Evaluation
Mechanized clothing reduced lumbar loading

First Study: Relevant to Reducing Overuse Injury Risk

Lamers et al. 2018. IEEE TNSRE
Question 1: Can mechanized clothing reduce muscle fatigue?
Question 1: Can mechanized clothing reduce muscle fatigue?

Second Study: Relevant to Endurance, Productivity & Retention

- 90 seconds
- 16 kg
- 15 minute break

N=6
Second Study: Relevant to Endurance, Productivity & Retention

Question 2: Are changes in fatigue consistent across muscles & users?

\[ N = 6 \]

16 kg
Question 2: Are changes in fatigue consistent across muscles & users?

- Left Longissimus Thoracis (LLT)
- Left Iliocostalis Lumborum (LIL)
- Left Lumbar Multifidus (LLM)

Second Study: Relevant to Endurance, Productivity & Retention

N=6

16 kg
Quantifying Fatigue Rate

Median frequency provides objective indicator of muscle fatigue

Farina et al. 2003, Merletti et al. 1990
Quantifying Fatigue Rate

Median frequency provides objective indicator of muscle fatigue

Farina et al. 2003, Merletti et al. 1990
Median frequency provides objective indicator of muscle fatigue

Farina et al. 2003, Merletti et al. 1990
Quantifying Fatigue Rate

Slope of median frequency vs. time = muscle fatigue rate
Quantifying Fatigue Rate

Slope of median frequency vs. time = muscle fatigue rate
Quantifying Fatigue Rate

Slope of median frequency vs. time = muscle fatigue rate

Normalized Median Frequency

Without Exo

N=1

time (s)
Quantifying Fatigue Rate

Less steep slope = slower rate of muscle fatigue
Quantifying Fatigue Rate

Key outcome metrics: % change in slope with vs. without exo

![Graph showing normalized median frequency over time with and without exo](image)

- % change in slope
- Analysis of covariance

\( N=1 \)
Q1: Can mechanized clothing reduce muscle fatigue?

Fatigue rate increased when wearing exo

Fatigue rate decreased when wearing exo

Lamers et al. In Review
Q1: Can mechanized clothing reduce muscle fatigue? **YES!**

<table>
<thead>
<tr>
<th>Fatigue rate increased when wearing exo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue rate decreased when wearing exo</td>
</tr>
</tbody>
</table>

Lamers et al. In Review
**Q1: Can mechanized clothing reduce muscle fatigue? YES!**

<table>
<thead>
<tr>
<th></th>
<th>Fatigue rate increased when wearing exo</th>
<th>Fatigue rate decreased when wearing exo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>![Image 1]</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>![Image 5]</td>
<td></td>
</tr>
</tbody>
</table>

Results

Fatigue rate decreased when wearing exo

Fatigue rate increased when wearing exo

Lamers et al. In Review
Q1: Can mechanized clothing reduce muscle fatigue? **YES!**

**Results**

Fatigue rate decreased when wearing exo

Fatigue rate increased when wearing exo

Lamers et al. In Review
Q1: Can mechanized clothing reduce muscle fatigue? **YES!**

**Results**

Fatigue rate decreased when wearing exo

Fatigue rate increased when wearing exo

Lamers et al. In Review
Q2: Are changes consistent across muscles & users? **NO!**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Muscles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 muscle*</td>
</tr>
<tr>
<td>2</td>
<td>2-4 muscles</td>
</tr>
<tr>
<td>3</td>
<td>2-4 muscles</td>
</tr>
<tr>
<td>4</td>
<td>5-6 muscles</td>
</tr>
</tbody>
</table>

Lamers et al. In Review
For exo evaluation standards which muscles should we test?

Key Implications

Lamers et al. In Review
Key Implications

Pros & cons to group-level (inter-subject mean) results

$N=6$

LIL

MDF slope (% initial MDF/s)

Lamers et al. In Review
Key Implications

Pros & cons to group-level (inter-subject mean) results

N=6

Lamers et al. In Review
Measuring muscle fatigue (especially back) can be very difficult.
Measuring muscle fatigue (especially back) can be very difficult
Key Implications

Unexpected adaptations: latissimus dorsi

latissimus dorsi

six lumbar muscle average

latissimus dorsi average

Lamers et al. In Review
Unexpected adaptations: latissimus dorsi kicked into high gear

Lamers et al. In Review
To improve fit & comfort for males & females, different sizes
What’s Next? Confirming Compatibility

To fit comfortably under uniforms
What’s Next? Industry Field Tests

Logistics, Manufacturing, Retail, Nursing, Construction, Military
What’s Next? Industry Field Tests

Working with industry partners to design tests (spring/summer 2019)

Observe

Pilot A

Refine

Pilot B
What's Next? Integrate Sensing & Machine Learning

Human-in-the-loop optimization of assistive stiffness
Ankle assistance

Yandell, Tacca & Zelik 2019 IEEE TNSRE
Reduced calf muscle activity during walking

\( N = 1 \)
\( 1.25 \text{ m/s} \)

\(~17\%\) reduction in average EMG over stride

Yandell, Tacca & Zelik 2019 IEEE TNSRE
Mechanized Clothing

Ankle assistance
Conclusions & key takeaways

Science
- small reductions in tissue load = big reductions in tissue damage

Design
- clutchable springs enable full range-of-motion + assistance on demand

Evaluation
- spring-powered exosuits can reduce muscle loading & fatigue
- inter-subject & inter-muscle variability: challenges for evaluation standards
  (for all exoskeletons)
One Problem...

“Where is my supersuit?!?!” - Frozone
Acknowledgements: Vanderbilt University & NIH
Why lumbar forces are primarily from muscles → lever system
Head
Arms
Trunk
(0.5 BW)

BW = body weight (e.g., 0.5 BW = 50% of body weight)
Head
Arms
Trunk
(0.5 BW)

Weight of Carried Load
(0.1 BW)

50 cm

BW = body weight (e.g., 0.5 BW = 50% of body weight)
Muscle Force = 0.1 BW * 50 cm / 5 cm = 1 BW
(provides torque to prevent tipping over due to carried load)
Head
Arms
Trunk
(0.5 BW)

Weight of Carried Load
(0.1 BW)

Muscle Force (1 BW)

Non-Intuitive Insight
spine force (1.6 BW) is mostly from muscles (1 BW)
Muscle Force (1 BW)

Head
Arms
Trunk
(0.5 BW)

Weight of Carried Load
(0.1 BW)

L5
Muscle Force (0.5 BW)

Device Force (0.25 BW)

Take-away from this example:
Muscle force reduced by 50%
Spine force reduced by 15%
Karl Zelik
Assistant Professor, Vanderbilt University
Department of Mechanical Engineering
Department of Biomedical Engineering
Department of Physical Medicine & Rehabilitation
Research Center: engineering.vanderbilt.edu/create
Research Lab: my.vanderbilt.edu/batlab
Email: karl.zelik@vanderbilt.edu
Twitter: @KarlZelik