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The authors do not have any real or perceived conflicts of interest that relate to this presentation.
Dynamic Limitations: The role of muscle mechanics on protracted quadriceps dysfunction

Steven Davi MS, ATC
Consequences of ACL Injury

- Nearly 300,000 ACL Injuries occur annually
- Upwards of $3 Billion spent on treatment and rehabilitation

Quadriceps Weakness

Post-Traumatic Osteoarthritis

Increasingly common source of disability in young athletes

Nearly 50% may develop PTOA within 10-20 years of injury
Importance of the Quadriceps

• Adequate quadriceps strength is necessary to function as a shock absorber

• Quadriceps dysfunction is associated with poor long-term outcomes
Quadriceps Dysfunction

How effective is the body at initiating contraction?
Nervous System
• Altered signaling from brain and spinal cord
• Changes in active areas of the brain

Volitional muscle activation
• Disrupted after ACL injury
• Results in protracted weakness
Quadriceps Dysfunction

How effective is the body at initiating contraction?

Is the muscle well-constructed for generating force?
What is Muscle Morphology?

- **Fiber Length**
  - Number of sarcomeres in series
  - Longer fiber = higher contraction velocity

- **Pennation Angle ($\theta$)**
  - Fiber orientation between deep and superficial aponeurosis
  - Increased angle associated with larger muscle volume

- **Cross-Sectional Area**
  - Snapshot of muscle volume
  - Larger area results in greater force production

**Morphology Diagram**

- **Superficial Aponeurosis**
- **Deep Aponeurosis**
- **Fiber Length**
- **CSA**
- **$\theta$**
Previous work on Morphology

1. Muscle Volume
   • Atrophy post-injury

2. Fiber Type
   • Transition to slower fiber types

3. Fiber size
   • Reductions in CSA

4. Animal models

Type 2a (green)
Type 2b (red)
Type 2x (black)
Quadriceps Dysfunction

- Neurologic Function
- Muscle Morphology
Where’s the gap?
Dynamic Assessment
- EMG
- Spinal-reflexive excitability
- Corticospinal excitability
- Volitional activation

Static Assessment
- MRI
- CT scans
- Ultrasound
- Tissue analysis

Neurologic Function

Dynamic Quadriceps Function

Muscle Morphology
Static vs. Dynamic

Muscle morphology must adapt during contraction

• PROs
• Strength
Dynamic Morphology

**Ultrasound**
- Affixed over the vastus lateralis using a custom 3D printed device

**Isokinetic knee extension**

**Capture Parameters Example**
- Initiation of contraction (>10Nm)
- Peak torque production
No difference at rest

Static Morphology

- Resting Length (mm)
- Resting Angle (degrees)

- Surgical
- Contralateral
- Control Right
- Control Left

No difference at rest
Dynamic deficits revealed

Dynamic Fascicle Function

- Length Excursion (mm)
- Angle Excursion (degrees)

- Surgical
- Contralateral
- Control Right
- Control Left

* statistically significant difference
What does this mean?

• Static morphology similar between groups

• Muscle “adaptation” likely component of function

• Illustrates importance of dynamic assessment

Next Step: Assess during a more “clinical” task
The Good Stuff
Research Objectives

- **Overall objective:** expand our understanding of the underlying mechanical causes behind protracted quadriceps dysfunction after ACLR

- **Rationale:** rehabilitation programs fail to adequately restore quadriceps function after ACLR. Understanding the complex mechanical factors that influence quadriceps function is critical for development of novel rehabilitation techniques that can aid in the prevention of long-term health ramifications.

- **Long-term goal:** provide clinicians with targetable outcomes to improve long-term health after ACLR
Central Hypothesis

History of ACLR is associated with altered quadriceps morphology, which impede quadriceps function, alter joint loading patterns, and are detrimental to PROs.
Research Aim #1

Aim 1: Test the hypothesis that a history of ACLR is associated with altered quadriceps morphology

Hypothesis 1.1: History of ACLR is indicative of less muscle adaptability
Research Aim #2

Aim 2: Test the hypothesis that alterations in quadriceps morphology influences loading patterns after ACLR

Hypothesis 2.1: Reductions in quadriceps adaptability after ACLR is associated with maladaptive loading patterns
Main Outcome Measures

- Patient Reported Outcomes (PROs)
- Fiber Dynamics
- Ground Reaction Force
Study Design

Inclusion Criteria

• Age 13-35
• First-time unilateral ACLR tear
• No previous lower extremity surgery
• No current lower extremity injury besides ACL tear
• Cleared by physician for full activity

PROs

5min Warmup
Self – Selected Pace
3 x 5 gait cycles
Methods

- **Equipment:**
  - Split-belt instrumented treadmill (1200Hz; Bertec Corp., Columbus, Ohio)
  - 6cm linear ultrasound transducer (150fps; ArtUs, Telemed, Vilnius, Lithuania)

- Transducer secured over the vastus lateralis at 50% thigh length and aligned with fiber orientation

- Quadriceps morphology analyzed from heel strike (vGRF > 10 N) to peak vGRF during each stance phase (Pro-suite, Dartfish USA, Alpharetta, GA)

- Geometric extrapolation of fiber length will be used when the entire fiber is not visible
Method for extrapolated length estimation described by Earp et al. 2014.

\[
\text{Extrapolated Fiber Length} = \frac{\text{Height}}{\sin(\theta)}
\]

\[
\text{Total Fiber Length} = \text{Visible FL} + \text{Extrapolated FL}
\]
Data Analysis

- Group differences: Independent t-tests
- Pearson Product Moment Correlations
- Hierarchical Multiple Linear Regression
- $\alpha = 0.05$

Fiber Dynamics

Patient Reported Outcomes (PROs)

Ground Reaction Force

Ground Reaction Force
Results
## Participants

<table>
<thead>
<tr>
<th></th>
<th>ACLR (n=10)</th>
<th>Healthy Controls (n=5)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong> (years)</td>
<td>24 ± 2</td>
<td>24 ± 2</td>
<td>P = 0.935</td>
</tr>
<tr>
<td><strong>Height</strong> (m)</td>
<td>1.72 ± 0.15</td>
<td>1.72 ± 0.18</td>
<td>P = 0.989</td>
</tr>
<tr>
<td><strong>Mass</strong> (kg)</td>
<td>70.49 ± 17.52</td>
<td>70.31 ± 21.31</td>
<td>P = 0.852</td>
</tr>
<tr>
<td><strong>Sex</strong> (m/f)</td>
<td>4m / 6f</td>
<td>2m / 3f</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Time from Surgery</strong> (years)</td>
<td>5 ± 3</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td><strong>Graft Type</strong> (PT/STG)</td>
<td>5 PT / 4 STG</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>IKDC Score</strong></td>
<td>79.08 ± 13.19</td>
<td>99.77 ± 0.51</td>
<td>P = 0.001</td>
</tr>
<tr>
<td><strong>Walking Speed</strong> (m/s)</td>
<td>1.08 ± 0.21</td>
<td>1.10 ± 0.12</td>
<td>P = 0.852</td>
</tr>
</tbody>
</table>

Abbreviations: Anterior cruciate ligament reconstruction (ACLR); International Knee Documentation Committee (IKDC); Patellar Tendon Graft (PT); Semitendinosus Graft (STG)
Morphology Recap

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Morphology Recap

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• ACLR group displayed less excursion compared to control group
• May indicate lack of adaptability during loading
• Similar to previous data
• Longer fascicle length associated with lower peak vertical ground reaction force (vGRF)

• Fascicles function eccentrically to help deaccelerate the body during weight acceptance

• Potentially: reduced lengthening results in less shock absorption

ACLR: Fascicle Length at pVGRF

\[ r = -0.693 \]
\[ P = 0.018 \]
Walking speed vs. loading

**ACLR: Self-Selected Pace vs. pVGRF**

- Faster walking speed associated with higher vGRF
- Traditional relationship
- Ex: walking vs. running
## Regression: Loading Factors

<table>
<thead>
<tr>
<th>Group</th>
<th>Variable</th>
<th>$r^2$</th>
<th>$\Delta r^2$</th>
<th>ANOVA</th>
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</thead>
<tbody>
<tr>
<td>ACLR</td>
<td>Walking Speed</td>
<td>0.641</td>
<td>0.641; $P = 0.005$</td>
<td>$P = 0.005$</td>
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<tr>
<td></td>
<td>Walking Speed + Fascicle Length</td>
<td>0.830</td>
<td>0.189; $P = 0.027$</td>
<td>$P = 0.002$</td>
</tr>
</tbody>
</table>

- Walking speed and fascicle length predict 83% of the variance in pVGRF
- Novel quadriceps assessments can help better understand loading after ACLR
Matched Group Results
## Participants

<table>
<thead>
<tr>
<th></th>
<th>ACLR (n=5)</th>
<th>Healthy Controls (n=5)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong> (years)</td>
<td>25 ± 2</td>
<td>24 ± 2</td>
<td>P = 0.503</td>
</tr>
<tr>
<td><strong>Height</strong> (m)</td>
<td>1.74 ± 0.17</td>
<td>1.72 ± 0.18</td>
<td>P = 0.860</td>
</tr>
<tr>
<td><strong>Mass</strong> (kg)</td>
<td>73.12 ± 23.36</td>
<td>70.31 ± 21.31</td>
<td></td>
</tr>
<tr>
<td><strong>Sex</strong> (m/f)</td>
<td>2m / 3f</td>
<td>2m / 3f</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Time from Surgery</strong> (years)</td>
<td>7 ± 3</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td><strong>Graft Type</strong> (PT/STG)</td>
<td>2 PT / 3 STG</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>IKDC Score</strong></td>
<td>77.01 ± 9.99</td>
<td>99.77 ± 0.51</td>
<td>P = 0.001</td>
</tr>
<tr>
<td><strong>Walking Speed</strong> (m/s)</td>
<td>1.06 ± 0.30</td>
<td>1.10 ± 0.12</td>
<td>P = 0.788</td>
</tr>
</tbody>
</table>

**Significance**

- P = 0.503
- P = 0.860
- P = 0.847
- N/A
- P = 0.001
- P = 0.788

**Abbreviations:** Anterior cruciate ligament reconstruction (ACLR); International Knee Documentation Committee (IKDC); Patellar Tendon Graft (PT); Semitendinosus Graft (STG)
Walking: Fiber Dynamics

Dynamic Fascicle Function: Matched Groups

Fascicle Length Excursion

- **ACLR**
- Healthy Control

Pennation Angle Excursion

- ACLR
- Healthy Control

![Graph showing Fascicle Length Excursion and Pennation Angle Excursion for matched groups.](image)
Discussion
Why walking?

Walking is harder than it looks

Injuries only make it worse
Why walking?

And sometimes the rehabilitation path isn’t clear
Why walking?

• Activity of daily living

• Previous work: Cartilage turnover vs. loading
  – Over vs. under loading

• Our work extends this by providing potential target for walking alterations
Sources of dysfunction

• Protein alterations
  – Loss of fiber force capacity
  – Fiber type transition
  – Atrophy

• Changes in muscle metabolism
Skeletal Mitochondria

Dysfunction → O₂ Free Radical → Synthesis, Proteolysis
Metabolic Disruption

* Significant difference from control group, $P < 0.05$
Translation: What can you do?

How can individuals be identified?

- Open a motion capture lab?
- Buy an ultrasound system?
Walking Program
Matched Patient Reported Outcomes

IKDC Score

- Match 1
- Match 2
- Match 3
- Match 4
- Match 5

ACLRL
Healthy Control

80
Clinical Importance

• Muscle “adaptation” key component of function

• Illustrates importance of dynamic assessment

• Continue to build in dynamic assessments

• Long-term follow up critical
Recap

1. Quadriceps function is disrupted following ACL injury, leading to poor long-term physical and patient reported outcomes

2. Muscle morphology is a key component of quadriceps function, but has traditionally only been assessed at rest

3. Dynamic morphologic adaptability is altered during both clinical strength and gait assessments

4. Assessment of quadriceps morphology during key physiologic events, such as pVGRF, provides a novel insight of the relationship between muscle function and joint loading patterns
Thank You

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