force!
   I. Must take injury into consideration
   II. Standing unloaded eccentric
Eccentric exercise

3. Progressively increase the length at which eccentric exercises are applied

\begin{itemize}
  \item e.g. Hamstrings:
    \begin{itemize}
      \item Can start with “hamstring lowers”
    \end{itemize}
\end{itemize}
Eccentric exercise

3. Progressively increase the length at which eccentric exercises are applied

e.g. Hamstrings:
   a. Can start with “hamstring lowers”
   b. prone knee extensions
      a. Short length to long
   c. Progress to sitting knee extensions
      a. Short length to long
Eccentric exercise

4. Progress from slow speeds to high speeds

a) Keep the F-V property in mind.

Very slow velocity = less tension

Moderate to high velocities have little influence on tension!
Take Home Message

- We can influence muscle architecture, and thus alter function.
- Be aware of inherent function of the muscle:
  - Force vs excursion
  - Eccentric vs concentric
  - Hamstrings should always be exercised eccentrically
- Apply exercise prescription to optimize these parameters
- Pay specific attention to two joint muscles during rehab.
Thank you!