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# Evaluation of a 3D-Printed Exoskeleton for Reducing Lower Back Muscle Load in Tomato Greenhouse Applications

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## Abstract

INTRODUCTION: Lifting and carrying tasks are known to increase the risk of work-related musculoskeletal disorders, particularly in the lower back region.
OBJECTIVES: This study aims to evaluate the effectiveness of a 3D-printed prototyping exoskeleton (RPE) in reducing the strain on lower back muscles during the transport of fruit boxes in a tomato greenhouse.
METHODS: A 3D-printed exoskeleton was designed and tested, with participants performing tasks such as lifting, carrying, and lowering heavy objects on tomato farms. The evaluation involved comparing muscle activity with and without the exoskeleton intervention. Muscle activity data were collected from 15 participants, focusing on the erector spinae (ES), latissimus dorsi (LD), anterior deltoid (AD), and medial deltoid (MD) muscles.
RESULTS: The results demonstrated that using the exoskeleton significantly reduced the load on back muscles by 55.65% to 63.55% during lifting. Additionally, during carrying tasks, the exoskeleton reduced the load on the anterior deltoid muscle by 7.00% to 8.61%.
CONCLUSION: The RPE also effectively decreased rectus femoris activity during dynamic lifting and carrying tasks, potentially alleviating pain and discomfort and reducing the risk of developing back-related disorders.

**Keywords:** Exoskeleton, Rapid prototyping, Electromyography

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## 1. Introduction

Work-related musculoskeletal disorders (WMSDs) are common occupational health concerns, particularly in tasks involving manual handling [1, 2]. Among these, lower back pain (LBP) stands out as a significant issue affecting workers in both developed and developing countries [3]. The causes of LBP are multifaceted, with major risk factors including exposure to high or repetitive forces on lumbar tissues, such as muscles, ligaments, vertebrae, and intervertebral discs [4]. Agricultural work, for example, frequently exposes individuals to ergonomic risks that contribute to back pain and shoulder fatigue [5]. Tomato farmers, in particular, often perform physically demanding tasks like handling and stacking heavy boxes. Unfortunately, the repetitive nature of these activities, such as lifting and carrying, places substantial strain on their bodies, leading to recurring pain in the back and shoulders. While industries worldwide have adopted robots, automation, mechanization, and ergonomic interventions, manual labor remains indispensable for many tasks. In certain roles, workers are essential for performing tasks that require observation and decision-making. In others, human precision, skill, and physical strength are crucial for completing specific tasks effectively [1, 6, 7].

In this context, wearable assistive devices, such as exoskeletons, offer a promising solution to further reduce the

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risks associated with strenuous manual [7]. Designed to enhance the mechanical capabilities of the human body, exoskeletons alleviate biomechanical loads, reducing strain on muscles, ligaments, and joints. This makes them particularly beneficial for labor-intensive roles, such as those of tomato farmers, who frequently engage in repetitive lifting and carrying tasks that lead to chronic back and shoulder pain Exoskeletons are broadly categorized into active and passive systems. Active systems use actuators to amplify human strength, while passive systems rely on elastic or spring components to store and release energy during motion, effectively supporting workers in physically demanding activities [8].

Exoskeletons available on the commercial market have largely been developed for rehabilitation, providing support and assistance to individuals who are physically weak, injured, or disabled during prescribed exercises and daily activities [9]. A smaller subset of exoskeletons has been designed for military applications, focusing on enhancing the muscular strength and carrying capacity of soldiers [10]. While active industrial exoskeletons remain predominantly in the research and development phase, passive exoskeletons have already entered the market. To achieve widespread adoption and commercial viability, particularly for active exoskeletons, it is essential to establish their efficacy and safety [7]. Several back-supporting exoskeletons designed to assist with trunk flexion or hip extension have undergone scientific evaluation, including PLAD [11], BackX [12], Robo-Mate [13], and SPEXOR [14]. Each of these devices features unique design attributes that can yield varying effects on users [15]. However, the demanding nature of tomato farming highlights the urgent need for a specialized exoskeleton tailored to this environment. Tomato farming tasks, such as lifting and carrying heavy loads, often take place in confined spaces like greenhouses and require prolonged physical effort throughout the day. These unique conditions necessitate a dual-function exoskeleton that combines an active back-support system and a passive shoulder-support system to address the distinct ergonomic challenges.

Tomato farming involves a variety of physically demanding tasks that place strain on different parts of the body, requiring a specialized exoskeleton design to address these challenges effectively. Lifting and bending movements, which are frequent during tasks such as picking or loading heavy crates, exert significant stress on the lower back muscles. For these activities, an active back-support exoskeleton is essential. Equipped with actuators, this system provides dynamic mechanical assistance to the lower back, reducing the load on the erector spinae muscles and minimizing fatigue and the risk of injury. On the other hand, carrying tasks, where farmers transport heavy loads over short distances, often strain the shoulders and upper body. For these activities, a passive upper limb exoskeleton is more suitable. Utilizing elastic or spring-based components, the passive system offers lightweight, energy-efficient support to the shoulder muscles by redistributing the load and reducing muscle effort without the need for external power sources. By combining an active back-support system for lifting and bending with a passive shoulder-support system for carrying, the exoskeleton can provide comprehensive support tailored to the unique physical demands of tomato farming. This integrated approach ensures optimal ergonomic benefits, enhancing both comfort and productivity while reducing the risk of work-related musculoskeletal disorders. Although a limited number of back-supporting exoskeletons have undergone field testing [16-18]. Muscle activity assessments have become a common method for evaluating their effectiveness. Research consistently highlights promising results, showing a significant reduction in muscle activity (ranging from 10% to 40%) in targeted areas, such as the back muscles responsible for torso elongation and arm lifting [19-21]. However, a thorough evaluation of the exoskeleton's effects on non-targeted muscle groups remains essential to ensure a holistic understanding of its overall impact and usability.

This study aims to examine the hypothesis that a combined exoskeleton designed for tasks in tomato greenhouses can effectively reduce muscle activation in the lower back, thereby decreasing the risk of lower back pain (LBP). To achieve this, we developed a preliminary dual-function exoskeleton, comprising an upper limb passive exoskeleton for the shoulders and a lower active exoskeleton for the back. The design process includes detailed parameters for fabricating its 3D-printed frame. A quantitative evaluation of the exoskeleton's performance during tomato farming tasks was conducted, focusing on its potential to reduce activation of the erector spinae muscles while minimizing any adverse effects on other muscle groups. By seamlessly integrating passive and active support systems, this innovative solution aims to provide enhanced ergonomic benefits and improve the physical well-being of farmers engaged in strenuous greenhouse work.

## 2. Materials and methods

### 2.1. Participants

Fifteen farmers (males) were also recruited; their average age, height and weight were 55.3 (SD = 9.8) years old, 168.3 (SD = 7.3) cm and 76.3 (SD = 13.5) kg, respectively. None of the recruited individuals had any musculoskeletal illnesses. The Kaohsiung Veterans General Hospital's Institutional Review Board (IRB) examined and approved the experimental design protocols with IRB number KSVGH20-CT6-10. All participants in this study signed a permission form.

### 2.2. Participants

The exoskeleton structure is designed as an arm and back assistant to reduce muscle strain while the farmers perform their usual activities. The exoskeleton structure was designed by Creo Parametric version 7.2 and fabricated with a 3D printer with poly (lactic acid) (PLA) plastic. We use the Repetier-Host V2.3.2 software to do the G-code for the 3D printer base on the CuraEngine slicer. The shell thickness is 3mm, and the infill density has been set at 0%. The total weight of the system is 6.4 kg. RPE is a combination of a passive exoskeleton that is lightweight and suitable for agile and dexterous movements of the hand and a back exoskeleton that is an active exoskeleton equipped with two servo motors with a total capacity of up to 400 w (MIT cheetah servo motor) and a maximum torque of up to 36 Nm to provide power to the user's back during lifting operations. The architecture of the exoskeleton is shown in Fig. 1.

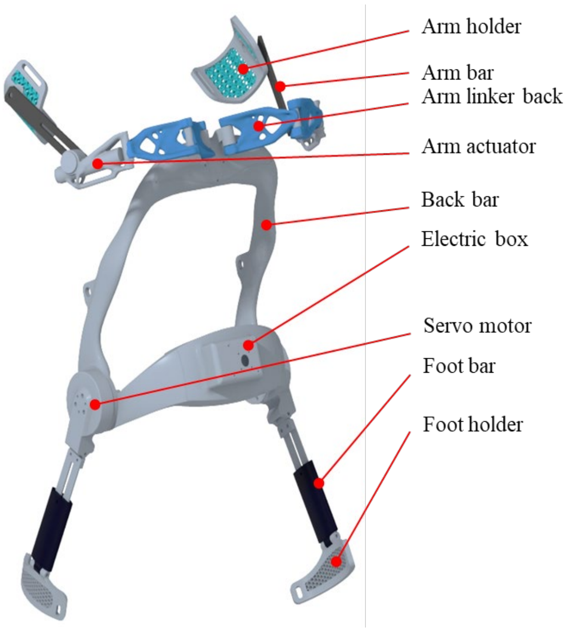


**Figure 1.** The architecture of prototype exoskeleton.

## 2.3. Procedures for electromyography measurement

We evaluated the feasibility of the exoskeleton by collecting electromyography (EMG) data from participants performing tasks in a tomato greenhouse under two conditions: with the exoskeleton (W) and without the exoskeleton (Wo). The evaluation process involved the following steps:

- Task performance without the exoskeleton: Farmers moved fruit crates from a cart to a truck in the Wo condition. Each participant moved 30 fruit crates, one at a time, with each crate weighing 6 kg. The researcher recorded the time taken for lifting, lowering, and carrying tasks. To ensure convenience and eliminate potential bias, measurements were first conducted in the Wo condition.
- Rest period: After completing the tasks, participants rested for 20 minutes to reduce fatigue.
- Task performance with the exoskeleton: Following the rest period, participants repeated the same task of moving the remaining crates, but this time in the W condition using the exoskeleton.

All simulation steps are illustrated in Fig. 2, and real-world task execution is depicted in Fig. 3. During these activities, EMG data was collected from four key muscles: the erector spinae (ES), latissimus dorsi (LD), anterior deltoid (AD), and medial deltoid (MD). This data provides valuable insights into the impact of the exoskeleton on muscle activation during typical farming tasks.

(a) (b) (c)

**Figure 2.** Farmer's activities during work: (a) lifting, (b) carrying, (c) lowering

## 2.4. Electromyography measurement

Electromyography (EMG) is a diagnostic technique used in medicine to record and assess the electrical activity generated by muscles during bodily movements. In this study, EMG data was collected and utilized to compare the differences in muscle activity between two conditions: with and without RPE, during four tasks are classified and detected. The measurement procedures and settings were based on previous experiments conducted by [22-25]. Bipolar electrodes were placed at cleaned sites with 25 mm intervals, while a ground electrode was positioned on the C7 spinous process. The EMG signals from four muscles were measured using a portable EMG system (Nexus 10, Mind Media BV, Netherlands) at a sampling frequency of 2048 Hz. The muscle activity data during lifting, putdown, and carrying trials were collected from 15 participants using Nexus Bio Trace software (V2018A1, Mind Media BV, Netherlands).

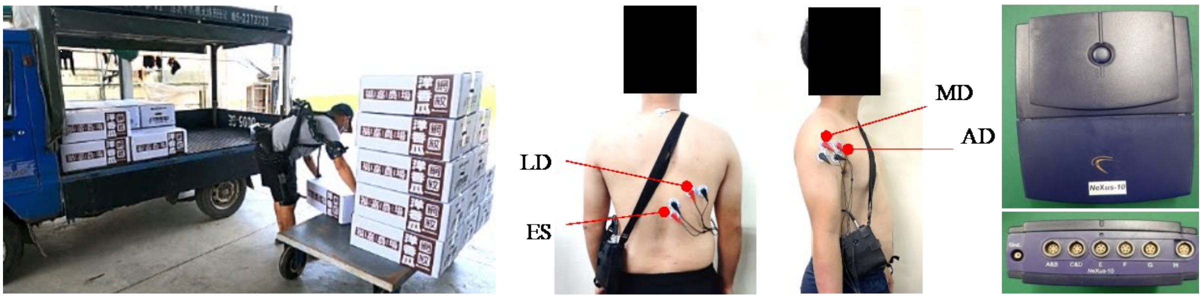


**Figure 3.** Illustrates the movement of fruit crates in a tomato greenhouse (a), positions of the measured points in this study (b), EMG data recording device in this study (c).

## 2.4. Data Analysis

The EMG data was normalized as a percentage of each participant's MVC. The collection of EMG data for long-term repetitive muscle activities produces a very large number of values. The data should therefore be shortened to facilitate analysis. We used an amplitude distribution probability function (ADPF) to collect normalised data, such as the 10th, 50th and 90th percentiles [26]. A significance level of 5% was accepted as statistically significant for all analyses, and SPSS (version 21, SPSS Inc., Chicago, USA) was used to perform the analyses. Additionally, a t-test is performed on two interventions W and Wo of data to obtain a p-value. The normalization of EMG is defined in equation (1).

$$\%MVC = \frac{EMG - MINEMG}{MAXEMG - MINEMG} \times 100 \quad (1)$$

# 3. Materials and methods

For the boxes lifting task, the use of the exoskeleton resulted in a statistically significant decrease in muscle activation. Specifically, the erector spinae (ES) muscle activity decreased by 55.65% at the 50th percentile and 63.55% at the 90th percentile. These reductions are notably higher compared to previous studies. For instance, Huysamen et al. (2018) observed a 12% reduction in muscle activity [13], while Ko et al. (2018) reported a 23.5% reduction in TED muscle activity with the use of the H-WEX exoskeleton [27]. Additionally, Thamsuwan et al. (2020) demonstrated a 48% reduction in muscle activity using a hip passive exoskeleton [28]. However, it is important to note that some studies, such as those conducted by Huysamen et al. (2018), Ko et al. (2018), and Thamsuwan et al. (2020), also reported a 12% increase in static muscle activity. The exceptional reductions in ES muscle activity observed in this study, surpassing earlier findings, can be attributed to two key factors. First, the relatively low load weight of 6 kg minimizes the strain on muscles. Second, the exoskeleton's advanced design ensures a close fit and optimal force transmission from the device's motors to the user's body, enhancing its effectiveness. Additionally, the study revealed significant reductions in latissimus dorsi (LD) muscle activity, with a 67.97% decrease at the 90th percentile. For the anterior deltoid (AD) and medial deltoid (MD) muscles, activity reductions were 67.36%, 63.31%, and 37.25% at the 10th, 50th, and 90th percentiles, respectively. Before using the exoskeleton, the activation levels in the AD and LD muscles were approximately 20% of maximal voluntary contraction (MVC). This indicates that adjustments to the spring coefficient of the exoskeleton can further optimize its performance, effectively reducing muscle activation without causing discomfort. These findings align well with prior studies on upper limb exoskeletons. For example, Gillette et al. (2017) reported an AD muscle activation level of around 20% using the Airframe™ [29], while the EksoVest™ demonstrated an average activation level of 28% in studies conducted by [30]. The observed reductions in muscle activation in this study highlight the potential of the exoskeleton in reducing physical strain, particularly in tasks involving repetitive lifting and carrying.

During the carrying task, a moderate reduction in muscle activation was observed with the use of the exoskeleton. Specifically, the erector spinae (ES) muscle showed reductions of 12.85%, 10.70%, and 8.97% at the 10th, 50th, and 90th percentiles, respectively. The latissimus dorsi (LD) muscle experienced decreases of 14.17%, 10.51%, and 13.05% for the same percentiles. Similarly, the anterior deltoid (AD) muscle exhibited reductions of 7.00%, 2.76%, and 8.61%. However, the medial deltoid (MD) muscle displayed non-statistically significant increases in activation, rising by 20.54%, 34.61%, and 34.62% at the 10th, 50th, and 90th percentiles, respectively. During carrying tasks, the shoulders bear considerable strain as they support the heavy load and prevent it from touching the ground. In this context, the upper extremity exoskeleton plays a pivotal role in redistributing part of the load from the arms to the legs, thereby bypassing the spine. This load-sharing mechanism contributes to the observed decreases in activation levels of the ES and LD muscles, even though the exoskeleton's support for the lower extremities is temporarily disengaged during carrying [31].

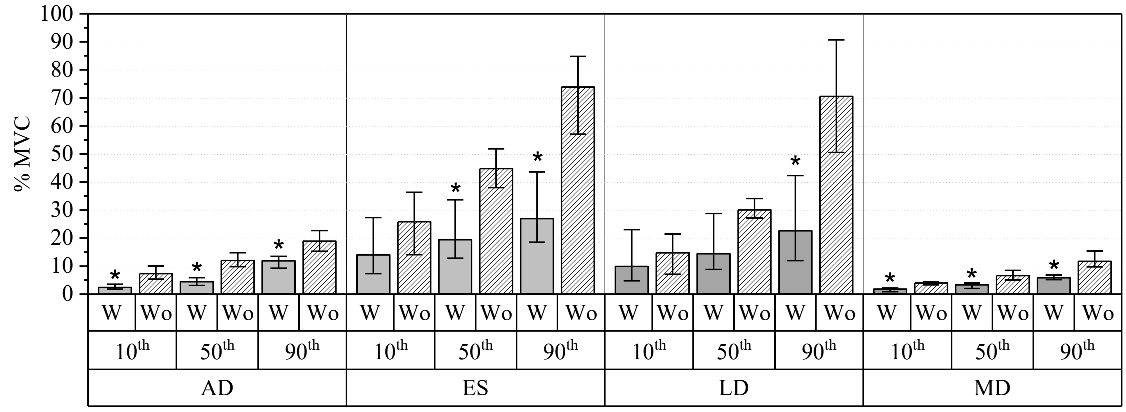


**Figure 4.** The activation of LS, LD, AD and MD during lifting task. The asterisk indicates significance when compared to the no exoskeleton condition. 10th is the ADPF of 10 percentiles, 50th is the ADPF of 50 percentiles, 90th is the ADPF of 90 percentile, ADPF is amplitude distribution probability function

These findings highlight the nuanced role of the exoskeleton in assisting muscle activity during lowering tasks. While the reductions in muscle activation are less pronounced than in lifting or carrying tasks, the exoskeleton still provides meaningful support. The static nature of the arm muscles during lowering may limit the extent of activation reduction, but the exoskeleton's ability to redistribute load and stabilize movements remains beneficial. Additionally, the increased activation levels in the LD and AD muscles during lowering emphasize the need for precise control when placing loads, which can otherwise increase strain and fatigue. The exoskeleton appears to alleviate this challenge by enabling more efficient force distribution, reducing the risk of overexertion and potential musculoskeletal injuries. From a practical perspective, these results suggest that the exoskeleton is particularly effective in tasks requiring controlled and precise movements, such as lowering, where muscle strain is focused on specific regions. However, further refinements to the exoskeleton's design could enhance its ability to provide consistent support across dynamic and static states, potentially improving its performance for lowering tasks even further. Future studies could explore optimizing the device's adaptability to static muscle conditions and its impact on long-term muscle fatigue during repetitive lowering tasks.

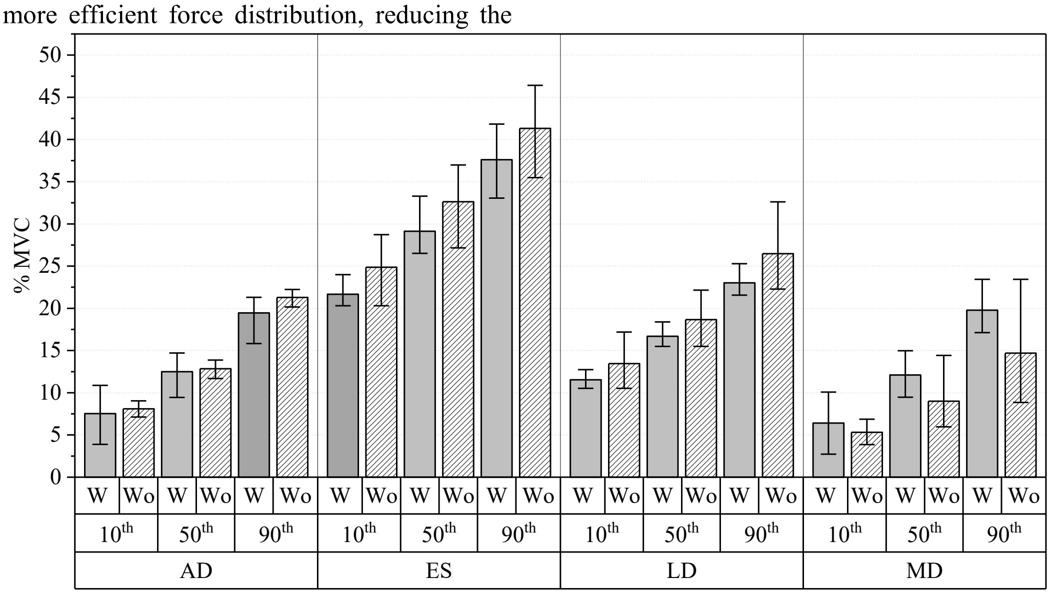


**Figure 5.** The activation of LS, LD, AD and MD during carrying. The asterisk indicates significance when compared to the no exoskeleton condition. 10th is the ADPF of 10 percentiles, 50th is the ADPF of 50 percentiles, 90th is the ADPF of 90 percentiles, ADPF is amplitude distribution probability function

Table 1. p-Values from Paired t-Test Comparing Without Exoskeleton Intervention to Exoskeleton Intervention for Lifting Tasks

| | ES | LD | AD | MD |
|---|---|---|---|---|
| 10th | .266 | .547 | .013 | .000 |
| 50th | .025 | .053 | .015 | .009 |
| 90th | .007 | .007 | .035 | .038 |

Notes: Values in bold indicate statistical significance when compared to the exoskeleton intervention. 10th is the ADPF of 10 percentiles, 50th is the ADPF of 50 percentiles, 90th is the ADPF of 90 percentile, ADPF = amplitude distribution probability function. ES = the erector spinae, LD = latissimus dorsi, AD = anterior deltoid, and MD = medial deltoid.

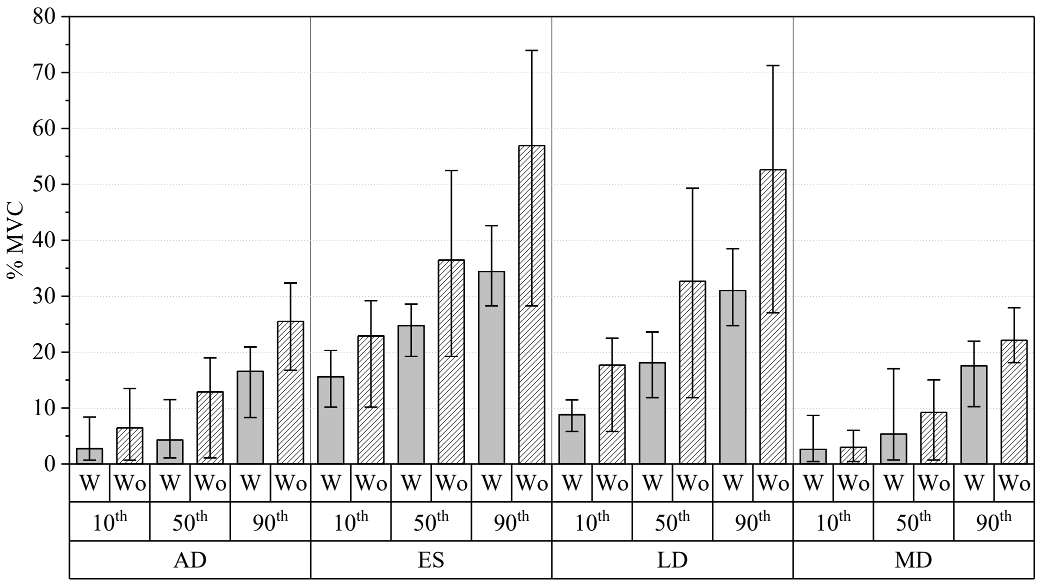


**Figure 6.** The activation of LS, LD, AD and MD during lowering. The asterisk indicates significance when compared to the no exoskeleton condition. 10th is the ADPF of 10 percentiles, 50th is the ADPF of 50 percentiles, 90th is the ADPF of 90 percentiles, ADPF is amplitude distribution probability function

Table 2. p-Values from Paired t-Test Comparing Without Exoskeleton Intervention to Exoskeleton Intervention for carrying Tasks

| | ES | LD | MD | AD |
|---|---|---|---|---|
| 10th | .190 | .190 | .681 | .518 |
| 50th | .240 | .252 | .628 | .234 |
| 90th | .278 | .335 | .320 | .191 |

Notes: Values in bold indicate statistical significance when compared to the exoskeleton intervention. 10th is the ADPF of 10 percentiles, 50th is the ADPF of 50 percentiles, 90th is the ADPF of 90 percentile, ADPF = amplitude distribution probability function. ES = the erector spinae, LD = latissimus dorsi, AD = anterior deltoid, and MD = medial deltoid

Table 3. p-Values from Paired t-Test Comparing Without Exoskeleton Intervention to Exoskeleton Intervention for Lowering Tasks

| | ES | LD | MD | AD |
|---|---|---|---|---|
| 10th | .118 | .062 | .444 | .897 |
| 50th | .147 | .107 | .089 | .395 |
| 90th | .088 | .127 | .071 | .201 |

Notes: Values in bold indicate statistical significance when compared to the exoskeleton intervention. 10th is the ADPF of 10 percentiles, 50th is the ADPF of 50 percentiles, 90th is the ADPF of 90 percentile, ADPF = amplitude distribution probability function. ES = the erector spinae, LD = latissimus dorsi, AD = anterior deltoid, and MD = medial deltoid

## 3. Conclusions

This study highlights the effectiveness of a combined passive shoulder-support and active back-support exoskeleton in reducing muscle activation during tomato farming tasks. Significant reductions in erector spinae (63.55%), latissimus dorsi (67.97%), and anterior deltoid activity were observed during lifting, with moderate reductions during carrying and lowering tasks. The exoskeleton's lightweight design and efficient force transmission contributed to its performance, alleviating strain on the back and shoulders while minimizing discomfort. These results demonstrate the exoskeleton's potential to reduce the risk of lower back pain and improve occupational safety for farmers, paving the way for its broader application in greenhouse environments.


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