

Article

Biomechanical Effectiveness and Wearability of a Passive Shoulder Exoskeleton in an Automotive Assembly

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Featured Application

Potential applications of this study include preventing work-related musculoskeletal disorders (WRMSDs) in automotive assembly lines, specifically for tasks involving prolonged overhead work. The findings provide field-based evidence supporting the potential use of passive shoulder exoskeletons as an ergonomic intervention for overhead automotive assembly work.

Abstract

Background and Objectives: Exoskeletons may be useful in preventing musculoskeletal disorders. This study aimed to evaluate the biomechanical and subjective effects of a passive shoulder exoskeleton during overhead assembly work in a real-world automotive manufacturing environment. **Materials and Methods:** Sixteen workers performing overhead assembly tasks participated in this study. Muscle activity, joint angles, and joint reaction forces were compared between the No Exo and Exo conditions during overhead work. Muscle activity was measured using surface electromyography (EMG), upper-body kinematics were captured using inertial measurement units (IMUs), and shoulder joint torques and reaction forces were estimated using the AnyBody musculoskeletal modeling system. Additionally, user satisfaction was assessed through a questionnaire. **Results:** Comparison of biomechanical outcomes between the No Exo and Exo conditions showed that the Exo condition significantly reduced anterior and lateral deltoid activities by approximately 15.2% and 11.1%, respectively, and reduced glenohumeral joint reaction force by 115.24 N (all $p < 0.05$). Participants also reported lower physical workload ($p < 0.001$). **Conclusions:** The study results suggest that wearing an exoskeleton during overhead work may reduce shoulder muscle loading and improve biomechanical indicators associated with shoulder loading.



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Keywords: shoulder; exoskeleton; overhead work; muscle activity; joint kinetics

1. Introduction

Work-related musculoskeletal disorders (WRMSDs) are injuries or disorders affecting the musculoskeletal system, including muscles, nerves, tendons, ligaments, and joints. They may be caused by various workplace factors such as excessive force, repetitive movements, awkward postures, contact with sharp surfaces, vibration, and temperature extremes [1]. WRMSDs account for the largest proportion of occupational diseases in the Republic of Korea [2]. Musculoskeletal disorders of the shoulder account for the largest share of WRMSDs, for which applications for recognition of occupational disease were made, excluding injuries due to industrial accidents [3].

Occupational risk factors for musculoskeletal disorders of the shoulder include work involving repetitive movements, awkward postures (e.g., overhead work), and excessive force [4–6]. In particular, in the automotive assembly process, assembling the lower sections of vehicles inevitably involves overhead work because the vehicles pass above the workers' heads. Since this type of work is highly likely to cause shoulder disorders such as rotator cuff syndrome, measures should be taken to reduce or prevent their occurrence. In this context, the exoskeleton has been attracting attention as a potential solution. The exoskeleton is a wearable device that augments, enables, assists, or enhances motion, posture, or physical activity [7]. There are two types of exoskeletons: passive and active. Active exoskeletons receive additional energy from electric motors or pneumatic actuators and thus provide precise and versatile assistive torques [8–10]. However, they are large, and maintenance costs are significant [11]. On the other hand, passive exoskeletons store and release the user's motion using gas, coil springs, flexible beams, or elastic elements [12,13]. Passive exoskeletons are characterized by a cheaper and lighter design compared to active exoskeletons, and provide arm gravity compensation without an external power source when performing overhead work [14,15].

So far, exoskeletons have been widely studied for specific medical conditions, such as stroke and spinal cord injury, to help patients regain mobility, improve walking, and enhance rehabilitation outcomes by providing adaptive, real-time support [16,17]. Recently, there has been active research on developing auxiliary exoskeletons for occupational activities to support workers in physically demanding jobs and reduce strain and fatigue. Among these, passive shoulder exoskeletons have been studied the most. Recent systematic reviews on exoskeletons confirm their effectiveness in cross-sectional laboratory studies [18,19], while field evaluations have been found to reduce muscle activity and other variables (please specify which) [20,21]. Assessment of the utility of exoskeletons among automobile assembly workers has primarily been conducted through self-reported questionnaires [22–26] or with electromyographic analysis [27]. It has not been possible to conduct biomechanical analysis due to difficulties in controlling work activities in the real world. Shoulder exoskeletons used in industrial settings, including automotive assembly processes, need to meet specific requirements. They need to be portable and lightweight to avoid burdening the worker's body [26]. In addition, they should not restrict the shoulder range of motion and should provide maximum assistance during overhead work [27].

Therefore, to address this gap, the primary objective of this study was to comprehensively evaluate the biomechanical effects and subjective comfort associated with the use of a passive shoulder exoskeleton during overhead work in individuals working in an automobile assembly process. Specifically, we aimed to quantify the physical workload by measuring changes in muscle activity via electromyography (EMG), upper-body kinematics

using inertial measurement units (IMUs) with Xsens MVN motion capture software, and shoulder joint torque and joint reaction force via simulation. Ultimately, this study sought to determine whether the exoskeleton effectively reduces shoulder biomechanical loading during overhead automotive assembly work.

2. Materials and Methods

2.1. Shoulder Exoskeleton

The shoulder exoskeleton (X-ble Shoulder, Hyundai Motor Company, Ulsan, Republic of Korea) used in this study is a passive wearable exoskeleton that assists arm lifting via a multi-linkage spring-energy-dissipation mechanism [28]. Its torque generator, which is fixed to the upper arm, is connected to a rigid support at the back; this support rod is connected to a clip with a ball joint located at the waist (Figure 1). The exoskeleton allows shoulder elevation range of motion from 0° to 180°. The reported range refers to upper-arm elevation movements, including shoulder flexion and abduction, from the arm-at-side position to an overhead posture. The total weight of this exoskeleton is 1.4 kg. The X-ble Shoulder includes adjustable components, including shoulder-width adjustment, arm-support position adjustment, arm-support band adjustment, and length adjustment, allowing the device to be fitted to workers with different anthropometric characteristics.



Figure 1. Structure of X-ble shoulder and appearance while wearing.

2.2. Participants

The participants in this study were recruited from workers performing overhead assembly at an automobile factory in Ulsan, Republic of Korea. Participants were recruited through a presentation on the device, and only volunteers were included in the study. The inclusion criteria were as follows: (1) Workers who have had no musculoskeletal injuries in the upper limbs in the past year; (2) Workers who only perform specific tasks in an overhead working posture. A total of 16 male workers were finally selected. Female workers could not be included because none were present in the workplace. The basic physical condition and working environment of the recruited participants were assessed using a questionnaire prior to their participation in the study (Table 1). Each participant provided a signed informed consent form in accordance with ethical standards. This study was conducted after receiving approval from the Institutional Review Board (IRB) of Pusan National University Yangsan Hospital (IRB No. 21-2024-0009).

Table 1. Participant characteristics-Automobile assembly part.

Classification	Participants	Min	Max	Mean	Standard Deviation
Age (yr)	16	25	59	49.4	10.3
Total years of work (yr)	16	0.4	35	20.3	11.1
Current department years of work (yr)	16	0.4	35	11.4	9.6
Height (cm)	16	160	183	174.0	6.6
Weight (kg)	16	62	94	76.1	8.9
Arm Circumference (cm)	16	28.0	37.0	32.4	2.9
Grip Strength (N)	16	34.3	61.3	46.1	6.7
Classification	Current	Past	Never		
Smoking	7	6	3		
Drinking	10	3	3		
Classification	Yes	No			
Regular exercise	14	2			
Classification	S	M	L	XL	
Vest size	1	11	3	1	
Arm rest size	3	9	4	0	

2.3. Study Protocol

Approval for the experimental protocol was obtained from the occupational safety and health committee and the labor union prior to the recruitment of study participants, and detailed explanations about the protocol were provided during the participant recruitment presentation (Figure 2). This study was conducted over 4 days. On the first day, the participants were given an introduction to the exoskeleton, and the methodology for its use was explained. During the first three days, participants wore the exoskeleton while performing their routine overhead assembly work to become familiar with the assistive force, the fitting procedure, and the device's wearing method. The familiarization protocol was the same for all participants and was conducted under the same production conditions before biomechanical measurements were taken. Data was collected on the fourth day. Each worker was fitted with electromyography (EMG) and motion-tracking sensors to measure bio-signals.

Grip strength was measured as an indicator of baseline upper-extremity strength before the assembly task. Afterward, the participants assembled five vehicles without the exoskeleton and a further five with it. The order of exoskeleton use for each worker was randomized using a computer-generated sequence. The evaluated task was a chassis assembly operation performed on an automotive assembly line. Specifically, this underbody assembly process involved fastening and securing the tie rod, a core steering component, and other steering system parts with pins while the vehicle body passed overhead, using a 1.8 kg air impact wrench. Participants used an impact wrench to fasten chassis components while repeatedly elevating their arms above shoulder level. The assembly of one vehicle was considered a single assembly cycle. The work pace was determined by the production-line cycle time, and the same workstation, task content, and tools were maintained with and without the exoskeleton. Data obtained from the five vehicle assemblies with and without the exoskeleton were averaged for statistical analysis.

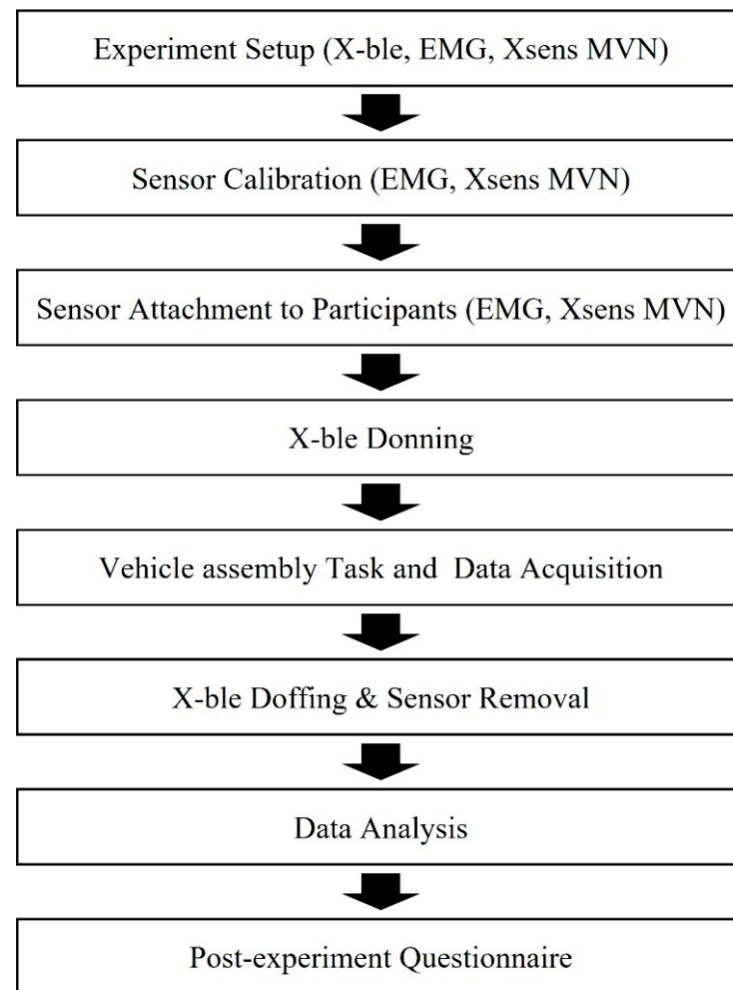


Figure 2. Flow chart of the experimental phase of the research.

2.4. Data Collection

Muscle activity was measured using the seven-channel surface EMG sensor (Delsys Trigno, Natick, MA, USA) with a sampling rate of 2148 Hz. Muscle activity was measured, focusing on the shoulder muscles and the surrounding muscles. Hence, sensors were attached to the following six muscles: Anterior deltoid (DA), lateral deltoid (DL), pectoralis major (PM), upper trapezius (UT), infraspinatus (IS), and erector spinae (ES). The raw EMG signals for each participant's muscle were band-pass filtered with a 4th-order Butterworth filter between 20 and 450 Hz. These signals were rectified and smoothed with a 6 Hz low-pass filter. Extraneous powerline noise was eliminated by applying notch filters at 60 Hz and harmonics. Finally, for each participant and condition, the EMG signals were normalized by the average peak value across all trials without an exoskeleton for each muscle. All EMG signal processing was performed in MATLAB R2024a (MathWorks Inc., Natick, MA, USA). The normalized EMG values therefore represent relative muscle activity, referenced to the condition without the exoskeleton rather than percentages of maximum voluntary contraction (%MVC).

In addition, kinematic measurements of upper-limb movements were conducted on a three-dimensional human body model created using a motion capture system based on inertial measurement units (IMUs) with a sampling rate of 60 Hz (Xsens MVN Awinda version 2024.1, Movella, Enschede, The Netherlands). IMU sensors were placed across the following upper-body segments: head, shoulders, upper arms, forearms, hands, pelvis, and trunk. The local coordinate system for each segment and joint was created to calculate

joint angles by measuring the angles between segments. For data collection and analysis, the shoulder was divided into the thoracohumeral (TH), acromioclavicular (AC), glenohumeral (GH), and sternoclavicular (SC) joints. Joint kinematics were calculated from three-dimensional segment orientations obtained from the XSENS MVN system. Shoulder flexion/extension and abduction/adduction angles were calculated as TH joint angles between the upper arm and trunk in three-dimensional space. Back flexion/extension was defined as sagittal-plane motion of the trunk relative to the pelvis, whereas neck flexion/extension was defined as sagittal-plane motion of the head relative to the trunk. Joint coordinate systems and anatomical angle definitions followed those implemented in the AnyBody Managed Model Repository™ (AMMR).

The measured joint kinematics data were filtered with a Kalman filter and exported to biomechanical human modeling and simulation software (the Anybody Managed Model Repository™ (AMMR) v2.4.4 upper-body model in the AnyBody Modeling System™ v.7.4, AnyBody Technology A/S, Aalborg, Denmark) [28]. To represent the biomechanical interaction between the worker and the exoskeleton, the standard human model was individually scaled for each participant using the length-mass scaling method based on individual heights and weights. A virtual, computer-aided design (CAD)-based mechanical representation of the X-ble Shoulder device—explicitly including its total mass of 1.4 kg, full mass distribution, and inertia—was incorporated into the simulation framework. The assistive force generated by the exoskeleton was modeled as an angle-dependent rotational spring function based on the device’s actual torque profile, and conditional contact/support forces were applied at the human-device interfaces (the upper-arm brackets and waist vest structures). Joint kinetics were subsequently calculated using fully dynamic inverse-dynamics procedures implemented in the AMS, ensuring that the estimated torques reflect the net biological joint torques required by the worker’s muscles after accounting for the mechanical assistance provided by the exoskeleton. GH net torque was decomposed in TH coordinates into flexion–extension, abduction–adduction, external–internal rotation components; GH/AC/SC joint reaction forces were computed over the entire assembly cycle and summarized as cycle-mean magnitudes per experimental condition. For each participant, the biomechanical variables were calculated separately for each of the five assembly cycles under each experimental condition. The resulting cycle-specific values were averaged across the five trials to obtain representative participant-level values for subsequent statistical analyses.

2.5. Questionnaire Survey

A questionnaire survey was conducted after completion of the experimental protocol to evaluate participants’ perceptions of the exoskeleton. Responses were collected anonymously. Subjective physical workload was assessed using the Physical Demand component of the National Aeronautics and Space Administration Task Load Index (NASA-TLX) under both the No Exo and Exo conditions using a 0–100 visual analog scale.

In addition, participants completed six descriptive questionnaire items regarding their perceptions of the exoskeleton, including overall satisfaction, perceived usefulness for preventing work-related musculoskeletal disorders (WRMSDs), arm assistance, wear comfort, perceived weight, and intention to use. These items were included to descriptively assess user perceptions of the exoskeleton. The six descriptive questionnaire items were originally collected using a five-point Likert scale (strongly disagree, disagree, neutral, agree, and strongly agree). Because of the limited sample size, responses were dichotomized for descriptive presentation. In other words, responses of “strongly disagree” and “disagree” were classified as “Unfavorable,” whereas “neutral,” “agree,” and “strongly agree” were classified as “Non-unfavorable”, respectively. This categorization was used solely to sum-

marize participants' perceptions and was not intended to imply that neutral responses represented positive satisfaction.

2.6. Statistical Analysis

Data analysis was performed using the SPSS system ver. 27 (IBM, Armonk, NY, USA). To analyze the participants' characteristics, the minimum, maximum, arithmetic mean, and standard deviation were calculated. Normality of paired differences was assessed using the Shapiro–Wilk test. Because several variables did not meet the assumption of normality and as the sample size was relatively small, comparisons between with and without the exoskeleton were performed using the Wilcoxon signed-rank test. Given the exploratory nature of this field investigation and the distinct biomechanical domains represented by the outcome variables (kinematics, EMG, joint torque, joint reaction forces, and subjective outcomes), no formal adjustment for multiple comparisons was performed. Therefore, the p -values should be interpreted as exploratory rather than confirmatory.

3. Results

3.1. Changes in Muscle Activities

In this study, EMG was used to measure changes in muscle activity. Normalized mean EMG activity was compared with and without the exoskeleton during overhead work (Table 2).

Figure 3 shows the comparison of normalized EMG activity between the No Exo and Exo conditions. The muscle activity of the DA and DL muscles decreased ($p < 0.05$), but the muscle activity of the PM, UT, IS, and ES muscles did not show a significant difference.

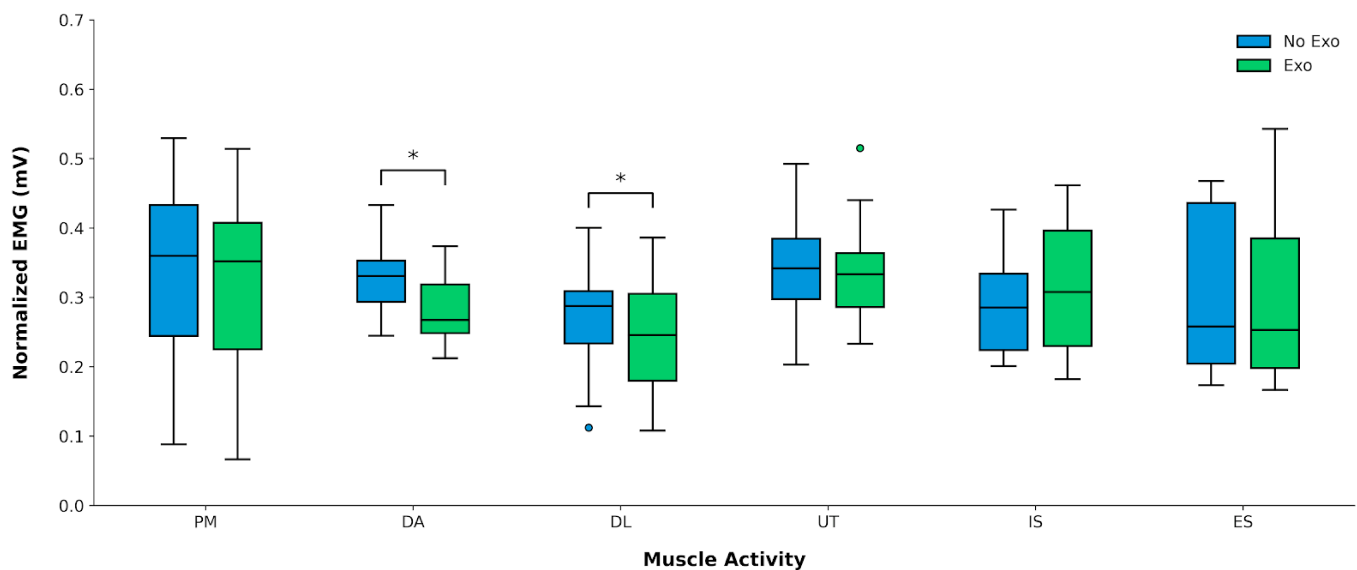


Figure 3. Comparison of normalized mean EMG activity with and without an exoskeleton. * $p < 0.05$ in the Wilcoxon signed-rank test. PM: Pectoralis major; DA: Anterior deltoid; DL: Lateral deltoid; UT: Upper trapezius; IS: Infraspinatus; ES: Erector spinae, Exo: With exoskeleton; No Exo: Without exoskeleton. The dots represent outliers.

3.2. Changes in Joint Kinetics

This study compared shoulder kinematic variables and joint kinetics in individuals with and without an exoskeleton during overhead work. Figure 4 shows that the average shoulder flexion and abduction angles increased with the exoskeleton compared to without it. The results of inverse-dynamics analysis showed significant differences in the mean thoracohumeral joint torques in the external-rotation and flexion directions with and

without the exoskeleton ($p < 0.05$). In contrast, no significant difference was observed for thoracohumeral abduction torque (Figure 4).

Table 2. Comparison of biomechanical outcomes with and without an exoskeleton.

	Classification	Mean	SD	SE	95% Low	95% Upper	Z	<i>p</i> -Value *	ES (<i>r</i>)
EMG outcomes	normMean PM No Exo/Exo	0.33/ 0.31	0.14/ 0.15	0.03/ 0.04	0.25/ 0.24	0.40/ 0.40	−1.551	0.121	0.39
	normMean DA No Exo/Exo	0.33/ 0.28	0.06/ 0.05	0.01/ 0.01	0.30/ 0.27	0.36/ 0.31	−2.844	0.004	0.71
	normMean DL No Exo/Exo	0.27/ 0.24	0.08/ 0.09	0.02/ 0.02	0.23/ 0.19	0.32/ 0.28	−2.534	0.011	0.63
	normMean UT No Exo/Exo	0.24/ 0.33	0.07/ 0.07	0.02/ 0.02	0.30/ 0.30	0.38/ 0.38	−0.259	0.796	0.06
	normMean IS No Exo/Exo	0.29/ 0.31	0.07/ 0.09	0.02/ 0.02	0.25/ 0.26	0.33/ 0.36	0.879	0.379	0.22
	normMean ES No Exo/Exo	0.30/ 0.30	0.11/ 0.12	0.03/ 0.03	0.24/ 0.24	0.36/ 0.37	0.310	0.756	0.08
Kinematic outcomes	Peak shoulder FE (°) No Exo/Exo	66.25/ 71.25	11.90/ 15.00	2.97/ 3.74	59.91/ 63.28	72.59/ 79.22	−2.617	0.009	0.65
	Mean shoulder FE (°) No Exo/Exo	42.53/ 46.83	8.28/ 12.16	2.07/ 3.04	38.11/ 46.83	46.94/ 53.32	−2.482	0.013	0.62
	ROM shoulder FE (°) No Exo/Exo	62.46/ 58.57	12.03/ 11.77	3.01/ 2.94	55.74/ 52.60	68.57/ 65.14	−1.862	0.063	0.47
	Peak shoulder AB (°) No Exo/Exo	22.64/ 27.14	8.20/ 11.38	2.05/ 2.85	18.27/ 21.08	27.01/ 33.21	−2.896	0.004	0.72
	Mean shoulder AB (°) No Exo/Exo	6.46/ 10.67	6.39/ 8.28	1.60/ 2.07	3.06/ 6.26	9.86/ 15.09	−3.516	<0.001	0.88
	ROM shoulder AB (°) No Exo/Exo	28.25/ 25.20	5.33/ 7.71	1.33/ 1.93	25.41/ 24.09	31.09/ 32.31	−0.103	0.918	0.03
	Peak back FE (°) No Exo/Exo	9.63/ 11.16	10.08/ 12.18	2.52/ 3.05	4.25/ 4.67	15.00/ 17.65	−0.879	0.379	0.22
	Mean back FE (°) No Exo/Exo	−1.82/ 1.08	8.73/ 11.12	2.18/ 2.78	−6.47/ −4.85	2.83/ 7.00	−2.327	0.020	0.58
	ROM back FE (°) No Exo/Exo	17.76/ 15.40	4.96/ 4.43	1.24/ 1.11	15.12/ 13.04	20.41/ 17.76	−2.741	0.006	0.69
	Peak neck FE (°) No Exo/Exo	18.92/ 16.53	9.41/ 9.46	2.35/ 2.36	13.90/ 11.49	23.94/ 21.57	−1.551	0.121	0.39
	Mean neck FE (°) No Exo/Exo	−14.92/ −16.09	7.86/ 9.03	1.96/ 2.26	−19.10/ −20.90	−10.73/ −11.28	−1.655	0.098	0.41
	ROM neck FE (°) No Exo/Exo	46.60/ 44.69	8.95/ 10.17	2.24/ 2.54	41.83/ 39.27	51.37/ 50.11	−1.241	0.215	0.31
Joint torque outcomes	TH abduction torque (Nm) No Exo/Exo	2.32/ 2.68	0.75/ 1.20	0.19/ 0.3	1.93/ 2.04	2.72/ 3.32	−1.138	0.255	0.28
	TH External Rotation torque (Nm) No Exo/Exo	1.29/ 1.51	0.41/ 0.50	0.10/ 0.12	1.07/ 1.24	1.51/ 1.77	−2.585	0.10	0.65
	TH Flexion torque (Nm) No Exo/Exo	11.04/ 7.85	0.90/ 1.55	0.22/ 0.39	10.56/ 7.02	11.51/ 8.68	−3.516	<0.001	0.88
Joint reaction force outcomes	AC joint reaction force (N) No Exo/Exo	333.36/ 190.73	56.02/ 67.52	14.00/ 16.88	303.51/ 154.75	363.21/ 226.71	−3.516	<0.001	0.88
	GH joint reaction force (N) No Exo/Exo	378.23/ 262.99	36.96/ 34.43	9.24/ 8.61	358.54/ 244.65	397.93/ 281.34	3.516	<0.001	0.88
	SC joint reaction force (N) No Exo/Exo	72.98/ 57.45	12.97/ 9.79	3.24/ 2.45	66.07/ 52.23	79.89/ 62.66	−3.464	<0.001	0.87

* Z and *p*-values are from Wilcoxon signed-rank tests. SD: Standard Deviation, SE: Standard Error, ES: Effect size. Difference = No Exo − Exo. Exo: with exoskeleton; No Exo: Without exoskeleton.

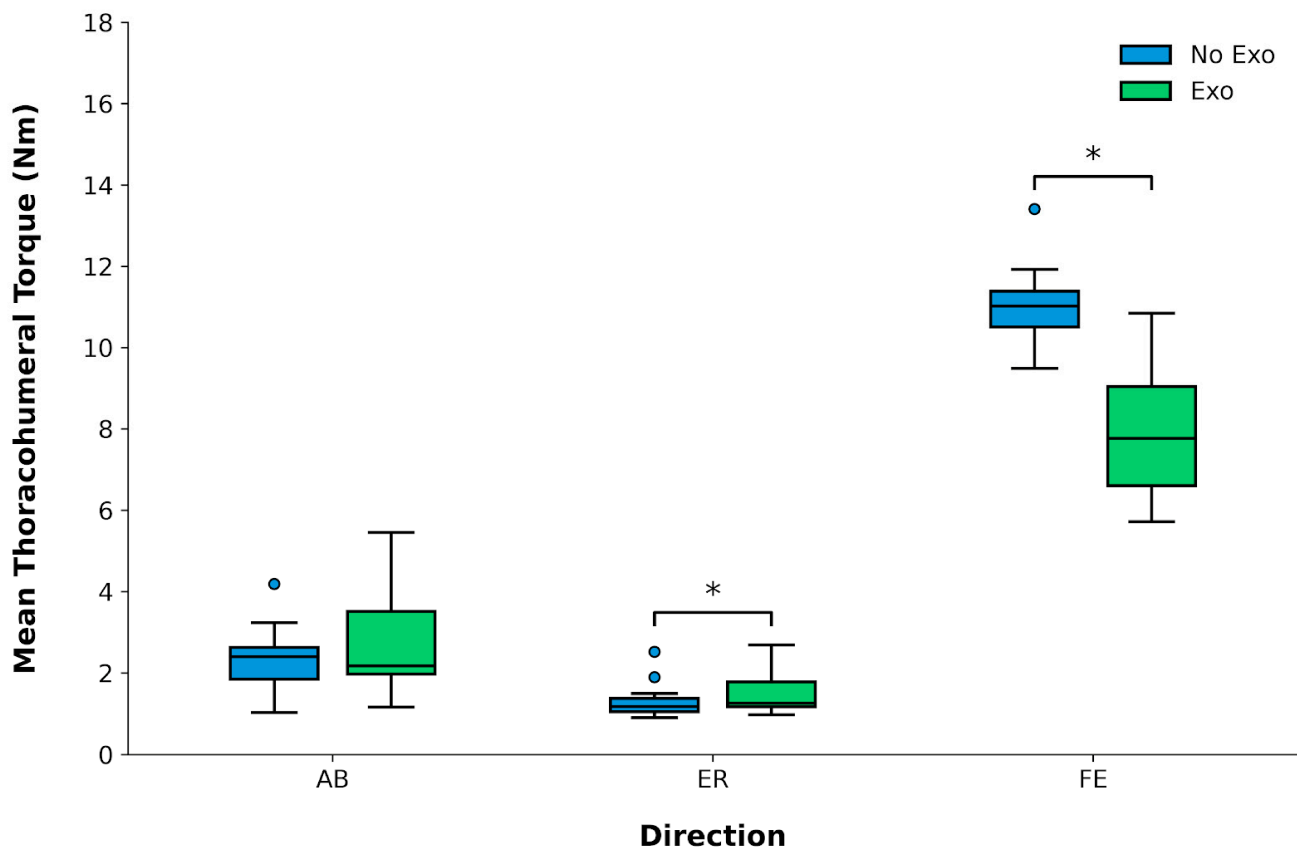


Figure 4. Comparison of mean thoracohumeral joint torques with and without an exoskeleton. Joint torques were estimated using inverse-dynamics analysis in the AnyBody Modeling System™. * $p < 0.05$ in the Wilcoxon signed-rank test. Mean thoracohumeral torque; AB: Abduction, ER: External rotation, FE: Flexion (directions), Exo: With exoskeleton; No Exo: Without exoskeleton. The dots represent outliers.

Analysis of torque changes revealed that the torque for thoracohumeral external rotation increased, while the torque thoracohumeral for thoracohumeral flexion decreased. Furthermore, the estimated AC, GH, and SC joint reaction forces were significantly lower with the exoskeleton than without it (all $p < 0.05$; Figure 5).

3.3. The Results of Questionnaire

The satisfaction questionnaire consisted of six questions. Regarding overall satisfaction, 2 people chose ‘Unfavorable’ from the two response options, and 14 chose ‘Non-unfavorable.’ As to WRMSD prevention, no respondent chose ‘Unfavorable,’ and all 16 respondents chose ‘Non-unfavorable.’ For the assistive force provided by the use of the exoskeleton, 5 people responded ‘Unfavorable,’ and 11 responded ‘Non-unfavorable.’ For exoskeleton wear comfort, 8 people responded ‘Unfavorable,’ and 8 people responded ‘Non-unfavorable.’ As for comfort with exoskeleton wear weight, 3 people responded ‘Unfavorable’ and 13 responded ‘Non-unfavorable.’

Regarding intention to use, 2 people responded ‘Unfavorable’ and 14 responded ‘Non-unfavorable.’ The NASA-TLX score for subjective physical workload significantly decreased from 54.38 ± 20.81 without the exoskeleton to 30.31 ± 14.08 with the exoskeleton ($p < 0.001$), corresponding to an approximate 44% reduction in perceived workload (Table 3). The questionnaire responses suggested that participants generally perceived the exoskeleton as potentially helpful for reducing physical workload and preventing WRMSDs. However, these findings represent participants’ subjective perceptions rather than evidence of actual prevention of WRMSDs.

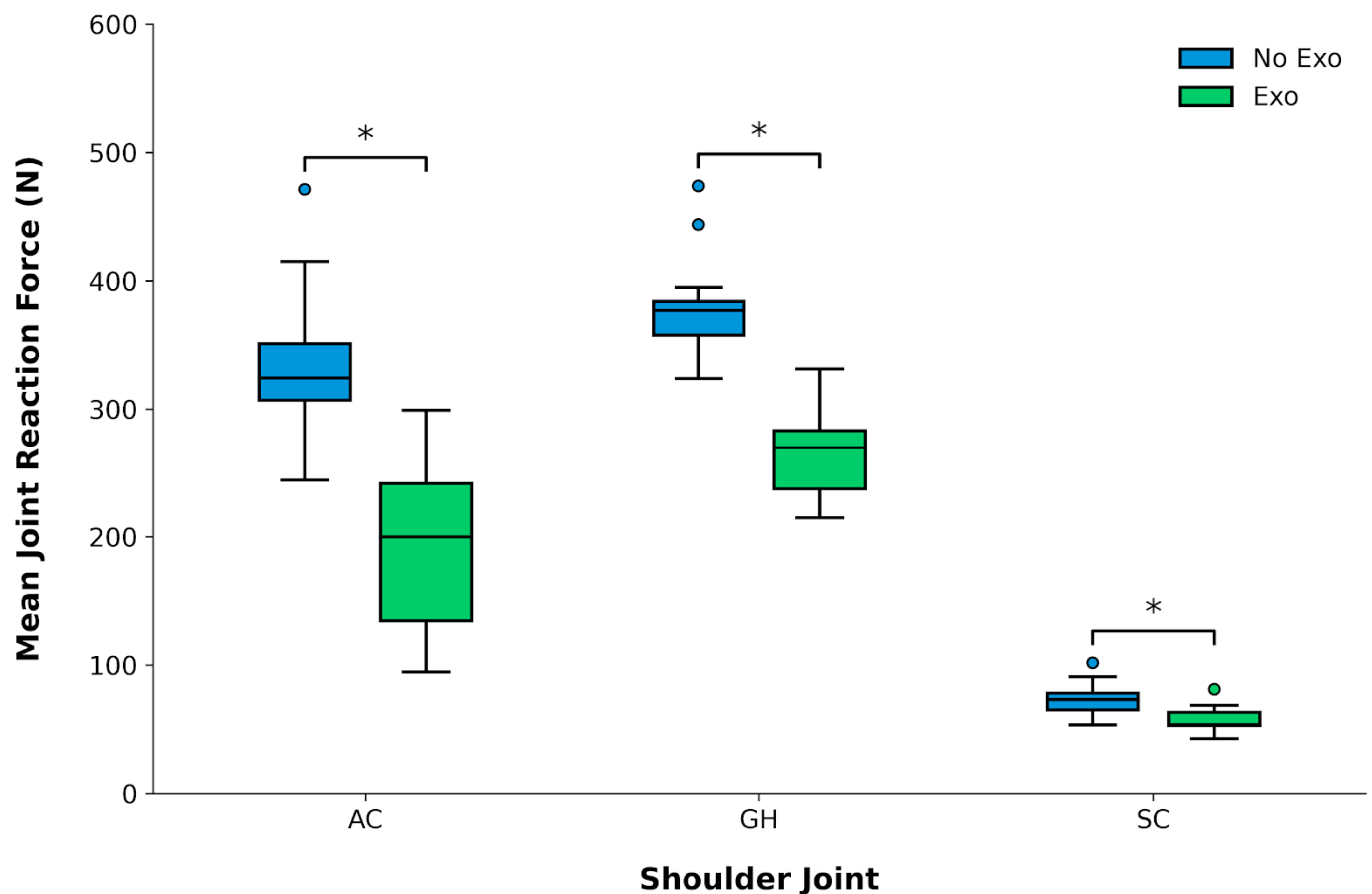


Figure 5. Comparison of mean joint reaction forces with and without and exoskeleton. Joint reaction forces at the acromioclavicular (AC), glenohumeral (GH), and sternoclavicular (SC) joints were estimated using musculoskeletal simulation. * $p < 0.05$ in the Wilcoxon signed-rank test. Exo: With exoskeleton; No Exo: Without exoskeleton. The dots represent outliers.

Table 3. Descriptions of questionnaire results (X-ble shoulder).

Classification	Unfavorable					Non-Unfavorable		
Overall satisfaction	2					14		
WRMSDs prevention	0					16		
Arm assistance	5					11		
Exo wear comfort	8					8		
Exo wear weight	3					13		
Intention to use	2					14		

Classification	Mean	SD	SE	95% Low	95% Upper	Z	p-value *	ES (r)
Physical workload No Exo	54.38	20.81	5.202	43.29	65.46	−3.534	<0.001	0.88
Physical workload Exo	30.31	14.08	3.520	22.81	37.81			

* Z and p-values are from Wilcoxon signed-rank tests. SD: Standard Deviation, SE: Standard Error, ES: Effect size, Exo: With exoskeleton; No Exo: Without exoskeleton; WRMSDs: Work related musculoskeletal disorders. Difference = No Exo – Exo.

4. Discussion

The current study found that shoulder flexion and abduction angles increased when workers used the exoskeleton for overhead work. Despite this, reduced muscle activity suggests a decrease in shoulder load. The increased shoulder angles may reflect the exoskeleton's assistive mechanism, which facilitates arm elevation without increasing muscular demand. Therefore, the observed kinematic changes do not appear to indicate

movement restriction during task performance. The exoskeleton assists workers by supporting shoulder elevation movements, thereby promoting natural motion and effectively reducing shoulder load. These changes in shoulder joint angles are consistent with findings from an earlier investigation on the use of a passive exoskeleton for overhead work [29]. The existing literature suggests that the use of an exoskeleton during overhead tasks in industries such as logistics, textiles, slaughtering, and wiring reduces muscle activity in the DA, DL, ES, and UT muscles [11–13,26]. In the present study, a statistically significant reduction in normalized muscle activity was observed in the DA and DL muscles. Both prior research and our findings consistently demonstrate that exoskeleton use reduces muscle activity in the DA and DL, thereby decreasing shoulder load. However, our evaluation revealed a statistically significant decrease in muscle activity only in the deltoid muscle. This discrepancy in findings may be attributed to differences in the type of work and the equipment used. Further, the results of this study are similar to those of a study that conducted an EMG evaluation of exoskeleton use in an automobile factory [26]. The deltoid muscle is involved in moving the upper arm in all directions during shoulder movements, and weakness of the deltoid muscle can place excessive load on the rotator cuff, which is responsible for the stability of the shoulder joint [30]. The deltoid muscle is subjected to significant stress during overhead work. Using an exoskeleton may reduce biomechanical loading on the shoulder by reducing demand on the deltoid muscle. Previous biomechanical studies have reported functional relationships between deltoid loading, glenohumeral mechanics, and rotator cuff function [31,32]. Therefore, the reduction in deltoid muscle activity observed in the present study may indicate reduced shoulder muscle demand and potentially favorable changes in biomechanical factors associated with shoulder loading. However, because rotator cuff loading and clinical outcomes were not directly measured, implications regarding rotator cuff disorders should be interpreted with caution.

Furthermore, shoulder joint kinetics were evaluated through musculoskeletal simulation. When the exoskeleton was used, the joint torque was reduced only in the thoracohumeral flexion direction, and the joint reaction forces at the AC, GH, and SC joints also decreased significantly. The decrease in joint torque and joint reaction force also reduced the force acting on the shoulder joint, thereby decreasing shoulder burden. In comparable studies, joint torque and joint reaction force were reduced when an exoskeleton was used during shoulder assembly, wiring, drilling, and screw tightening tasks [33–36]. Using an exoskeleton while working may reduce shoulder fatigue by lowering joint torque and joint reaction force, potentially reducing biomechanical risk factors associated with shoulder musculoskeletal disorders. A survey of participants' perceptions of the exoskeleton showed the following results: Most participants reported non-unfavorable perceptions regarding overall satisfaction, perceived WRMSD prevention, exoskeleton weight, and arm assistance. In contrast, only 50% reported favorable wear comfort as unfavorable. However, half of the study participants felt uncomfortable when wearing the exoskeleton. Vests of various sizes were prepared considering the participants' physiques during the evaluation, but actually, some participants wore vests that were larger or smaller than their properly fitted vest sizes, which could cause discomfort when moving the shoulder or the arm. In addition, because it was worn in the form of a vest, the participants may have felt uncomfortable as the exoskeleton was attached closely to the body; earlier research has shown that exoskeletons are not used due to their weight and discomfort [23–25,37]. Therefore, future exoskeleton development should focus on improving vest fit, body-device interface, weight distribution, and overall wearing comfort to enhance user acceptance in industrial workplaces. Since the present study focused primarily on biomechanical evaluations rather than qualitative usability assessments, identifying the exact ergonomic sources of discomfort was beyond the scope of this investigation. This detailed qualitative analysis remains an important

direction for future research. In addition, the NASA-TLX score decreased from 54.38 to 30.31, representing an approximately 44% reduction in perceived workload. This reduction is consistent with the observed decreases in deltoid muscle activity, thoracohumeral flexion torque, and shoulder joint reaction forces, suggesting that the exoskeleton may provide meaningful biomechanical unloading during overhead assembly work.

This study has several limitations. First, a major limitation of this study is the small sample size, which consisted solely of 16 male workers performing a single overhead automotive assembly task. Although the final sample size was smaller than initially planned, field-based biomechanical evaluations of occupational exoskeletons are often conducted with relatively small sample sizes due to operational constraints in active production environments. This study targeted workers performing a single task, i.e., only overhead work, on an automobile assembly line. However, the selected task was intentionally chosen because sustained overhead work is widely recognized as one of the most important biomechanical risk factors for musculoskeletal disorders of the shoulder and represents the primary target application of shoulder-support exoskeletons. In addition, participants were aware of whether they were wearing the exoskeleton, and a sham-control condition was not feasible in the actual production environment. Therefore, subjective outcomes such as perceived workload and satisfaction may have been influenced by expectancy effects. However, the primary findings of this study were based on objective biomechanical measurements, including electromyography, kinematics, joint torque, and joint reaction forces, which are less likely to be affected by such bias. Based on the power analysis, the target sample size was 30, but due to the nature of their work, only 16 were included. The remaining workers were ineligible for this study because they did not perform only overhead work; instead, they engaged in job rotation to prevent musculoskeletal disorders. Consequently, these findings should be interpreted as preliminary, field-based evidence specific to this particular occupational context. Due to the lack of female participants, differences related to gender and varied physical characteristics could not be distinguished. The results may not be generalizable to other industrial settings, different types of tasks, or female workers. Future research involving larger and more diverse populations across various workstations is required to confirm these exploratory findings. Second, the evaluation was conducted over a short 4-day period. Although this study compared the No Exo and Exo conditions, this short timeframe only allowed for the assessment of immediate effects. It does not provide information on long-term physical adaptation, user compliance, fatigue accumulation, or the actual prevention of WRMSDs. Therefore, it is difficult to definitively determine whether wearing the exoskeleton prevents common occupational diseases such as rotator cuff disorders. Future longitudinal studies are highly recommended to investigate these sustained benefits and potential long-term health outcomes. Third, automobile assembly processes include many other tasks involving postures contributing to shoulder joint problems as well as overhead work, but the participants of this study were limited to workers performing a specific task, overhead work, so it is difficult to generalize research findings to all automobile assembly processes. In addition, multiple outcome variables were evaluated without adjustment for multiple comparisons. Because this study was exploratory and included several distinct biomechanical outcome domains, the results should be interpreted with appropriate caution and confirmed in future studies with larger sample sizes. And the present findings should be interpreted as preliminary field-based evidence obtained from a specific overhead automotive assembly task and should not be generalized to all industrial settings. Future longitudinal studies are warranted to evaluate long-term adaptation, compliance, fatigue accumulation, and potential effects on musculoskeletal health.

5. Conclusions

This study provides field-based biomechanical evidence, integrating EMG, kinematics, joint torque, and joint reaction force analyses, that the tested shoulder exoskeleton may reduce shoulder muscle and joint loading during overhead automotive assembly work. By increasing shoulder joint angles while decreasing normalized deltoid muscle activity, joint torque, and reaction forces, exoskeletons serve as a viable assistive intervention that reduces shoulder muscle and joint loading and may reduce biomechanical risk factors associated with WRMSDs. Therefore, in the future, additional research is needed to develop exoskeleton equipment that is more convenient to use than the current one, taking into account various factors such as the fit and weight of the exoskeleton, and the physical condition and gender of the worker, to reduce shoulder biomechanical loading and biomechanical risk factors associated with shoulder musculoskeletal disorders. Also, to clearly determine whether the use of an exoskeleton can prevent WRMSDs, including rotator cuff disorders, epidemiological studies, such as case–control or cohort studies, are needed.

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Abbreviations

AC	Acromioclavicular
AB	Abduction
AMMR	Anybody Managed Model Repository
DA	Anterior Deltoid

DL	Lateral Deltoid
EMG	Electromyography
ES	Erector Spinae
Exo	Wearing the exoskeleton
FE	Flexion
GH	Glenohumeral
IMU	Inertial measurement units
IRB	Institutional Review Board
IS	Infraspinatus
NASA-TLX	National Aeronautics and Space Administration-Task Load Index
NIOSH	National Institute for Occupational Safety and Health
No Exo	Without wearing the exoskeleton
PM	Pectoralis Major
SC	Sternoclavicular
TH	Thoracohumeral
UT	Upper Trapezius
WRMSDs	Work-related musculoskeletal disorders
X-ble	X-ble shoulder (exoskeleton model name)

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