Lab-based Assessments of Occupational Exoskeleton Technologies for Overhead Work and Lifting

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The current exoskeleton landscape

What are the potential benefits/limitations of different industrial exoskeleton technologies?

Opportunity:
physical demands; performance

Risks:
load transfer; safety

Challenges:
no practical guidelines; limited evidence
What is the current evidence?

- Extensive existing research for applications in healthcare and rehabilitation, and in the military
- Many prototypes, and increasing numbers of commercial devices
- Limited occupationally-relevant reports

Some research highlights for passive devices

- **Personal Lift Augmentation Device (PLAD) (low-back support)**
  - Reduced low-back demands and muscle fatigue during lifting\(^1,2\)
  - Well received in automotive assembly; shoulder (10%) and knee (40%) discomfort\(^3\)

- **Levitate AirFrame™ (upper-extremity support)**
  - Decreased muscle activity in field trials; decreased fatigue and pain in surgery\(^4,5\)

- **Laevo™ (low-back support)**
  - Less low-back muscle activity and discomfort, increased endurance, in prolonged forward-bending work\(^6\)
  - Adoption of “over-extended” knee postures evident

- **Vest + articulated arm (tool support)**
  - Simulated tool use; increased muscle activity and compressive spine loads\(^7\)

A summary of recent research at VT

- Lab-based studies of different exoskeleton technologies
- Applications to different occupational task demands
- Diverse outcome measures for evaluation

Many available solutions

<table>
<thead>
<tr>
<th>Energy Source(s)</th>
<th>Body Part(s)</th>
<th>Task(s)</th>
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</thead>
<tbody>
<tr>
<td>Active</td>
<td>Upper body</td>
<td>Lifting</td>
</tr>
<tr>
<td>Passive</td>
<td>Back</td>
<td>Carrying</td>
</tr>
<tr>
<td>Mixed</td>
<td>Lower body</td>
<td>Overhead</td>
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<td>Whole body</td>
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\(^1\) Abdoli-E et al. 2006; \(^2\) Lotz et al. 2009; \(^3\) Graham et al. 2009; \(^4\) Abdoli-E & Stevenson, 2008; \(^5\) Gillette and Stephenson 2017; \(^6\) Lu et al. 2018; \(^7\) Bosch et al. 2018; \(^8\) Weston et al. 2018
Why overhead work?

- Tasks requiring prolonged and/or repetitive arm elevation are prevalent
- Can be difficult to “design out”
- Associated with increased risk of shoulder WMSDs

Lab Study 1: Is a wearable assistive device feasible for overhead work?
Rashedi et al. (2014) Ergonomics

- Shoulder loads
- Discomfort
- Load Path

Lab Study 1: Simulated intermittent overhead work task

Lab Study 1: Major Results

- Reduced demands on the upper extremity, particularly with heavier tools (> 3 kg)
- Consistency in ratings of discomfort and muscle activation (surface EMG)
- Increased low-back demands; smaller relative to upper extremity
Develop and apply several (lab-based) testing/evaluation methods

**Expected or Anticipated Benefits**
- Reduced exertion (muscle activity)
- Less discomfort or fatigue
- Same or enhanced task performance

**Unexpected or Unanticipated Effects**
- Thermal discomfort, chafing, hygiene
- Donning/doffing
- Range-of-motion
- Balance
- Slip or trip risks
- Load transfer

**Lab Study 2: Assessing a prototype upper-extremity exoskeleton during simulated tasks involving arm elevation**
Kim et al. *Applied Ergonomics (2018a&b)*

Complete simulated tasks, working as quickly & accurately as possible

**Lab Study 2: Major Results regarding “expected” benefits**

- Perceived discomfort largely unchanged (decreased at forearm)
- Some decreases in muscle activity (up to 45%)
- Faster performance (20% overall); but increased errors in some conditions
  - In a follow-up study, no difference in errors when pace controlled
Lab Study 2: Major Results regarding “unexpected” effects

- Donning/doffing learned quickly; not time-consuming (~65 & 15 sec.)
- Reductions in max. voluntary shoulder flexion and abduction angles (~3 & 10%)
- Increased challenge to postural control (sway velocity increased ~12%)
- No evidence for increased risks of slips (RCOF) or trips (MFC)
- 3D lumbosacral forces reduced in several cases

Lab Study 3: Comparing different technologies for a simulated repetitive drilling task

Alabdulkarim et al. (Submitted)

- While working as accurately as possible, converge on the “maximum acceptable frequency” (MAF) of drilling
- Tool mass = 2 & 5 kg

Lab Study 3: Major Results

- MAF consistent for males; females had highest values using Tiffen/zeroG
- Usability: Tiffen/zeroG > SuitX > Fortis
- SuitX reduced peak shoulder loading, increased median and static loadings
- Increased low-back demands using devices w/ mechanical arms
  - Load counter-balancing (Fortis) reduced this effect
  - Influence of tool mass was consistent across devices
  - No one technology appeared superior overall

Lab Study 4: The influence of task precision demands when using different technologies

Alabdulkarim et al. (In Preparation)

- In an externally-paced task, complete simulated repetitive drilling at three levels of precision (hole sizes)

Tiffen™ and zeroG™ (~10kg)

Forts™ (~19-28kg)

SuitX™ Shoulder (~6kg)

EksoWorks Vest EksoBionics (~4kg)
Lab Study 4: Major Results

- Consistent overall influence of precision level on quality
  - More errors when using devices with mechanical arms
  - Arm support appeared to increase errors only in the high precision condition
- Some evidence that increasing precision led to increased loading in the shoulders and low back (regardless of exoskeleton used)

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A Novel Passive Lift-Assist Exoskeleton

- Goal:
  - Decrease overexertion and back injury risk during lifting
- Developed at VT (PI: Alan Asbeck) in collaboration with Lowe's Innovation Labs
- Fully passive (no motors)
- Energetic return provided by carbon fiber beams
- Preliminary field testing (3 months at a Lowe’s store)
- Lab testing in process

Exoskeleton Overview (~4.2kg)
Lab Study 5: Muscle activity and metabolic demands during repetitive lifting
Alemi et al. (In Preparation)

Freestyle lifting:
• ~0 and 20% of body weight (BW)
• With & without the exoskeleton

Changes in back muscle activation levels
\((n=11; \text{peak surface EMG-RMS})\)

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<th>Muscle</th>
<th>Weight (%BW)</th>
<th>Mean Reduction</th>
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<tr>
<td>TES</td>
<td>0</td>
<td>39%*</td>
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<tr>
<td></td>
<td>20</td>
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<tr>
<td>LES</td>
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<td>36%*</td>
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<tr>
<td></td>
<td>20</td>
<td>30%*</td>
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*Exo vs no-exo \(p < 0.05\)

Changes in metabolic demands
\((n=15; \text{via oxygen uptake rate})\)

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<th>Weight (%BW)</th>
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<tbody>
<tr>
<td>0</td>
<td>8.0*</td>
</tr>
<tr>
<td>20</td>
<td>6.9%*</td>
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*Exo vs no-exo \(p < 0.05\)

Key Points
- The benefits of exoskeletons can differ between designs and task demands
- There is clear potential to achieve the dual goals of health promotion and enhancing/maintaining performance
- Likely substantial task-dependency in benefits of a given device
- For now, a “trial-and-error” approach may be needed
- While no major adverse effects were evident, only controlled lab-based studies
- More realistic and diverse testing scenarios needed, for longer durations, and with broader populations
Several challenges and questions remain

- How should we treat industrial exoskeletons?
  - Augmentation, PPE, otherwise?
- What testing scenarios are most relevant; to what extent are benefits/limitations task-dependent?
- Do lab-based results transfer to the field?
- What learning (or other chronic) effects exist?
- Additional testing methods needed (e.g., for standardization)
- Short of a trial-and-error approach, can the effects of industrial exoskeleton use be predicted-modeled?

Current and Future Work

- What are the metabolic demands (reductions) when using upper-body and low-back exoskeletons?
- Does using an exoskeleton affect movement stability, coordination, and control?
- What are the effects of different exoskeleton designs for repetitive lifting tasks?
- Two prospective studies of exoskeleton implementation in the field

ASTM F48 Committee on Exoskeletons and Exosuits

ASTM F48 Committee on Exoskeletons and Exosuits was formed in 2017 to develop voluntary consensus standards for exoskeletons and exosuits. Subcommittees will address safety, quality, performance, ergonomics and terminology for systems and components during the full lifecycle of the product - from before usage, to maintenance, to disposal - including security and information technology considerations. The activities cover industrial, emergency response, medical, military and consumer applications serving private and public sectors, enhancing and decreasing efforts systems, as well as systems with physical and cognitive integration, and much yet to be defined. Standards and technical specifications will be published in the Annual Book of ASTM Standards, Volume 15.09. F48 and F49 standards and related work are available from the MeetingInfo. For information on this subcommittee structure and F48, see ASTM F48 Committee on Exoskeletons and Exosuits - 2017-2018 Drafting Session. F48 standards will be published in the Annual Book of ASTM Standards, Volume 15.09. F48 has 8 technical subcommittees to develop and maintain standards. Information on this subcommittee structure and F48's special issue can be found at the ASTM website. The special issue of the Journal of the American Medical Association will be published in the first quarter of 2018.
Acknowledgements

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