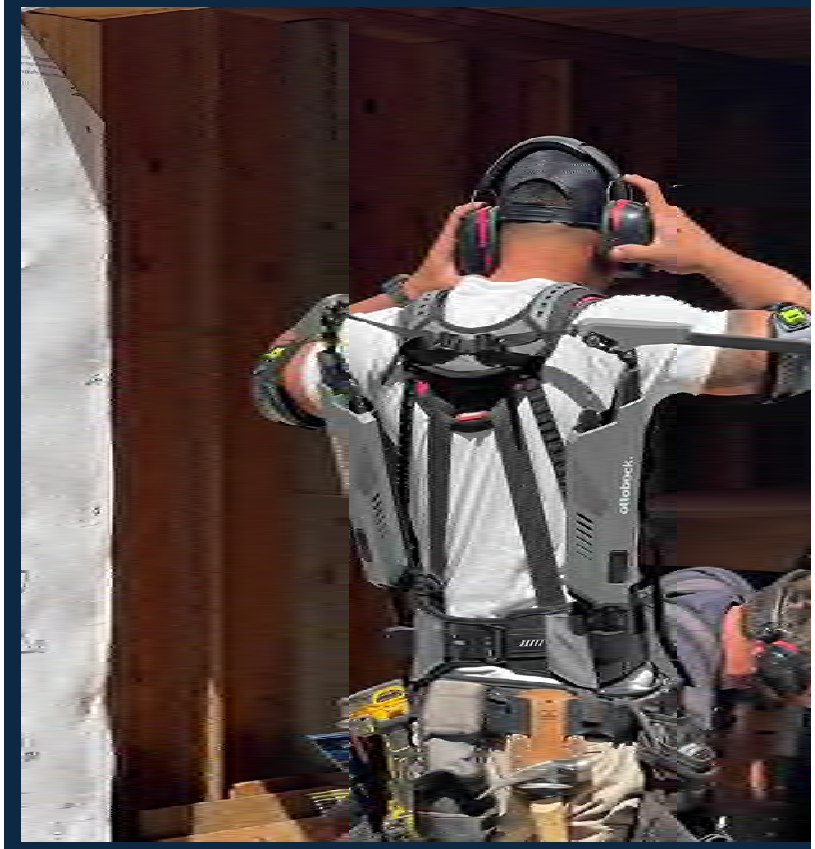
Research to Practice: Exoskeletons in Construction



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THE CENTER FOR CONSTRUCTION RESEARCH AND TRAINING

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"The findings and conclusions in this presentation are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention."

Burden of MSDs among Construction Workers

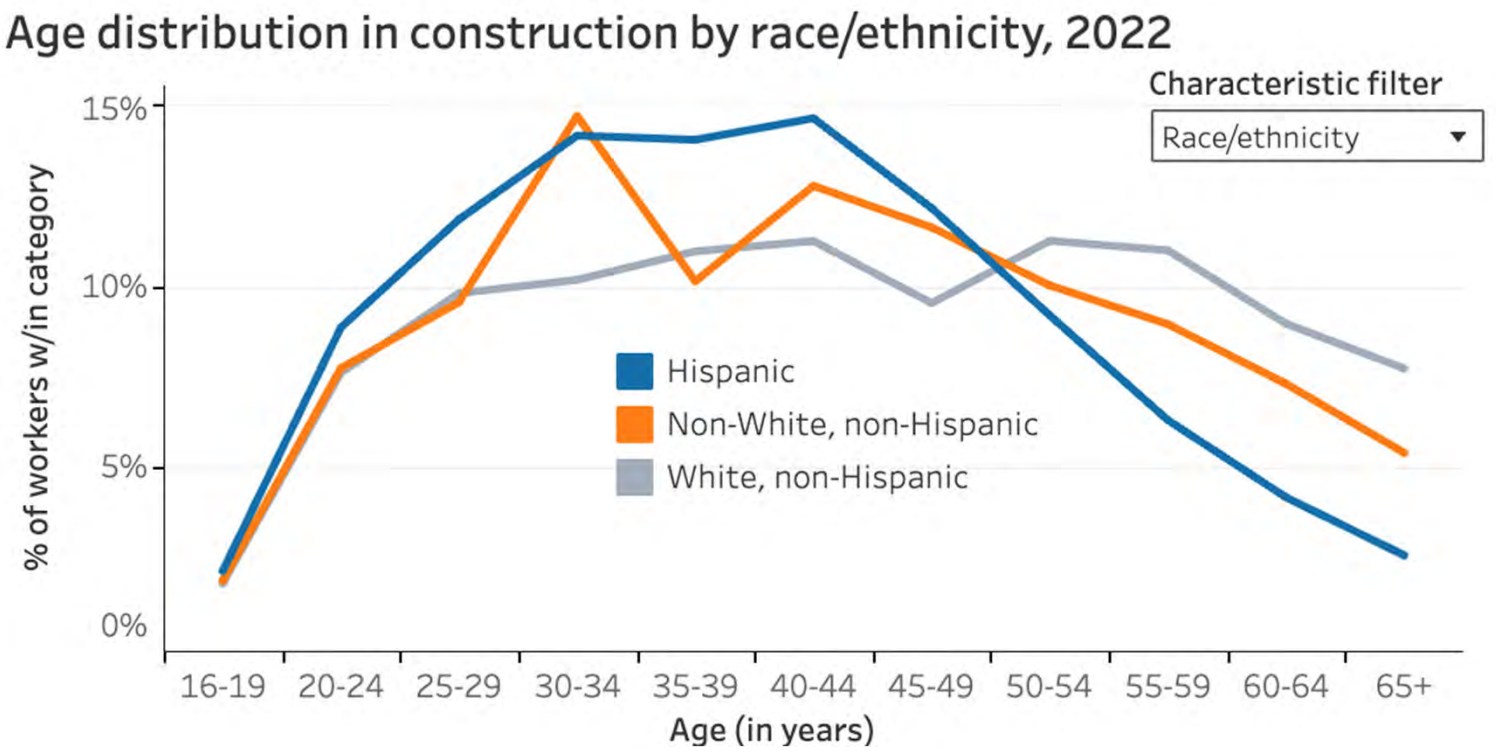
Construction workers continue to experience high rates (32.5 per 10,000FTEs) of work-related musculoskeletal disorders (WMSDs) - 11% higher than all other industry sectors in 2016[1,2].

The back and the shoulder were the most impacted body regions

Back injuries account for 43% of all cases, with a median of 8 lost work days[1].	Shoulder injuries account for 16% of all cases, with a median of 25 lost work days[1].

1. Bureau of Labor Statistics. Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work. 2018.
2. Wang X, Dong XS, Choi SD, Dement J. Work-related musculoskeletal disorders among construction workers in the United States from 1992 to 2014. *Occup Environ Med*. 2017;74(5):374-380.

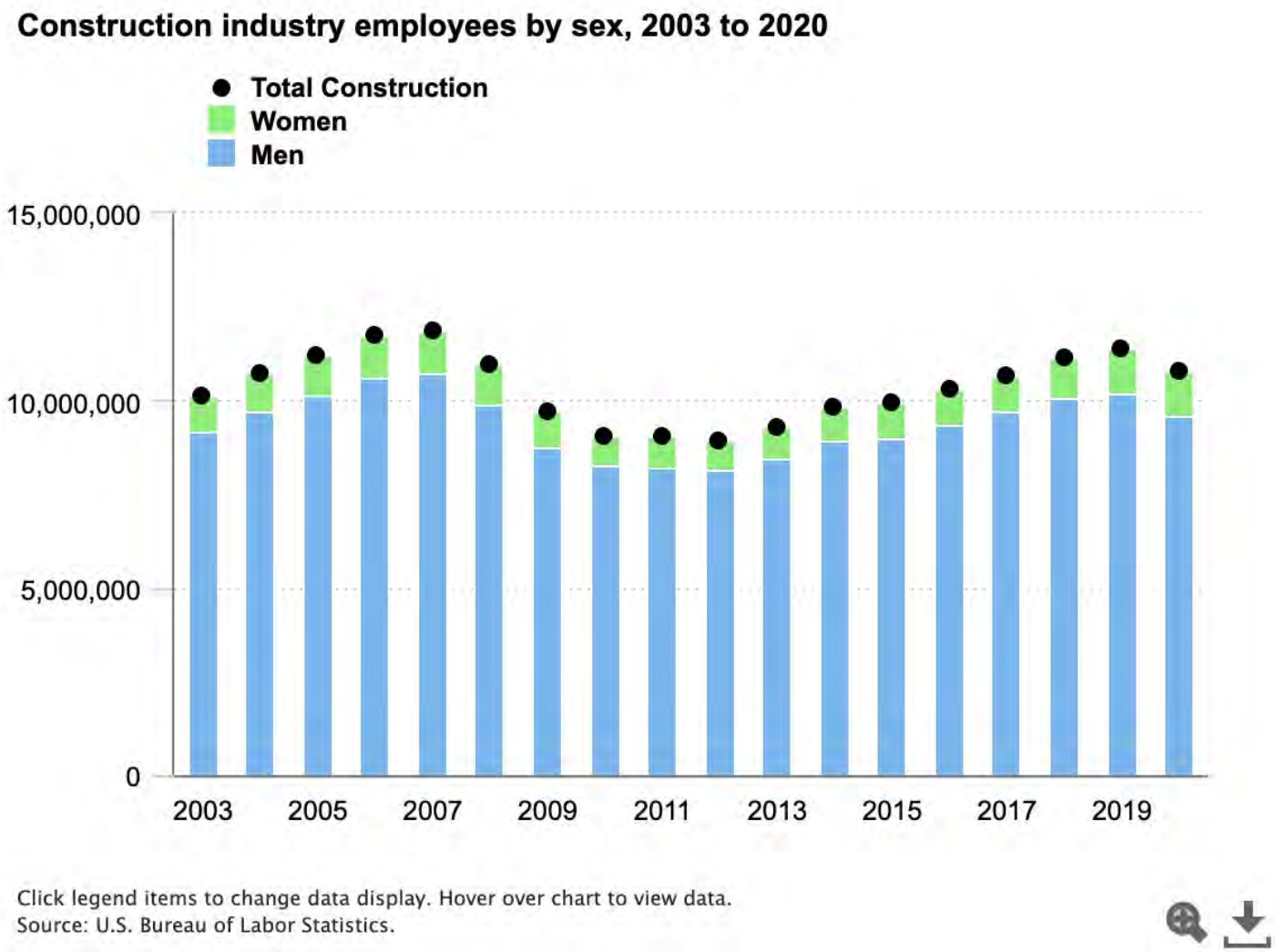
Background



Construction industry labor projection models identified a shortage of 650,000 workers to meet the increase in critical infrastructure across the United States.

CPWR-The Center for Construction Research and Training. [2023]. Aging Workers in Construction [dashboard].
ABC: Construction Industry Faces Workforce Shortage of 650,000 in 2022 | News Releases. Accessed April 28, 2023.

Background



https://www.bls.gov/spotlight/2022/the-construction-industry-labor-force-2003-to-2020/home.htm

One in ten construction workers is female

Industrial Exoskeletons

exoskeletonreport.com

Wearable devices that **work with** a user; act to **augment**, **reinforce**, or **restore** human performance.

AIRFRAME

LEVITATE TECH

shoulderX

SUITX

Paexo Shoulder

OTTOBOCK

Ekso Works

EKSO BIONICS

Paexo Back

OTTOBOCK

backX

SUITX

Apex

HEROWEAR

FORTIS

LOCKHEED MARTIN

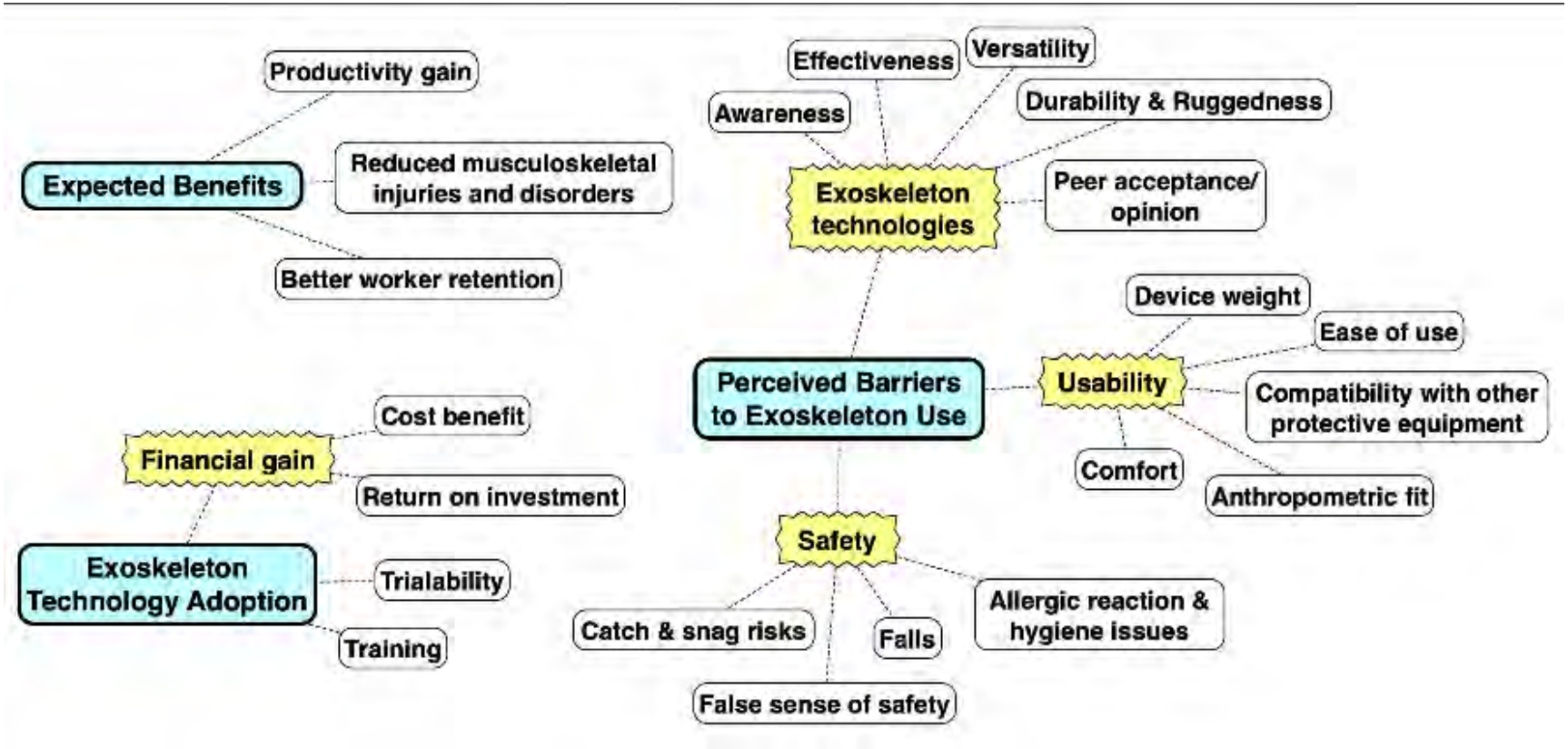
Background

- Occupational exoskeletons may reduce the risk of WMSDs
- ASEs have been shown to lower muscle activity of the shoulder[1]
- ASEs have been used on manufacturing lines such as in the automotive industry

Variations in construction tasks, environments, companies, and worker demographics present challenges to the implementation of ASEs.

Van Engelhoven L, Poon N, Kazerooni H, Rempel D, Barr A, Harris-Adamson C. Experimental Evaluation of a Shoulder-Support Exoskeleton for Overhead Work: Influences of Peak Torque Amplitude, Task, and Tool Mass. *IISE Transactions on Occupational Ergonomics and Human Factors*. 2019;7(3-4):250-263.
Kim S, Nussbaum MA, Smets M, Ranganathan S. Effects of an arm-support exoskeleton on perceived work intensity and musculoskeletal discomfort: An 18-month field study in automotive assembly. Am J Ind Med. 2021 Nov;64(11):905-914. doi: 10.1002/ajim.23282. Epub 2021 Aug 6. PMID: 34363229.

Background



Sunwook Kim, Albert Moore, Divya Srinivasan, Abiola Akanmu, Alan Barr, Carisa Harris-Adamson, David M. Rempel & Maury A. Nussbaum (2019) Potential of Exoskeleton Technologies to Enhance Safety, Health, and Performance in Construction: Industry Perspectives and Future Research Directions, IISE Transactions on Occupational Ergonomics and Human Factors, 7:3-4, 185-191, DOI: 10.1080/24725838.2018.1561557

Evaluation of Exoskeletons for Construction

Aim 1

Obtain input from construction industry stakeholders

Aim 2

Determine the efficacy

Aim 3

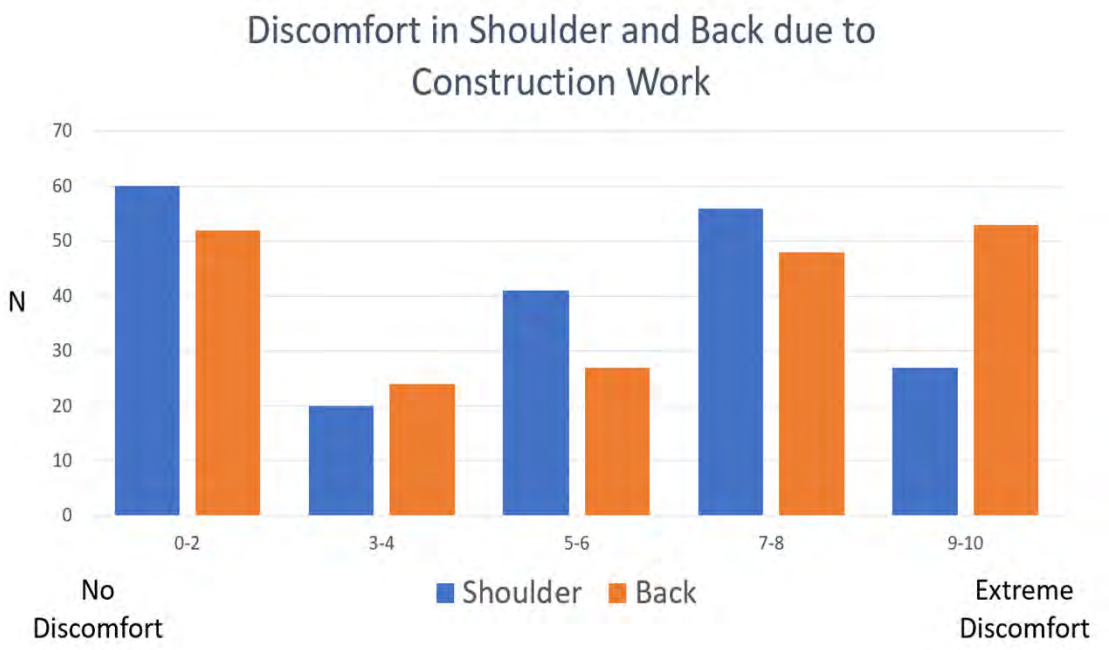
Assess the perceived safety, effectiveness, and acceptability

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

Benefits	**Augment Capacity** **Performance**
Barriers	**Usability** **Safety hazards** **Durability**
Adoption	**Training** **Cost** **Acceptance**

Aim 1: Input from Stakeholders

- 361 Respondents
  - 63% Caucasian
  - 24% Hispanic
  - 77% Male
  - 47 years median age
- Work Experience
  - 66% had >15 years of work experience in companies of various size
- Exoskeleton Knowledge
  - 36% have heard of workers using an exoskeleton
  - 35% had never heard of it

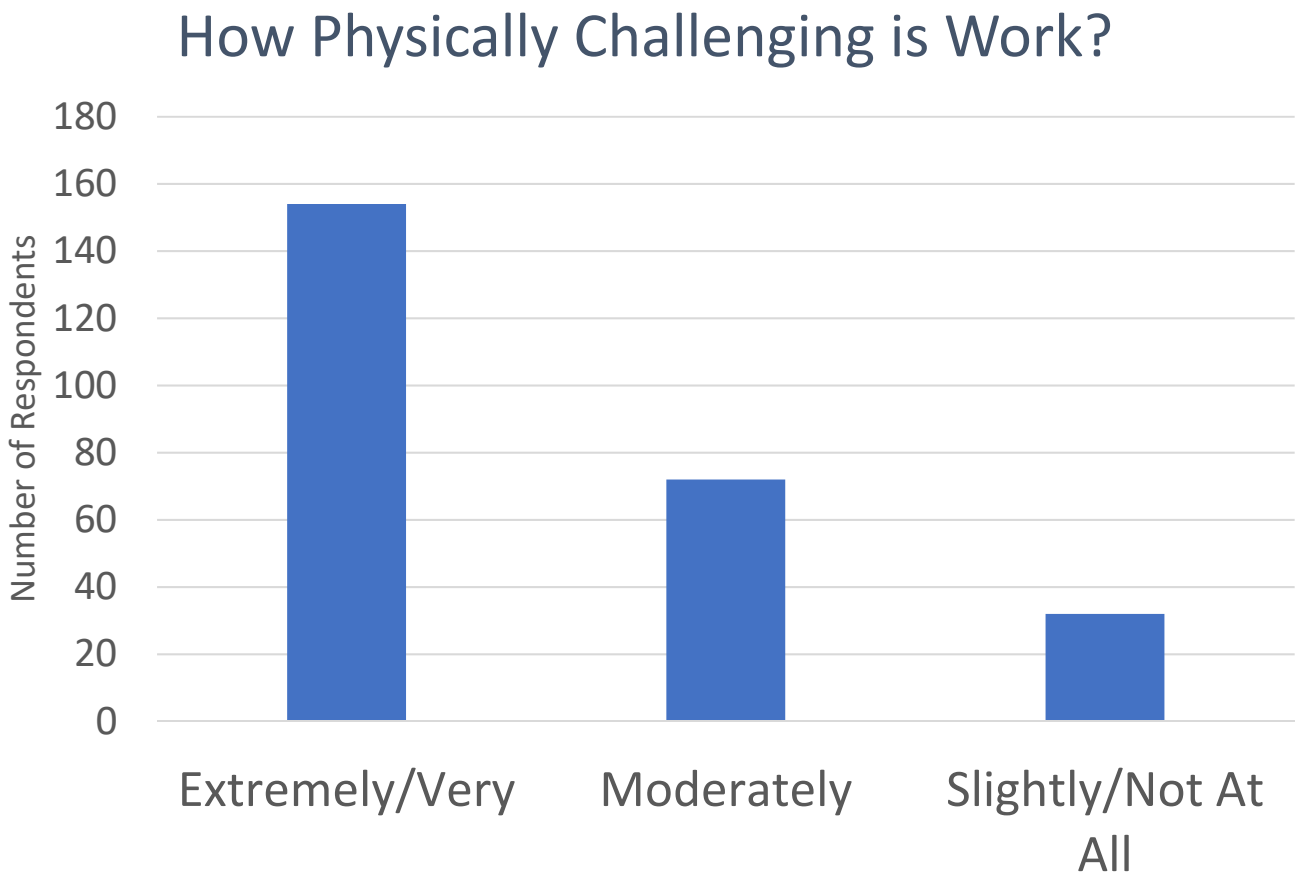


Gutierrez N, Ojelade A, Barr A, Kim S, Rempel D, Akanmu A, Nussbaum M, Harris-Adamson C. Perceived benefits, barriers, perceptions, and readiness to use exoskeletons in the construction industry: Differences by demographic characteristics. *Applied Ergonomics.* 2024: 116: 104199

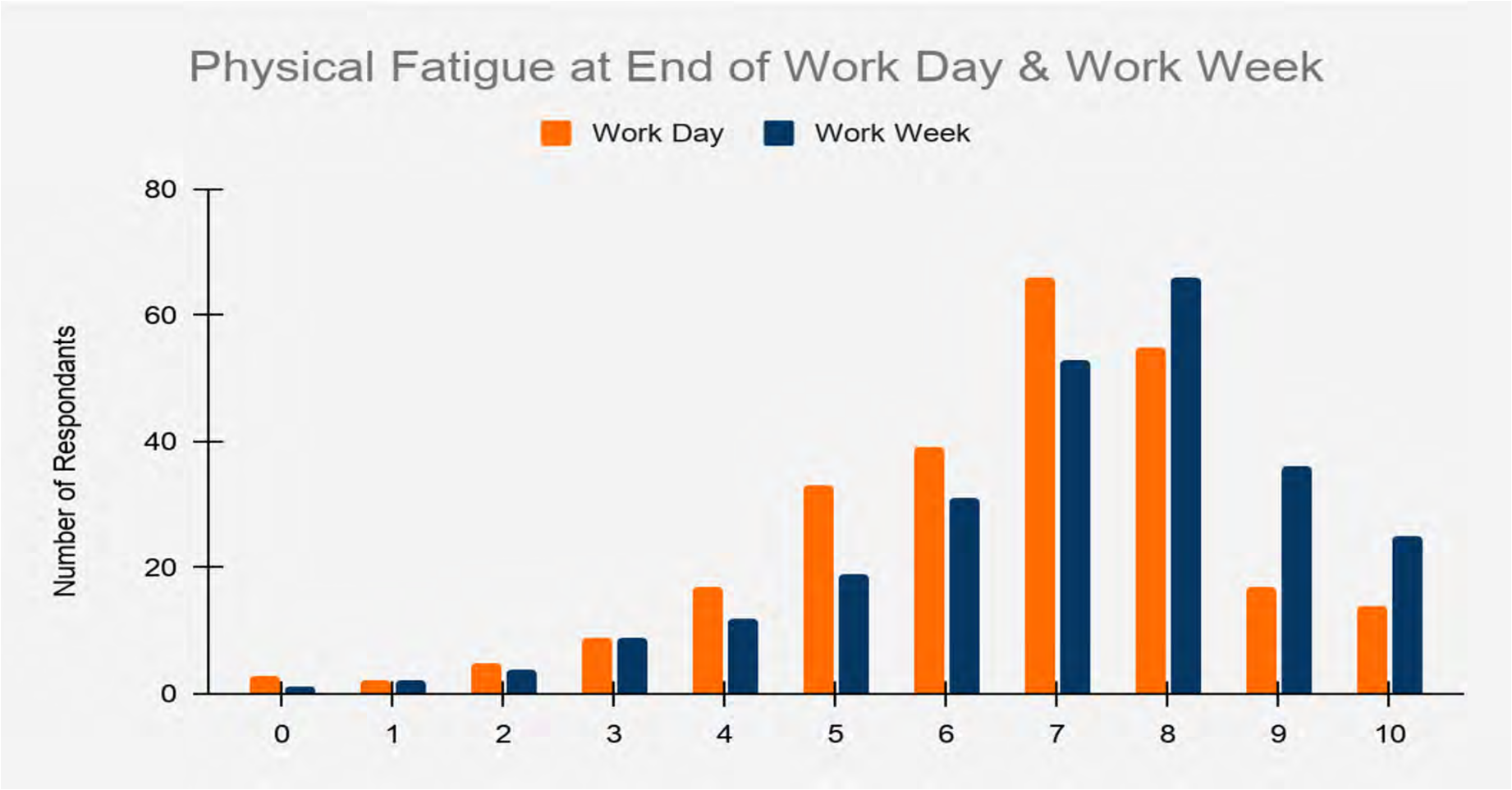

Bricklayer
Installer
Millwright
Mining
Marble
Asphalt
Mosaic
Concrete
Lineman
Laborer
Director
Structural
Pipefitter
roofing
Project
Iron
Sheet
Metal
Safety
Equipment
Cement
Crew
Helper
Tile
Welder
Roofer
Masonry
Foreman
Worker
etc tile
Lather
Carpenter
Plumber
Painter
General
Engineer
Operator
Contractor
Finisher
Builder
Boiler
Operating
Management
Terrazzo
Fence
Worker/Insulator
Elevator
Heavy
Tilesetter
Flooring
Steamfitter
Glazier
Rebar
Plasterer
Setter
Scaffold
Steel
Installations
Consultant
Mechanic/Constructor
Electrician

Aim 1: Work Demand

60% **Rate their work as very to extremely challenging (n = 258)**



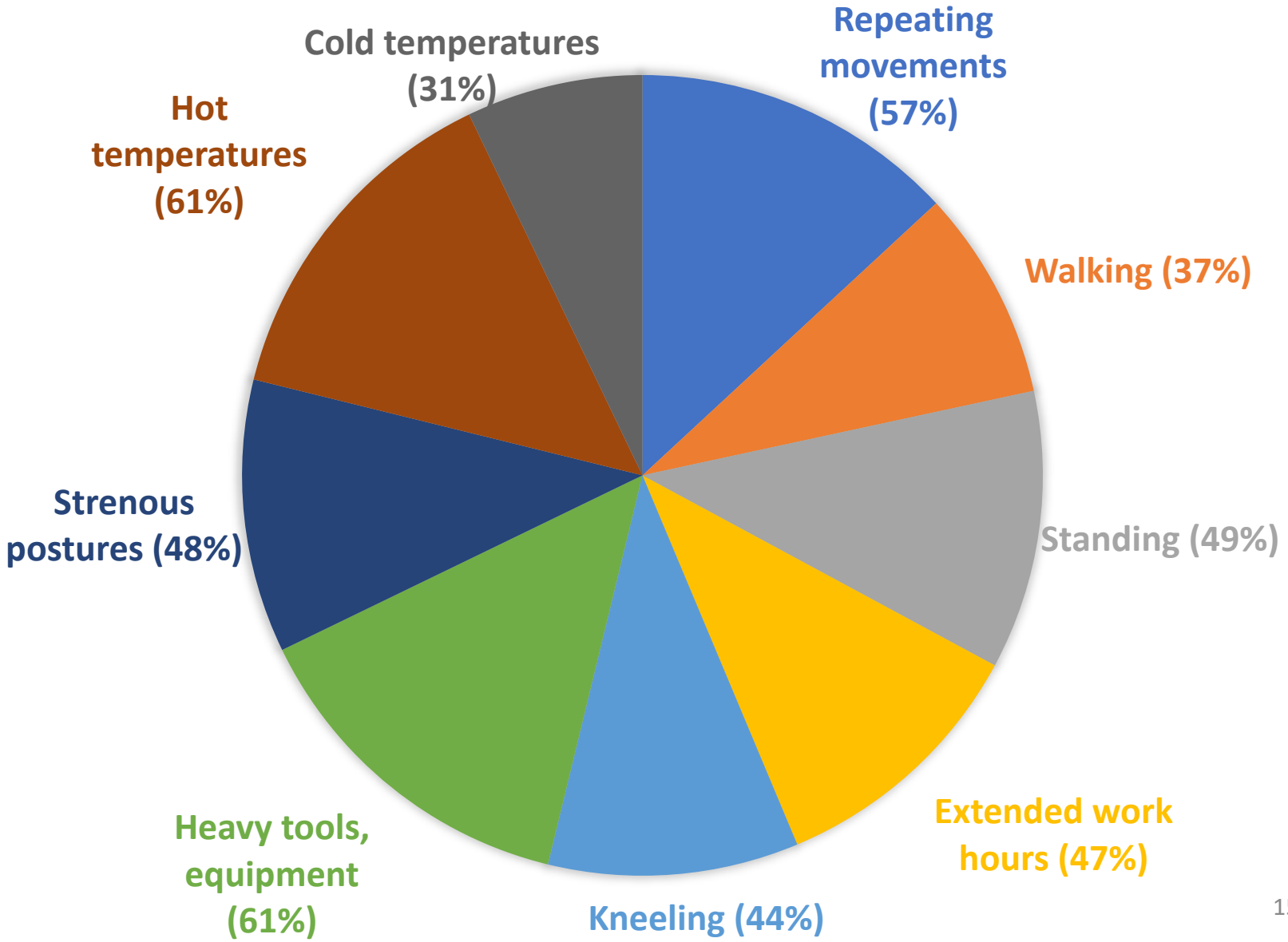
Aim 1: Fatigue



No Physical Fatigue

Extreme Physical Fatigue

Aim 1: Contributions to Fatigue



Aim 1: Summary of Input from Stakeholders

Barriers to Adoptions

- Sharing & fitting the exoskeleton was a barrier
  - 97% agreed they would share an exoskeleton
  - 80% agreed that sharing would make it difficult to refit and/or use
  - There is no systematic information available that can guide how to properly fit and select the support levels

- Common safety concerns included:
  - Slips, trips & falls
  - Struck by/caught in/between
  - Scaffold/Trench Work
  - Reduced Mobility

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Aim 2. Evaluate the efficacy of exoskeletons used in construction.

Normalize fit and support

Evaluate usability and safety.

Identify optimal settings based on task-characteristics

Aim 2: Fit and Support

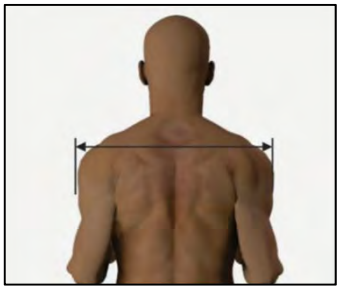
Fit and Support Prediction

Optimize the fit and support level settings of a passive ASE based on a subject's height, weight, and sex to facilitate use across construction workers.

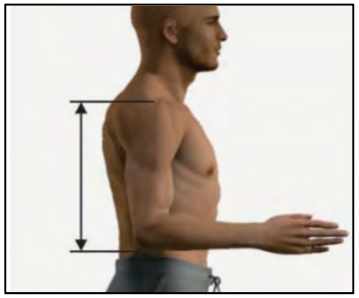
Aim 2: Deriving Equations for Anthro. Fit

- Sex-specific coefficients for specific body segments were selected from the ANSUR II database
- Each coefficient represents an average fraction of the relevant body segment to height

Bideltoid Length

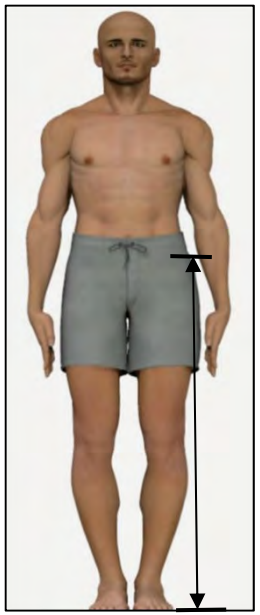


Shoulder to Elbow Length

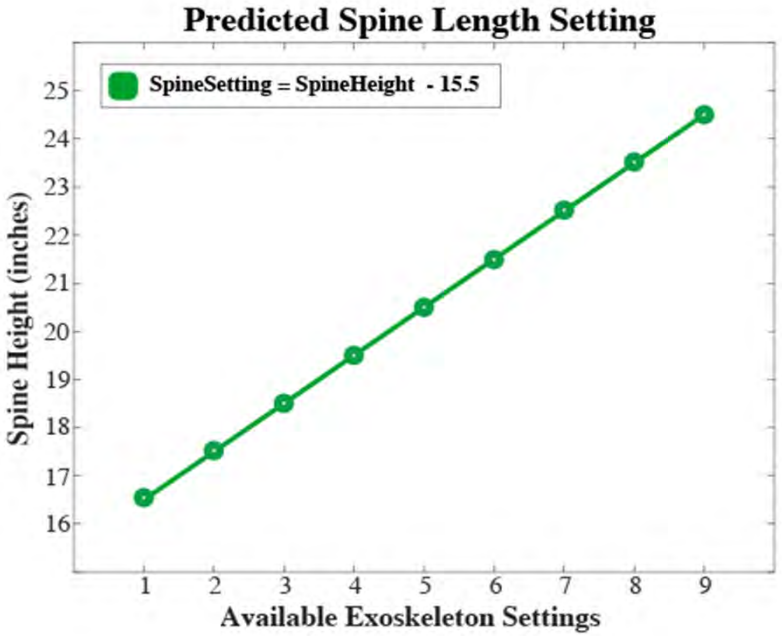


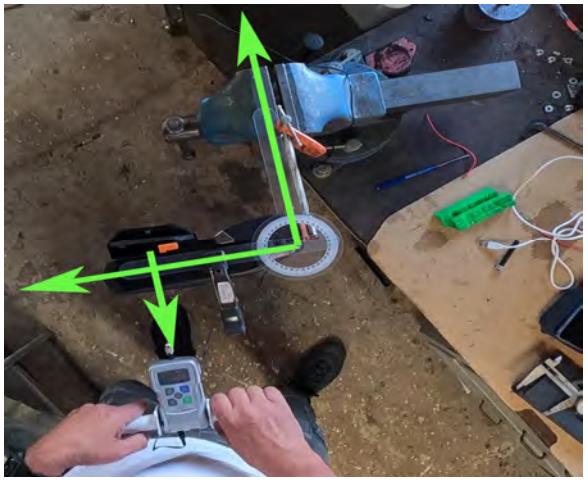
Cervical Height

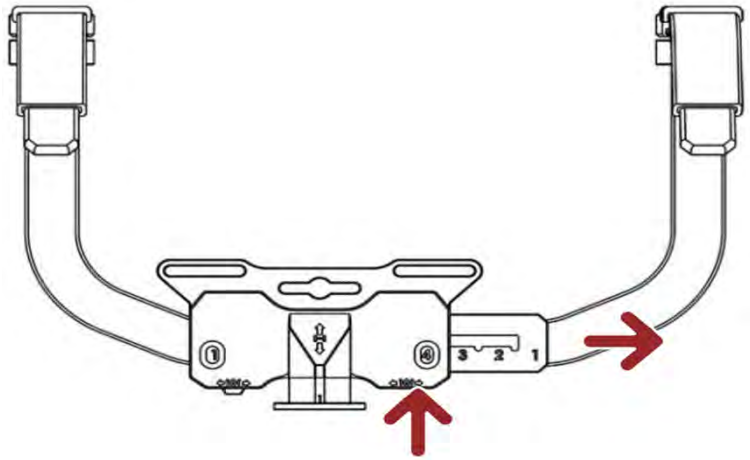
Iliocristale Height

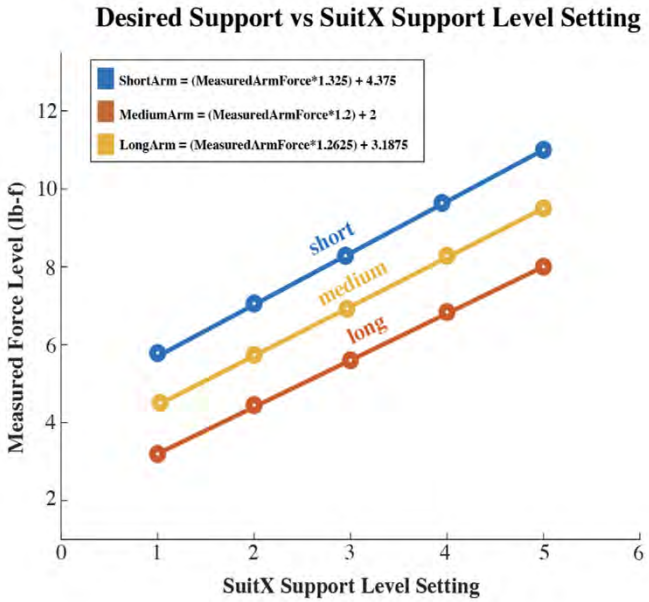


Aim 2: Estimating Fit and Support Settings









Definitions for “Correct” Fit and Support

- **SHOULDER BREADTH**
  - Small gap between the shoulder and the arm units
- **ARM LENGTH**
  - Arm cuff edge is aligned with the end of elbow when arm is bent
- **SPINE LENGTH**
  - No contact between the upper shoulder frame and the top of the user’s shoulder for entire range of motion
  - Hip pads are over the hip bones
  - Spine is vertical

Aim 2: Fit and Support

- Results demonstrate that the equations can predict support level fairly well (87%)
- Equations for anthropometric fit need to be refined -particularly arm length
- Equations for anthropometric fit worked better for males than females (8% difference in good predictions)

	Fit Prediction %Correct	Support Prediction % Correct
All	85%	87%
EVO	90%	98%
SuitX	72%	74%
Otto	94%	88%

Aim 2: Safety and Usability Evaluation

Impact of ASE (in on and off states) on maneuverability, balance, gait, climbing, and steps.

Dependent Variables

- **Time to Completion**
- **Number of "Errors"**
  - snags, bumps, contact
- **Body kinematics (IMU)**
  - Major joint kinematics
- **User perception**
  - Perceived Exertion
  - Comfort/Discomfort
  - Safety & Usability

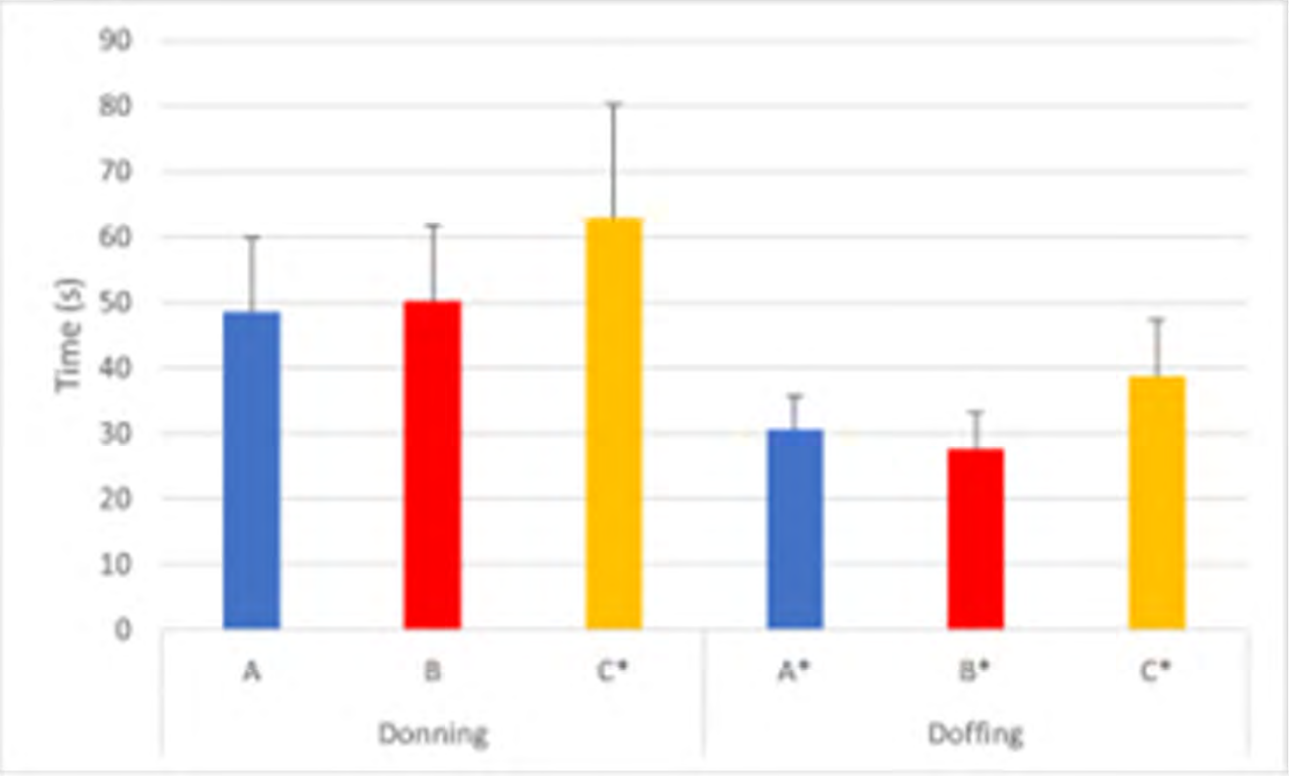
Protocol

40 participants (half with construction experience)

Tasks included:

1. donning and doffing
2. maneuvering through constrained spaces
3. ambulating on a balance beam and around cones (Figure 8 test)
4. climbing stairs and a ladder

Task 1: Donning & Doffing



Conditions

A: Ottobock

B: SuitX*

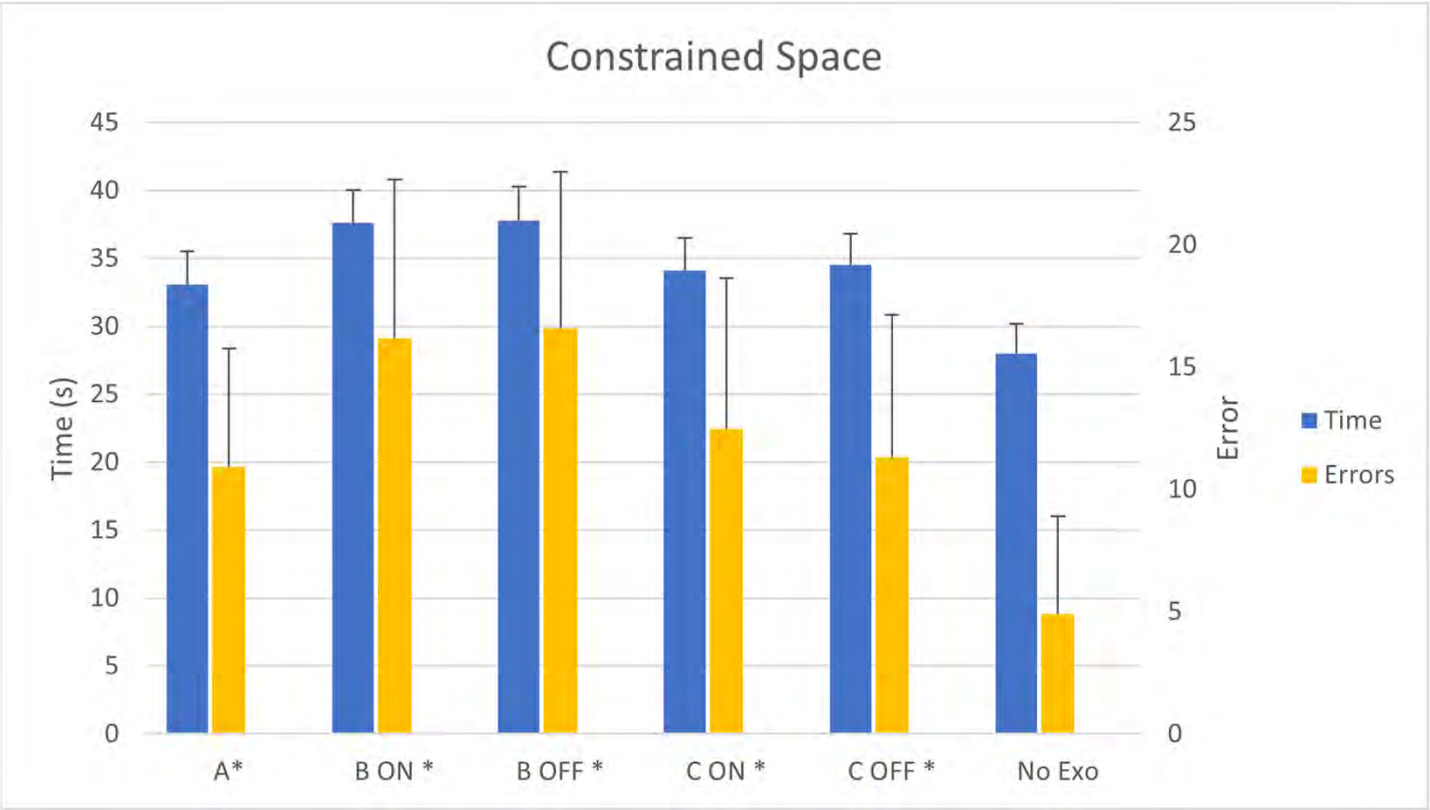
C: EksoBionics*

No Exoskeleton

*(on & off)

Task 2: Safety and Usability Evaluation

Time and Errors



Conditions

A: Ottobock

B: SuitX*

C: EksoBionics*

Meyer, R., Barr, A., Kim, S., Rempel, D., Nussbaum M.A., and Harris-Adamson, C. Impacts of using arm-support exoskeletons on task performance, perceived safety, and usability during simulated construction-relevant tasks. *In progress.*

Task 3 & Task 4: Time and Errors

Task 3: Balance Beam and Figure-eight

- No statistically significant differences in completion time across conditions ($p<0.60$)
- No significant effects of ASE use on errors during this task ($p<0.32$)

Task 4: Stairs and Ladder

- Wearing no ASE was faster than wearing any, though not quite statistically significant ($p<0.06$)

Conditions

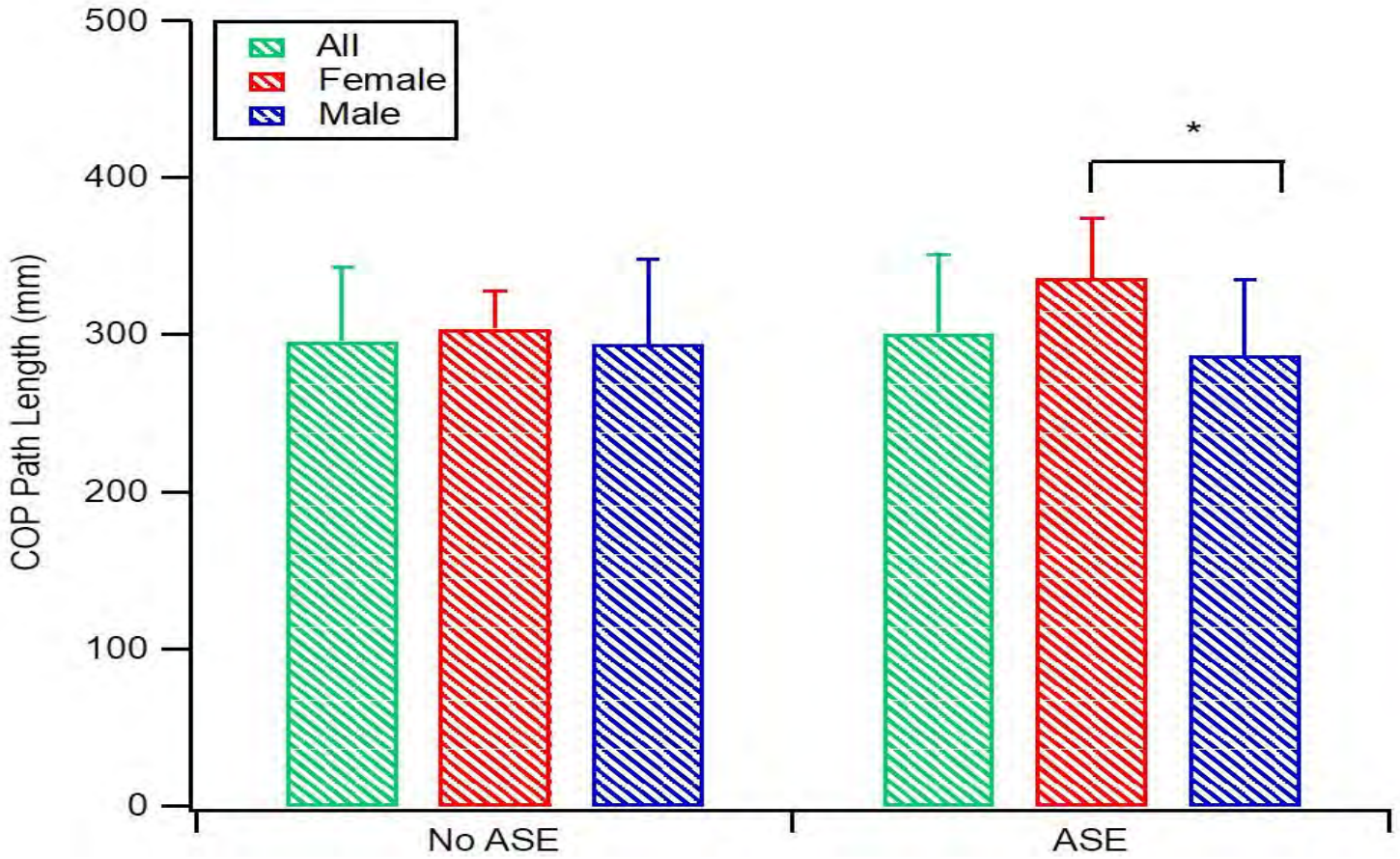
A: Ottobock

B: SuitX*

C: EksoBionics*

Aim 2: Safety and Usability Evaluation

Step Down Stability Results

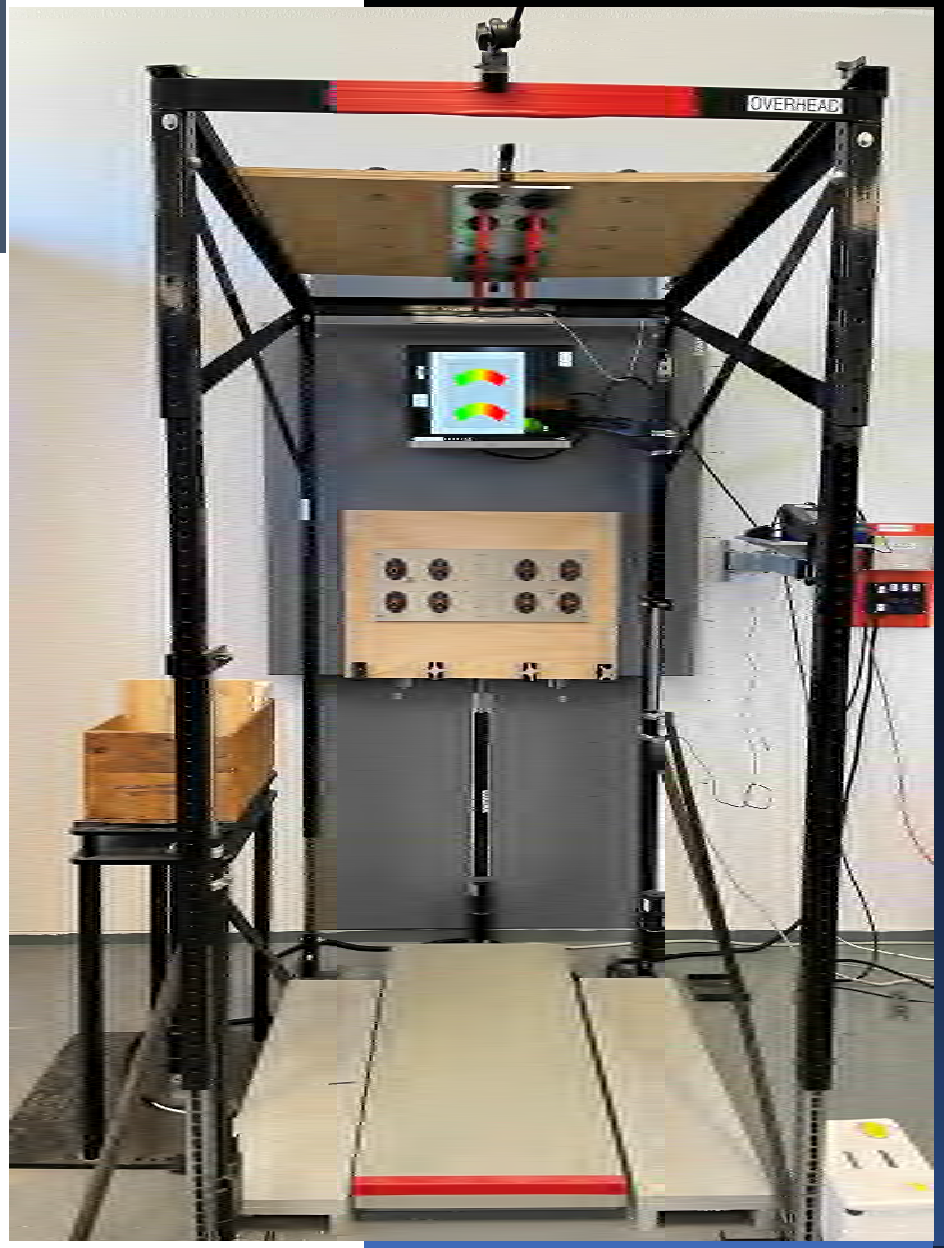


Arippa, F., Phillips, B., Barr, A., Kim, S., Nussbaum, M., Harris Adamson, C. The impact of arm support exoskeletons on balance during a step-down maneuver.

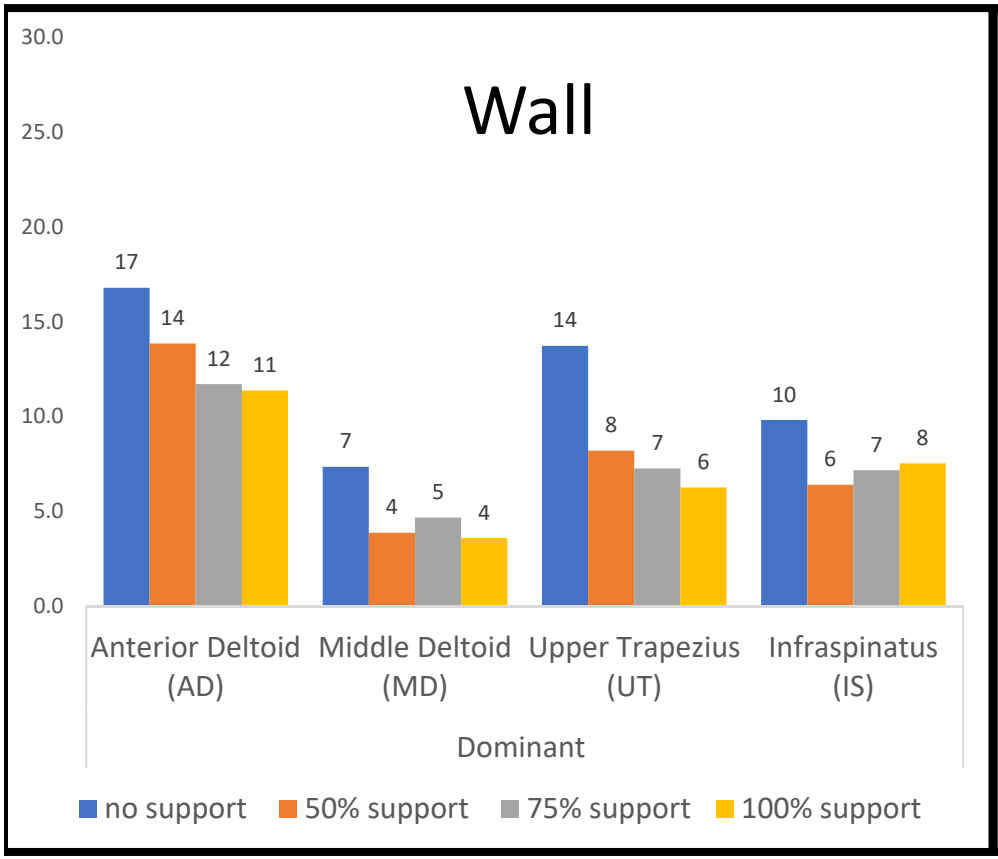
Aim 2: Support Level Evaluation

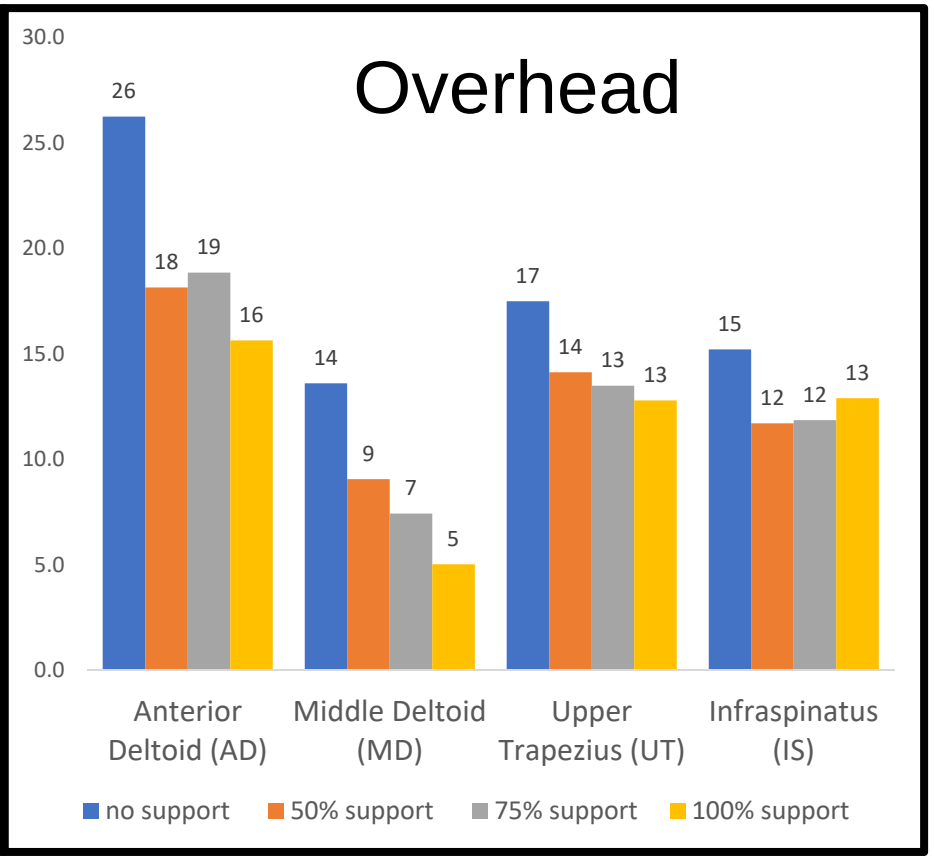
To evaluate the optimal and preferred support level setting by location and type of task

- Location – Overhead versus Wall
- Type of Task – Static versus Dynamic

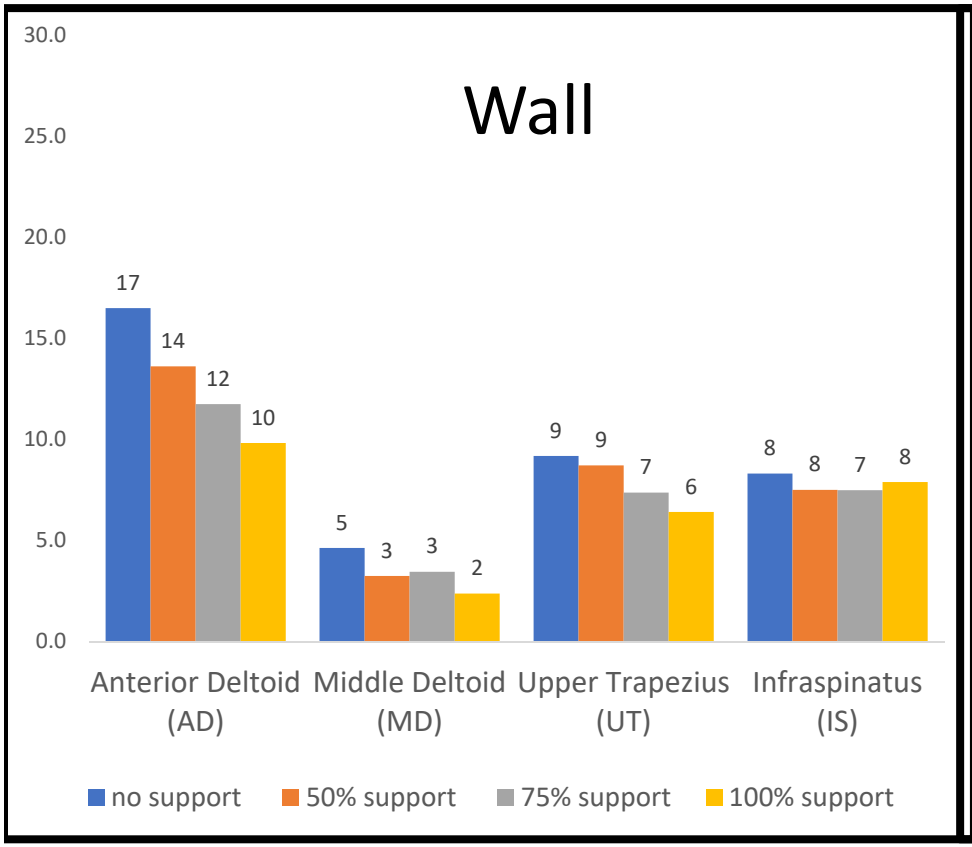


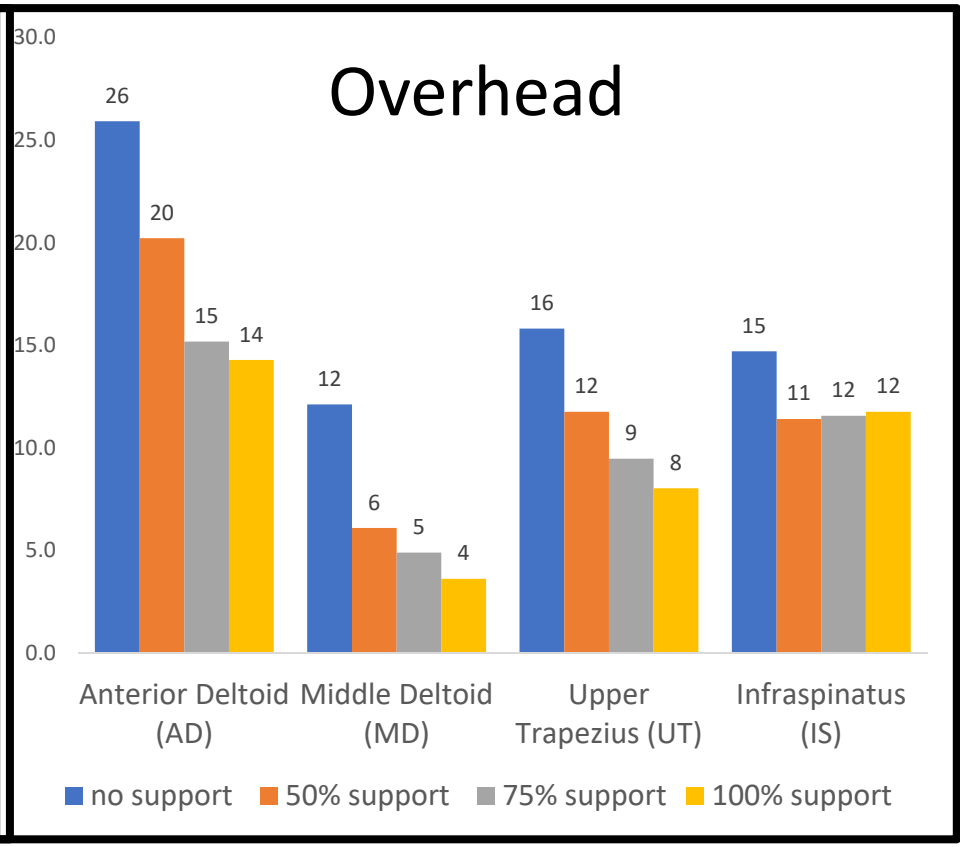
Static Wall vs Overhead – APDF 50



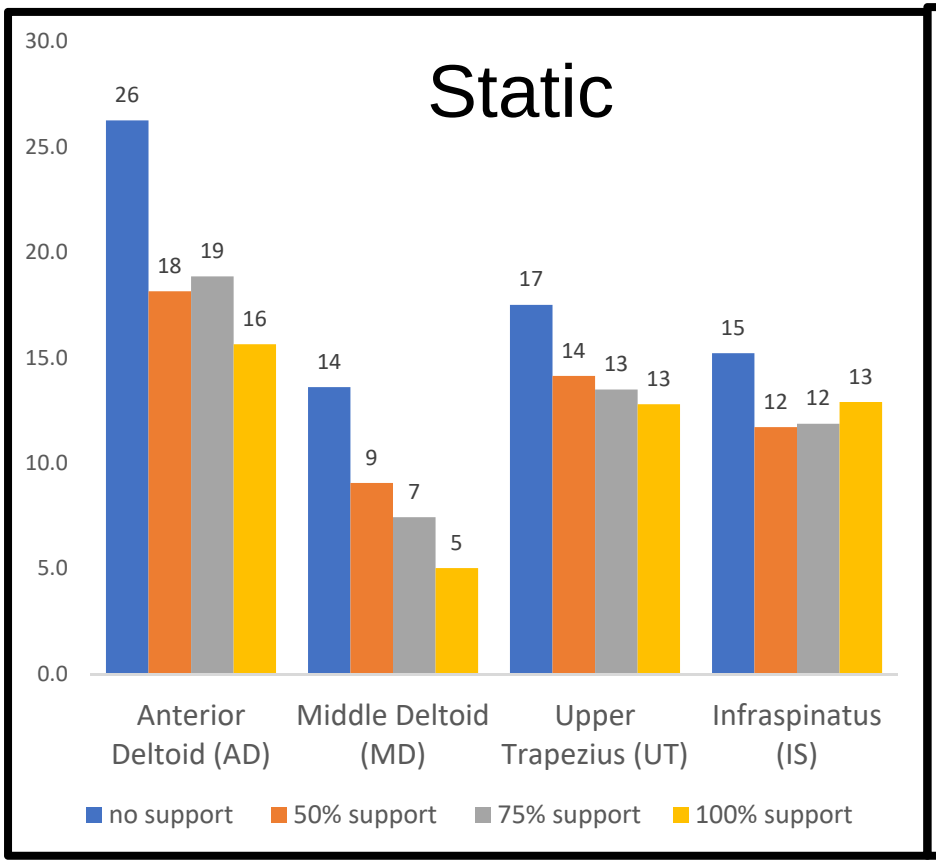


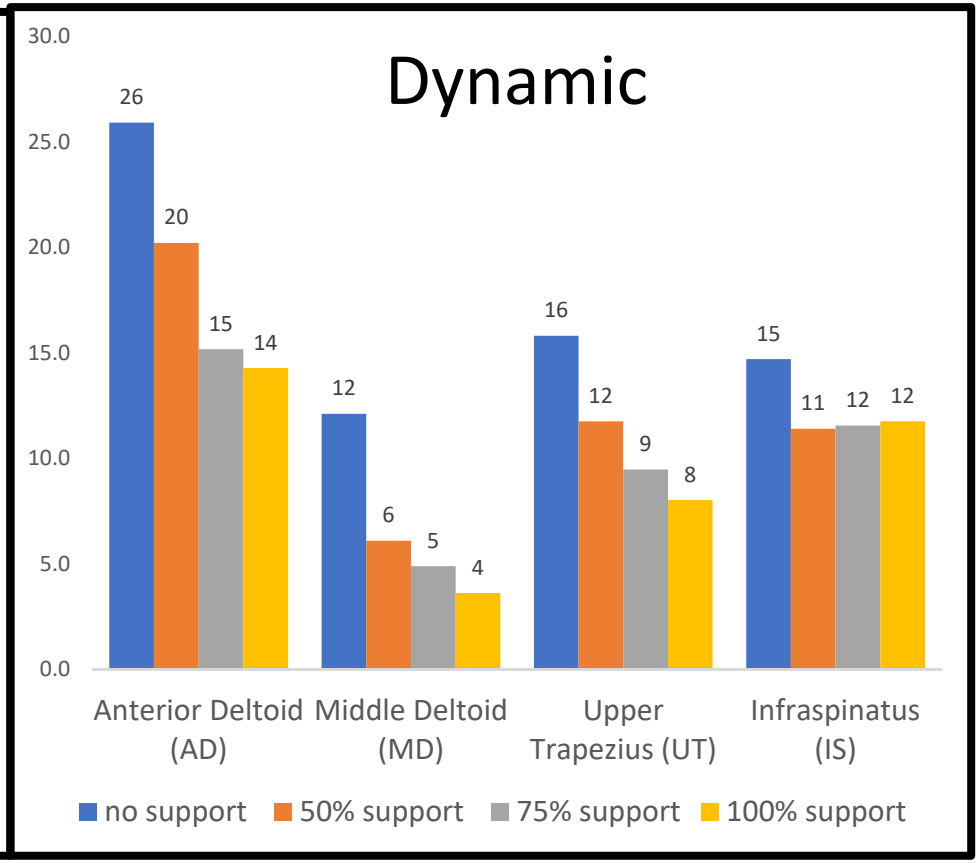
Dynamic Wall vs Overhead – APDF 50



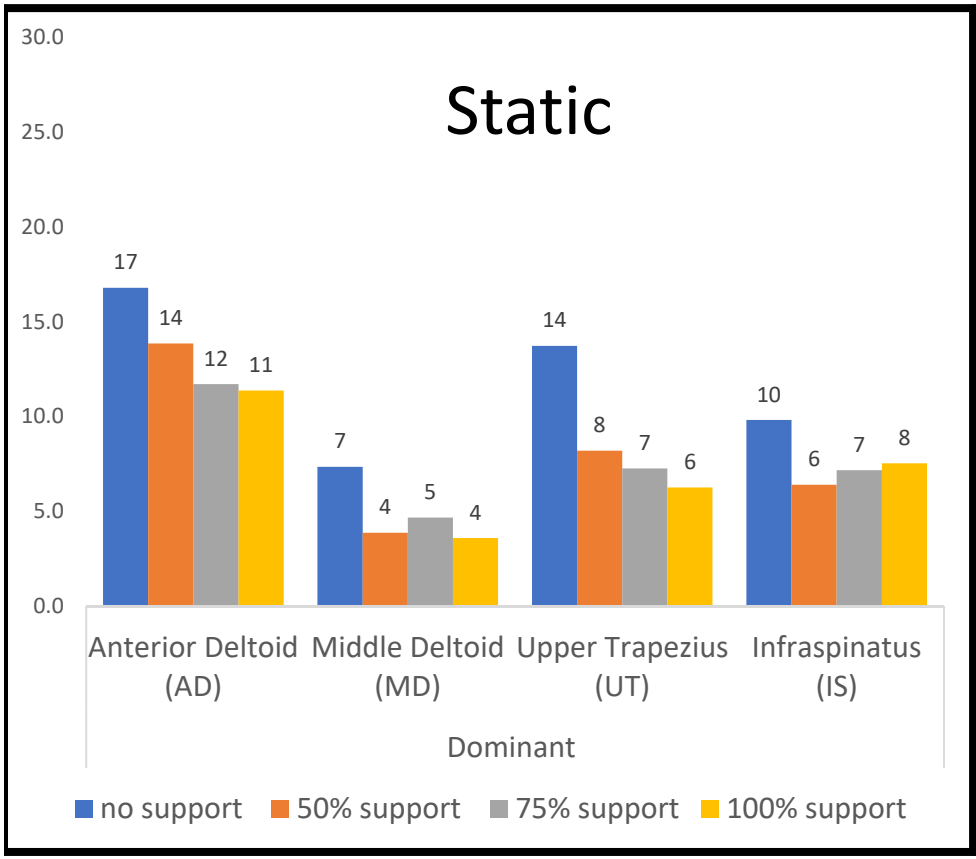


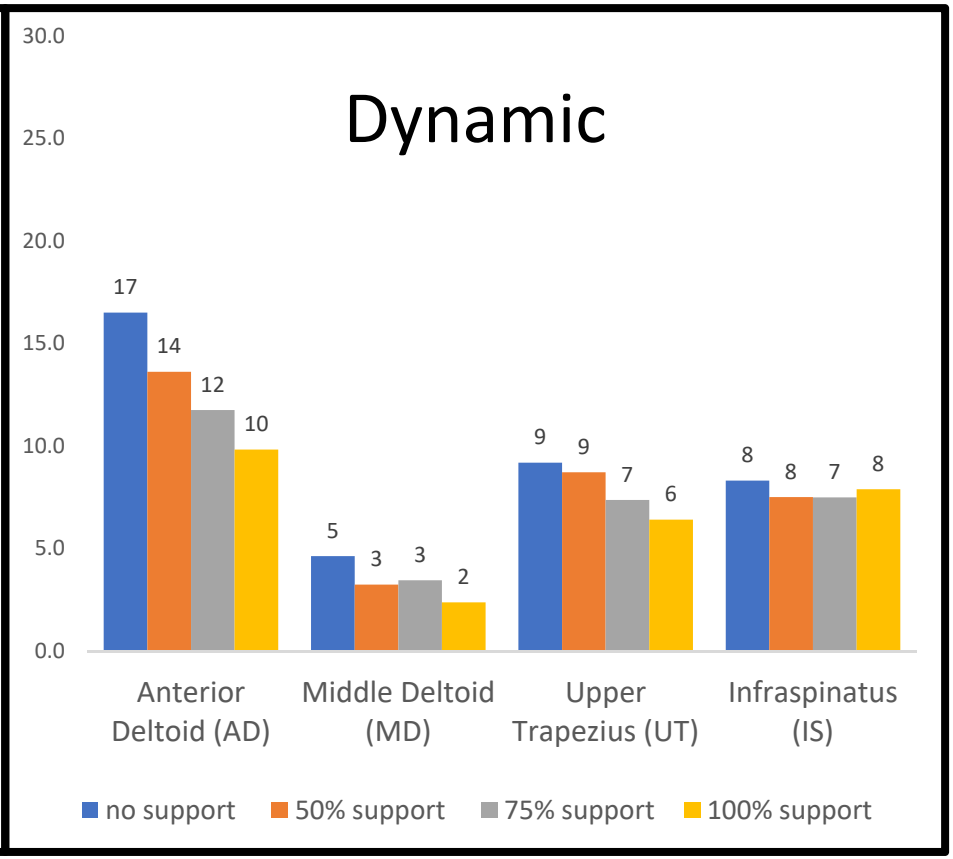
Overhead Static vs Dynamic – APDF 50



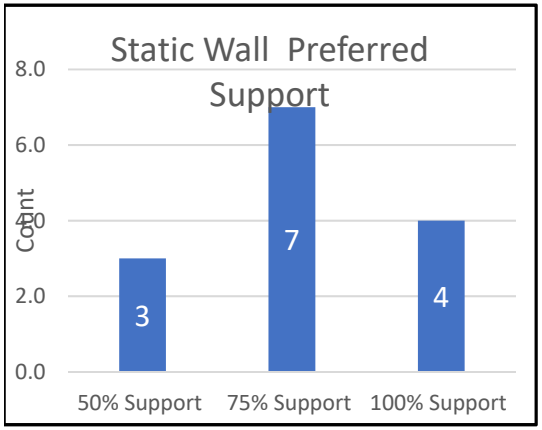


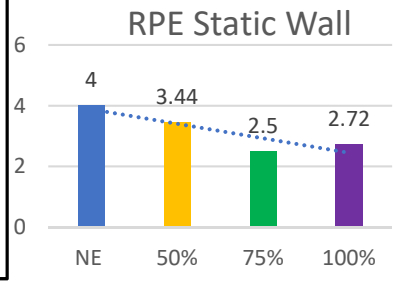
Wall Static vs Dynamic – APDF 50

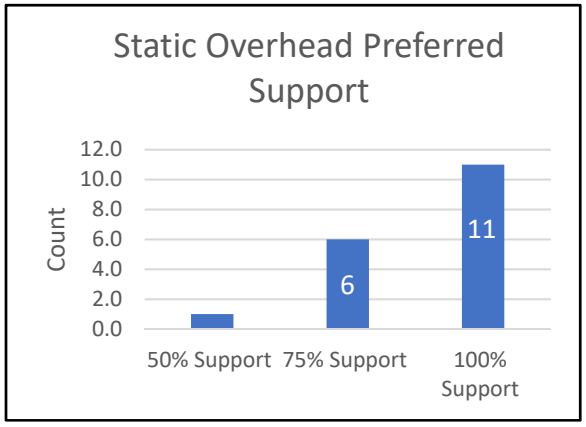


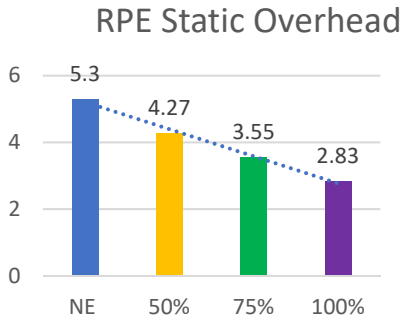


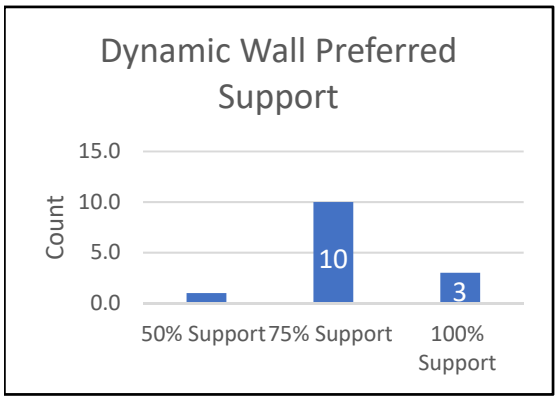
Aim 2: Support Level Evaluation

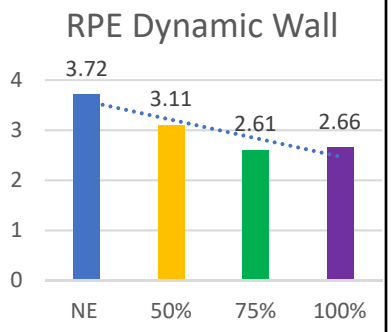


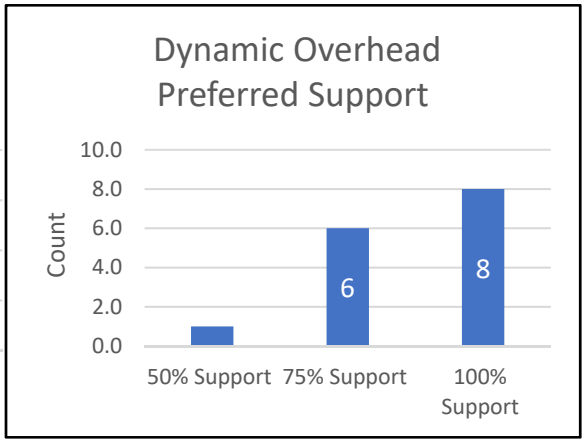


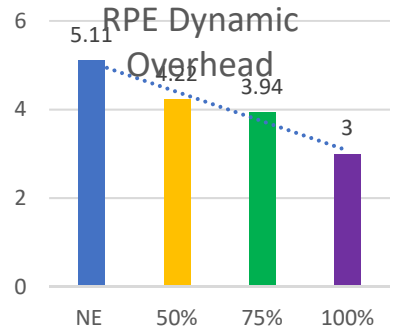












Barrajas-Smith, I., Casu, G., Phillips, B., Barr, A., Kim, S., Barr, A., Rempel, D., Nussbaum M.A., and Harris-Adamson, C. Evaluation of normalized support settings while performing static and dynamic drilling task overhead and on the wall. In progress.

Aim 2: Support Level Evaluation

- Muscle activity typically decreased as support increased
  - Muscle activity was higher for overhead versus wall tasks
  - Muscle activity was similar for dynamic versus static tasks
- RPE decreased as support level increased
- Preferences indicated that 100% support level was preferred for overhead work and 75% support was preferred for wall work
- Type of task did not impact support level preferences

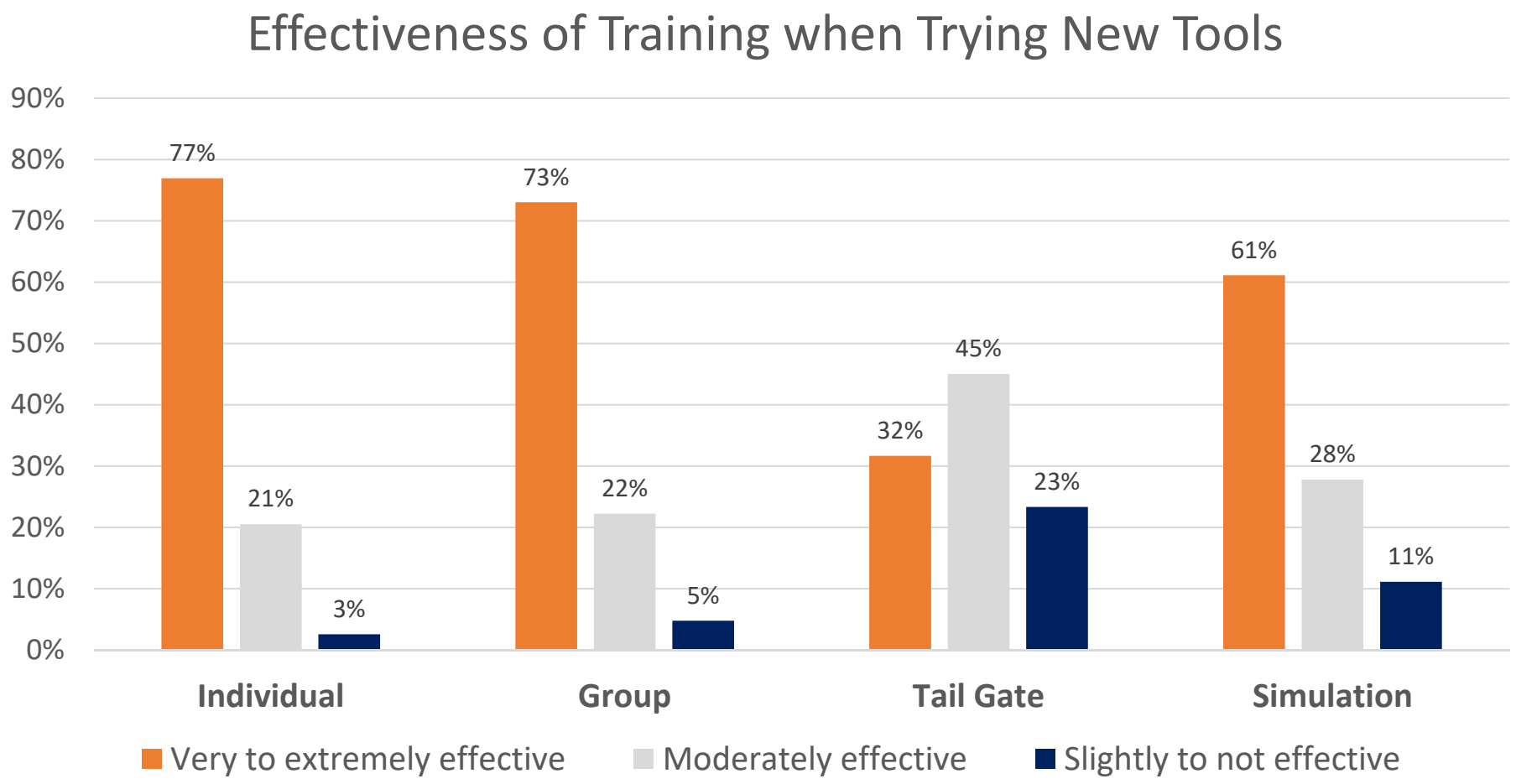
Barrajas-Smith, I., Casu, G., Phillips, B., Barr, A., Kim, S., Barr, A., Rempel, D., Nussbaum M.A., and Harris-Adamson, C. Evaluation of normalized support settings while performing static and dynamic drilling task overhead and on the wall. In progress.

Aim 3. Assess the perceived safety, effectiveness, and acceptability of EXO use by construction workers in the field

Develop EXO Implementation Guidelines

Field assessment of effectiveness

Effectiveness of Training



Aim 3: Field Evaluation

- Reported improvements
  - 64% less physical effort
  - 55% less fatigue
  - 58% less discomfort
- 49% thought exos should be standard issue for their type of work
- On a “likely to use” scale 0-10 responses varied widely from 1 to 10 with an average of 6.9

Aim 3:
ASE Guidelines

Tips and tricks for using exoskeletons safely and effectively in construction.

In partnership with CPWR, researchers at the University of California and Virginia Tech have been studying the impact of exoskeletons on construction workers and have compiled resources for you and your team.

- the right fit
- the right task
- the right support
- safety cautions
- contraindications

MORE INFORMATION

Quick Tips

ARM SUPPORT EXOSKELETON
SET UP GUIDE FOR CONSTRUCTION

When performing **overhead tasks**, consider setting the exoskeleton to **100%** of your arm and tool weight (visit www.tiny.url/exofit).

When performing **forward reach tasks**, consider setting the exoskeleton to **75%** of your arm and tool weight (visit www.tiny.url/exofit).

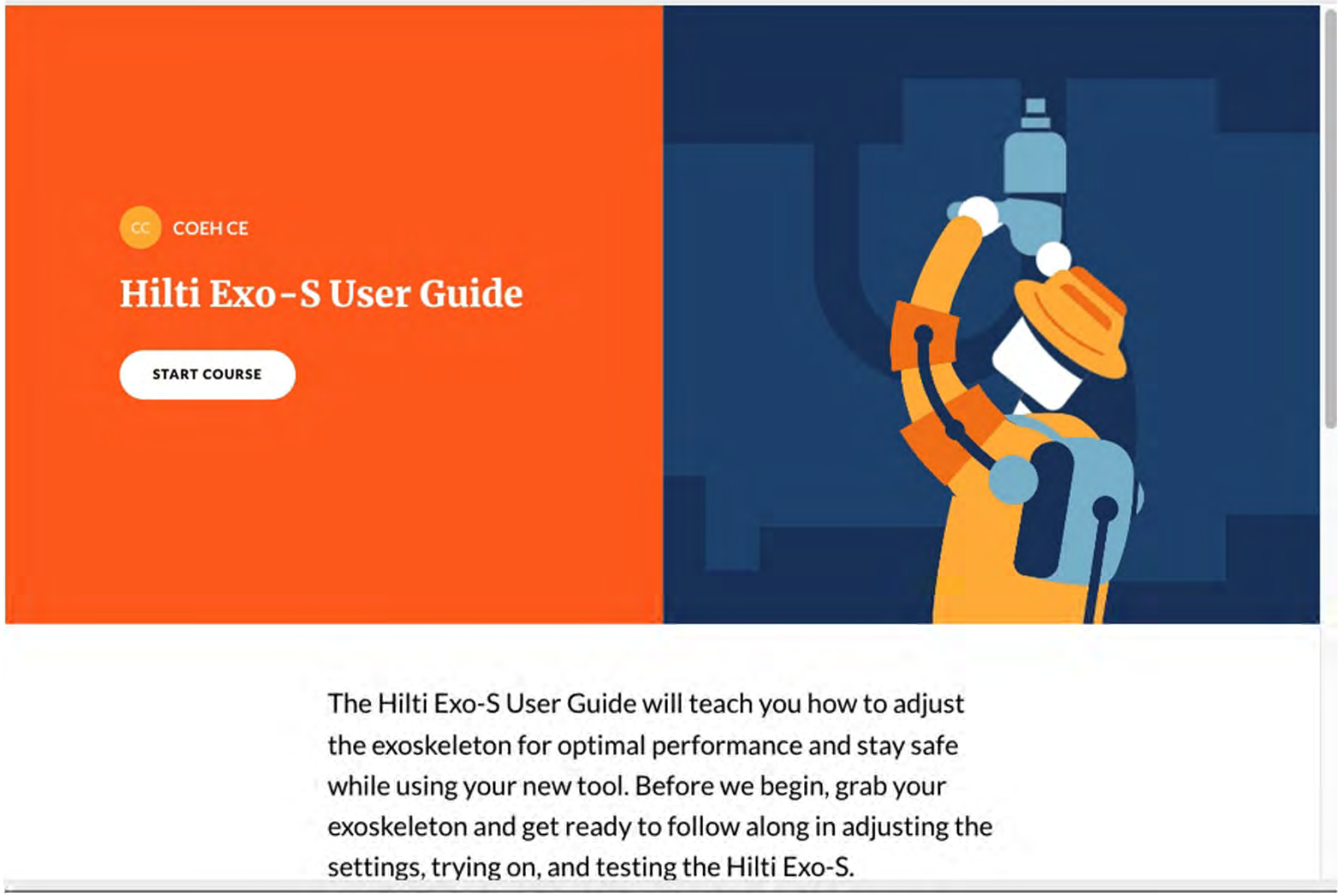
You will need **extra clearance and time** to maneuver through scaffolds or other constrained spaces.

Balance is minimally impacted while walking, even on beams, whether the device is on or off.

Be CAUTIOUS when wearing an Exo while climbing as it can impact your sense of balance and safety when reaching overhead.

Visit www.tiny.url/exofit to generate your individualized support settings based on your sex, height, weight, type of exoskeleton, and task that you will be performing.

Aim 3: Creating the Interactive ASE Guide



Aim 3: Creating the Interactive ASE Guide

Arm Support Exoskeleton Fit and Support Level Estimator

Exoskeleton Make:

Hilti ExoS

Preferred Activity:

Overhead Work

Your Height (cm):

160

Your Weight (kg):

65

Your Sex:

Male

Get Recommendation

Support Level Setting:		**Shoulder Breadth Setting:**	
Arm Length Setting:		**Waste Setting:**	
Spine Length Setting:		**Arm Cuff Size:**	

Aim 3: Evaluating the ASE Guide

	User Guide	**Hilti Exo S**
Learnability	Correctly identify different parts of the Exoskeleton	Proper adjustment of the exoskeleton was achieved without intervention
Efficiency	Total time to complete User Guide	Total time to don, doff, and adjust to user-specific measurements
Memorability	Score on five-question quiz given after guide completion	Proper adjustment and fitting were achieved without intervention
Errors	Errors made while navigating the User Guide (misclicks)	Total Errors made while adjusting and donning the exoskeleton
Satisfaction and Usability	SUS Score for the User Guide	SUS Score for the exoskeleton

Conclusions

- Laboratory research is needed to answer basic questions
- Translation of laboratory research findings into practice is critical for the research to have an impact
- Identifying the most effective way to share research is challenging but impactful
  - Ask the users
  - Try different mediums
  - Get consistent feedback

The “Interactive User Guide” is still under development and will be comprehensively evaluated in the field over the next year.

Mason Development Center of Northern CA
Tracy, CA

The Center for Construction, Research and Training- CPWR

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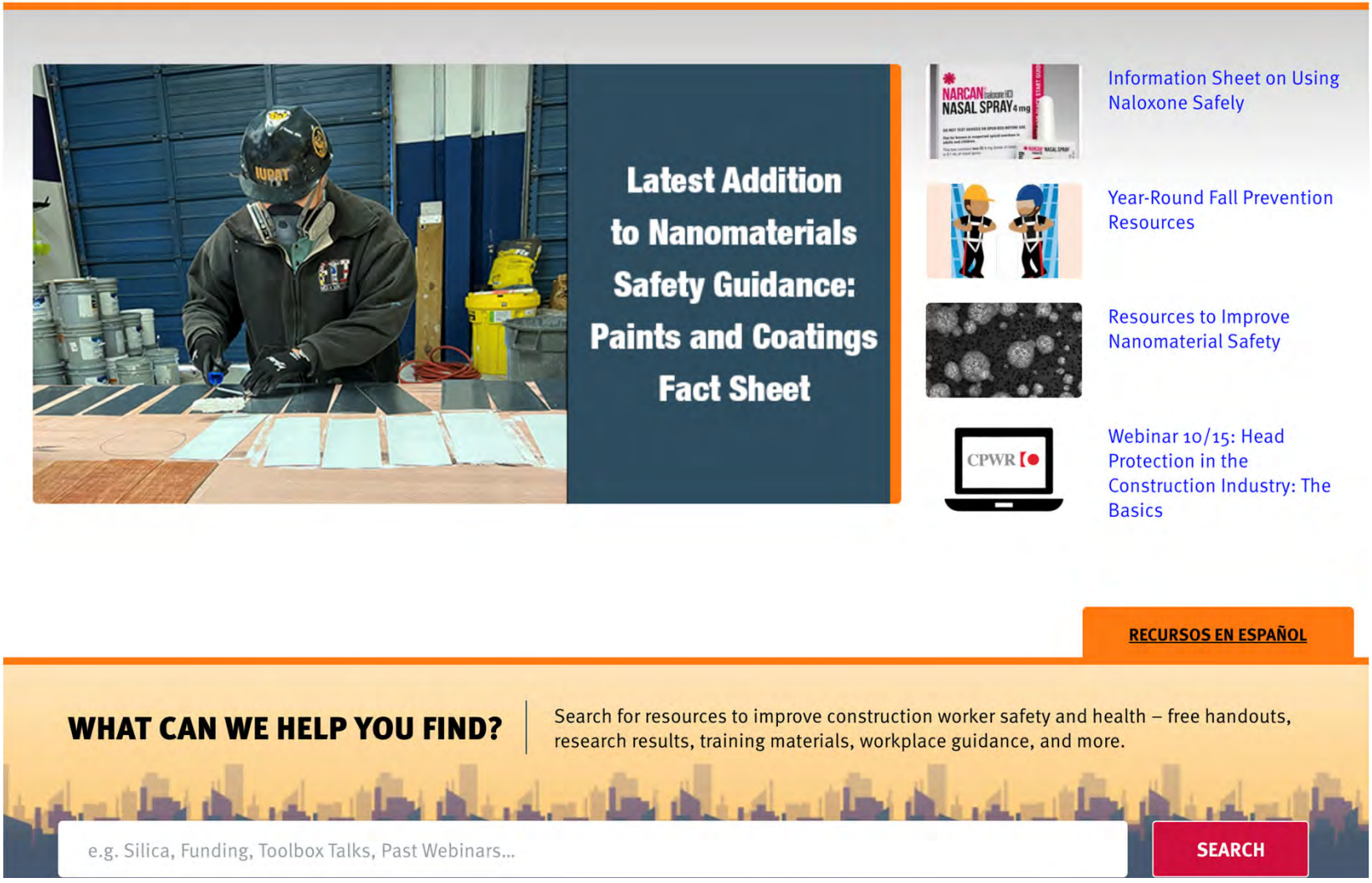

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