applied sciences

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The Development of an Innovative Occupational Passive Upper Extremity Exoskeleton and an Investigation of Its Effects on Muscles

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Abstract: Work-related musculoskeletal disorders are one of the main problems reducing the life quality of workers. Occupational exoskeletons are one of the most promising solutions for solving this issue. In this study, an innovative and passive upper-extremity exoskeleton design was presented and tested by measuring ten different muscle activities for two tasks: Task 1, for over-the-head tool handling, and Task 2, for completely stretched forearm tool handling. The special optimized switch mechanism design allowed for free motion when it was not active, which provided design advantages in comparison to the currently available designs. The muscle activity levels were measured via EMG for both tasks and the results were compared and evaluated with and without the exoskeleton on the human body. It was shown that the muscle activity for Task 1 was reduced by 55% for the middle deltoid, 37% for the posterior deltoid, and 27% for the anterior deltoid muscles, in comparison to no exoskeleton for Task 1. For Task 2, the muscle activity was reduced by 48% for the middle deltoid, 20% for the posterior deltoid, and 38% for the anterior deltoid. The exoskeleton presented in this study is an efficient design that significantly increases shoulder comfort, especially in working conditions, without bringing an additional metabolic cost for the secondary muscles.

Keywords: exoskeleton; upper limb; biomechanics; muscle forces; mechanism; musculoskeletal disorder; EMG; repetitive task; muscle fatigue

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Citation: Öçal, A.E.; Lekesiz, H.; Çetin, S.T. The Development of an Innovative Occupational Passive Upper Extremity Exoskeleton and an Investigation of Its Effects on Muscles. *Appl. Sci.* **2023**, *13*, 6763. https://doi.org/10.3390/app13116763

Academic Editor: Alejandro Rodriguez Pascual

Received: 28 April 2023
Revised: 28 May 2023
Accepted: 31 May 2023
Published: 2 June 2023

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1. Introduction

There are different types of musculoskeletal disorders related to the physical work performed by workers, however, one common reason for these disorders is repetitive motions and their resulting fatigue. Musculoskeletal imbalance emerges when fatigue outruns a worker's recovery system, which is followed by musculoskeletal disorders. Overhead tasks are not only the main reason for shoulder problems, but also for neck-related musculoskeletal disorders. The head is positioned above the cervical spine and normally the head's weight is balanced around it for anatomical position. However, overhead work requires the head to look upward, so it leads to torsional forces around the neck. These torsional forces are reason for joint inflammation and pain due to the compression of facet joints [1].

The shoulder joints and their surrounding musculature are the most susceptible due to their high range of motion and flexibility, especially for over-the-head tasks. The rotator cuff muscles and several surrounding tendons are responsible for the stability of the shoulder joints. There are several shoulder problems, but this paper focuses on disorders caused by repetitive movements performed for long-term overhead tasks. Excessive use of the shoulders under these conditions can lead to inflammation and swelling of the bursa between the rotator cuff and acromion, which is known as subacromial bursitis.

Work-related musculoskeletal disorders (WMSDs) generally occur due to repeated and sustained work activities at workshops [2]. The exact source location for these disorders may not be clearly defined because the neck, shoulder, and upper part of the arm operate as a functional unit. A further complication is that most musculoskeletal problems of this region are nonspecific and without well-defined diagnoses.

Increasing mental pressure to produce more monotonous tasks also leads to WMSDs. WMSDs are a serious health problem for workers and an important issue for companies and governments due to a lack of efficiency and health costs. WMSDs are also one of the reasons for the loss of mobility and autonomy [3]. Relaxing the muscles and letting them rest is very important when performing repetitive tasks, but some special tasks require pre-defined motions to be performed in a certain time. Additionally, manufacturing speed is very important for companies due to high competition. Disorders related to the shoulder complex comprise 15.2%, which is the second highest, following back-related WMSDs [4]. Schmalz et al. [5] indicated that monotonous, over-the-head work tasks are the major reason for shoulder WMSDs, and this risk rises to 65% if the arms are moved in a 90° anteversion and repeated for 10% of one shift. The execution time of a physical task is important, especially for car manufacturing lines, because the production speed is set and workers must adapt themselves to this speed to ensure that the required job is performed in time. Fritzsche et al. [6] clearly stated that unexpected work loss in the automotive industry is directly related to unergonomic working conditions. Automation efforts help to reduce the tasks that require handling tools and therefore potential WMSDs; however, there are still certain tasks for which precise human hand placement is necessary [7,8].

There is a growing interest in occupational exoskeletons—wearable supporting systems—because of their capacity to augment the structural stability and durability of workers during work tasks [9]. For decades, exoskeletons have mainly been developed for the purpose of medical rehabilitation and military applications; nevertheless, industrial exoskeleton applications are at quite an early stage. Still, exoskeletons are good example for human machine interactions and reducing WMSDs [10,11].

Exoskeletons can be classified based on their power source, i.e., active and passive [12]. In terms of external power sources, electric motors are mostly used for active exoskeletons, while passive exoskeletons utilize the human power of the wearer, along with compliant materials and mechanisms [7,13]. Attributed to their additional weight and strength requirements, active exoskeletons may be less flexible, along with having a lower dexterity when compared to lightweight passive exoskeletons [14]. The lighter structure of passive exoskeletons also creates a better safety perception for workers [9]. Exoskeletons are also categorized regarding which part of the human body to which they provide support. Exoskeletons that provide arm support are utilized for overhead and shoulder-level tasks. Lots of prototypes and commercialized products have been developed and tested recently, however, no standards have been developed yet to evaluate and approve the efficiency of industrial exoskeletons [15]. Therefore, researchers or companies evaluate them according to their own background and/or experience. There is a general propensity to perform EMG tests under some criteria and defined static tasks.

Huysamen et al. [12] investigated an occupational exoskeleton and confirmed the reduced activity in the shoulder musculature with the use of the exoskeleton. Spada et al. [15] indicated a better task performance and prolonged working time, and, consequently, less perceived fatigue, owing to the use of an occupational exoskeleton. Butler and Wisner [16] reported the increased productivity of welders and painters with the exoskeleton usage. Recently, Jorgensen et al. [17] examined and compared three different industrial exoskeletons and evaluated the influence of them on the shoulder and torso muscles. They carried out the tests for different arm levels of riveting tasks in aircraft manufacturing and compared the results with wearing no exoskeleton. Van der Have et al. [18] and Yin et al. [19] also inspected an upper-extremity exoskeleton and measured its effects on related muscles for various altitudes of work tasks. However, some welding, grinding, and similar work require workers to stretch both the upper arms and forearms for operations.

In the present work, an innovative, passive upper-extremity exoskeleton for supporting both over-the-head tasks and forearm-stretched tasks is introduced. A prototype is produced with a collaboration between the Bursa Uludag University, Mechanical Engineering Department and OCALIS Engineering Inc. company. The moment around the shoulder joint is calculated first, then, these moment values are used as inputs for the exoskeleton design. Additionally, the deltoid muscle force is calculated, which is the main muscle responsible for performing defined tasks. The design verification is performed by evaluating the effects of the presented exoskeleton on the related muscles under two different tasks. One is a widely preferred overhead condition, which is named Task 1 (T1), and the other is at the shoulder level, in which both the upper arm and forearm are kept parallel to the ground and pointing forward, which is named Task 2 (T2). The interventions for the aforementioned tasks were carried out at Eskişehir Technical University, Sports Science Faculty, Motion and Motor Control Laboratory. Comparisons between the muscle activities with and without the exoskeleton are provided and the effect of the exoskeleton is discussed in detail.

2. Materials and Methods

2.1. Biomechanics Design of Exoskeleton

The exoskeleton is designed according to the biomechanical conditions representing the working conditions of workers. Upper-extremity exoskeletons mainly support the upper arm against gravity; therefore, they help to decrease the moment around the shoulder joint. First, the shoulder moments without wearing the exoskeleton are determined for the pre-defined tasks, named Task 1 and Task 2, as shown in Figure 1. The moment for Task 1 can be calculated with the formula,

$$\begin{aligned} M_{s,T1} = g\big[&(m_{tool}) \times (L_{upperarm}) + (m_{hand}) \times (L_{upperarm}) + (m_{forearm}) \times (L_{upperarm}) \\ &+ (m_{upperarm}) \times (L_{upperarm} \times 0.436)\big] \end{aligned} \tag{1}$$

and, for Task 2,

$$\begin{aligned} M_{s,T2} = g\big[&(m_{tool}) \times (L_{upperarm} + L_{forearm} + L_{hand} \times 0.506) + (m_{hand}) \times (L_{upperarm} + L_{forearm} + L_{hand} \times 0.506) \\ &+ (m_{forearm}) \times (L_{upperarm} + L_{forearm} \times 0.43) + (m_{upperarm}) \times (L_{upperarm} \times 0.436)\big] \end{aligned} \tag{2}$$

where g is the gravitational acceleration. The coefficients 0.436, 0.43, and 0.506 that are seen in these equations are the ratios of the centroids measured from the proximal joint for the upper arm, forearm, and hand, respectively. These ratios are taken from the antropometric data presented in Neumann [20].

The deltoid muscles are the main muscles activated to perform both tasks, while the biceps brachii and trapezius muscles are the supporting muscles for creating balance. The biceps brachii muscles' main function is to balance the forearm, hand, and tool in given positions (flexion forearm). Therefore, the biceps brachii do not affect the required support force exerted by the exoskeleton. The trapezius muscle works to elevate and stabilize the scapula. The deltoid muscles' activation force is required for the design of the exoskeleton. For this purpose, a method of section is applied for the arm and free body diagrams for the segments of Task 1 and Task 2, which can be seen in Figure 2.

Since the tasks are performed in static equilibrium, the inertial effects can be neglected and the following equalities can be written.

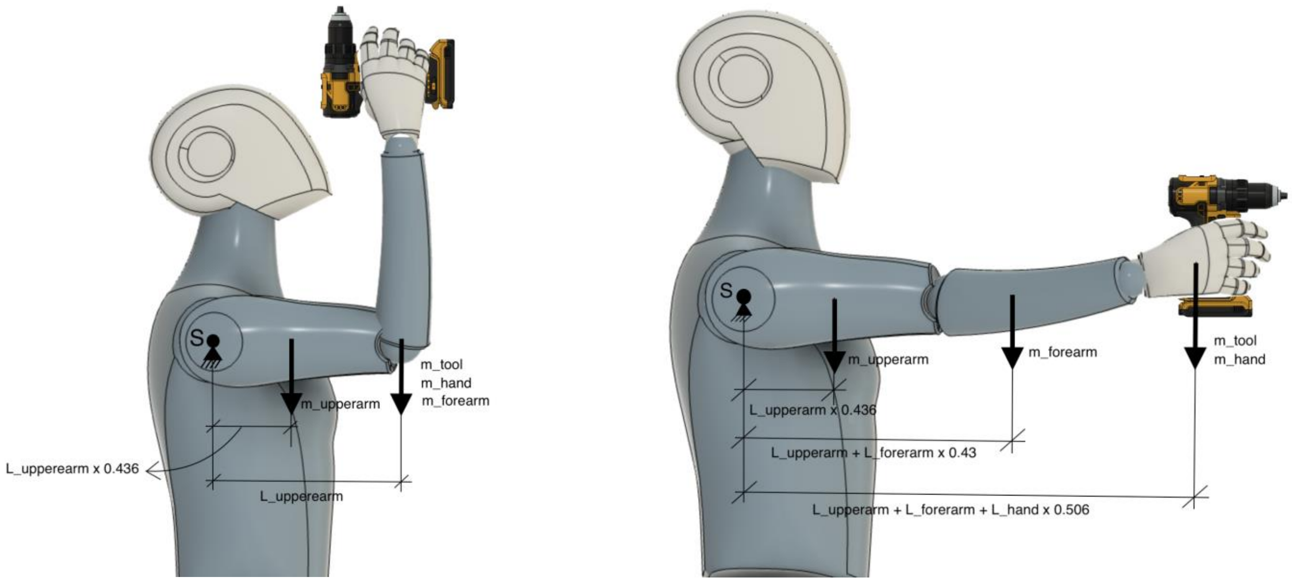
$$\sum \vec{M}_{s,t1} = \vec{0} \text{ and } \sum \vec{M}_{s,t2} = \vec{0} \tag{3}$$

$$\begin{aligned} g\big[&(m_{tool}) \times (L_{upperarm}) + (m_{hand}) \times (L_{upperarm}) + (m_{forearm}) \times (L_{upperarm}) \\ &+ (m_{upperarm}) \times (L_{upperarm} \times 0.436)\big] - [F_{deltoid,t1} \times 0.03 \times \sin(20^\circ)] = 0 \end{aligned} \tag{4}$$

and

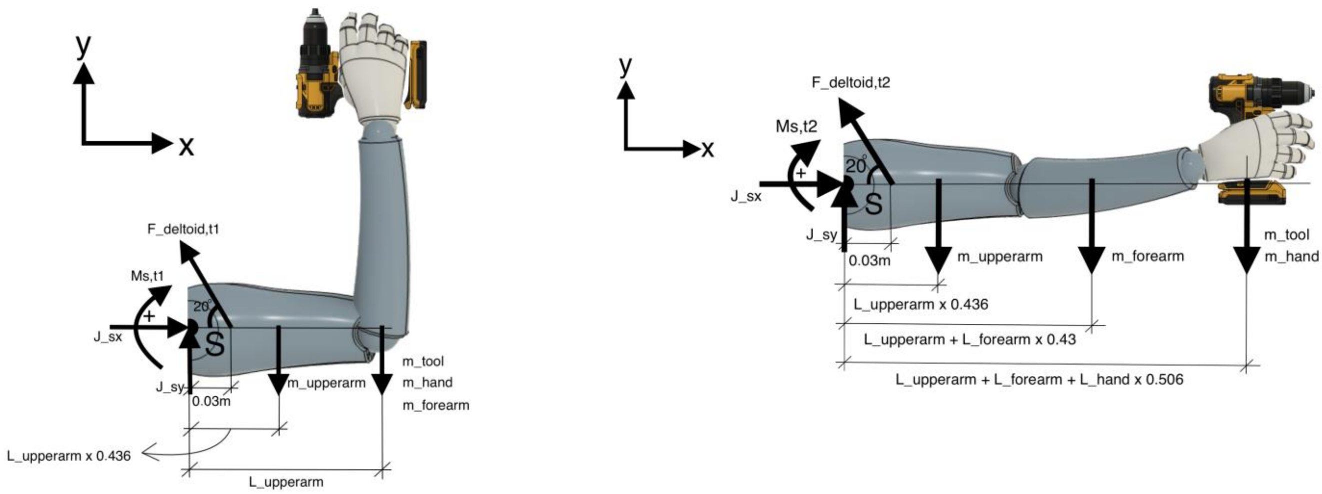
$$\begin{aligned} g\big[(m_{tool}) \times \big(L_{upperarm} + L_{forearm} + L_{hand} \times 0.506\big) + (m_{hand}) \times \big(L_{upperarm} + L_{forearm} + L_{hand} \times 0.506\big) \\ + (m_{forearm}) \times \big(L_{upperarm} + L_{forearm} \times 0.43\big) + (m_{upperarm}) \times \big(L_{upperarm} \times 0.436\big)\big] \\ -[F_{deltoid,t2} \times 0.03 \times \sin(20^{\circ})] = 0 \end{aligned} \tag{5}$$

The distance of the deltoid muscle attachment point on the humerus is taken as 30 mm and is directed at about 20 degrees.



(**a**) (**b**)

Figure 1. Weights and distances to calculate moment around shoulder: (**a**) Task 1; and (**b**) Task 2.



(**a**) (**b**)

Figure 2. Free body diagrams for calculating deltoid muscle forces: (**a**) Task 1; and (**b**) Task 2.

2.2. Development Exoskeleton Mechanism

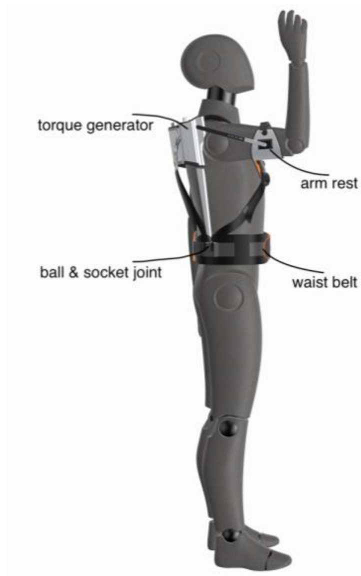
In total, a 50% moment reduction is aimed for in the design of the exoskeleton and it is not designed to carry all the moments, in order to avoid muscle atrophy for workers. Therefore, the exoskeleton should support the upper arm and the moment around the shoulders should be halved when the human wears the exoskeleton and receives assistance at the positions defined in Task 1 and Task 2. The exoskeleton force can be calculated with the formulas given below. H represents the human height, 0.186 H is the upper arm length, and 0.85 of the upper arm length is taken as the arm rest attachment distance from the shoulder joint. Then,

$$\frac{M_{s,t1}}{2} = F_{exo,t1} \times (H \times 0.186 \times 0.85) \quad (6)$$

$$\frac{M_{s,t2}}{2} = F_{exo,t2} \times (H \times 0.186 \times 0.85) \quad (7)$$

$F_{exo,t1}$ and $F_{exo,t2}$ represent the force supported by the arm support. The exoskeleton is designed such that it can be worn by the human like a backpack and a 3D solid sketch of the exoskeleton is shown in Figure 3. The mechanism that generates torque is located around the shoulder area and connected to the waist belt and arm rest via connecting rods. The waist belt connector is attached to the waist belt via a ball-and-socket joint so that the exoskeleton can move freely when the user moves their arm. The arm rest connecting rod is attached to a unit that is called a torque generator. The torque generator is designed such that it is initially deactivated at the anatomical position. It is activated when the user lifts their upper arm (flexion) 120 degrees from its anatomical position. A varying torque is generated upon this activation while supporting the upper arm until the mechanism releases itself. The torque increases when lowering the upper arm and the torque generator is deactivated at 89 degrees from the anatomical position. This range of free motion (0–120 degrees) is wider compared to other available occupational upper arm exoskeletons in the market or the literature, and this provides a very important advantage, because users can move their arms freely up to a 120 degree flexion and walk, sit, and carry out basic daily life activities with no disturbance. The exoskeleton design also allows for a shoulder flexion of up to 180 degrees. This is a very important feature, because once the exoskeleton is worn by workers, they may prefer to not take it off during breaks. It is activated even when pouring coffee or walking freely for other available similar exoskeletons. On the other hand, when a human walks, their arms swing, so this may cause an sudden, unexpected activation of the exoskeleton.

(**a**)



(**b**)

Figure 3. General views of exoskeleton: (**a**) perspective view; and (**b**) side view of exoskeleton on human.

A general perspective view and exploded view of the mechanism that is located inside the torque generator can be seen in Figure 4. A pinion gear rotates around a shaft and a bearing when the user moves their arm around their shoulder. The pinion gear is continuously connected to a rack gear, where the rack gear is arranged to make linear movements only. The rack gear has a specific design, in that its upper side touches to a latch bolt when the user lowers their arm (extension) from 120 degrees. The latch bolt belongs to a sliding body, which applies force to a spring and compresses it. The spring generates reverse force while compressing and provides support for the arm. The latch bolt touches the reset rod at 90 degrees. The latch bolt is mounted to slide inside the body when it touches the reset rod. The rack gear can slide freely when the latch bolt slides inside the body, which means it does not support the arm below 89 degrees. This design guarantees that users can freely move their arms around their shoulders until they flex their arms to 120 degrees again. This mechanism has torque amount adjustment feature to provide less or more torque according to the user's needs. Normally, a user can adjust this using a torque adjustment latch, but this is adjusted as the middle of the torque around the shoulder, according, specifically, to the height and weight values of the test participants, since torque change is not main scope for this study. Users can also change the arm support ending degree using the reset rod latch. This can be less or more than 89 degrees, according to work they carry out. However, this feature is set to 89 degrees for the anatomical position during the tests. Since it is a prototype exoskeleton, most of the parts were produced by an FDM technology 3D printing machine with PLA materials, including the mechanism parts, except the waist belt, arm rest connector, and other fabric parts that connect the exoskeleton to the human body. The total weight of the exoskeleton used in the evaluations is 1.5 kg.

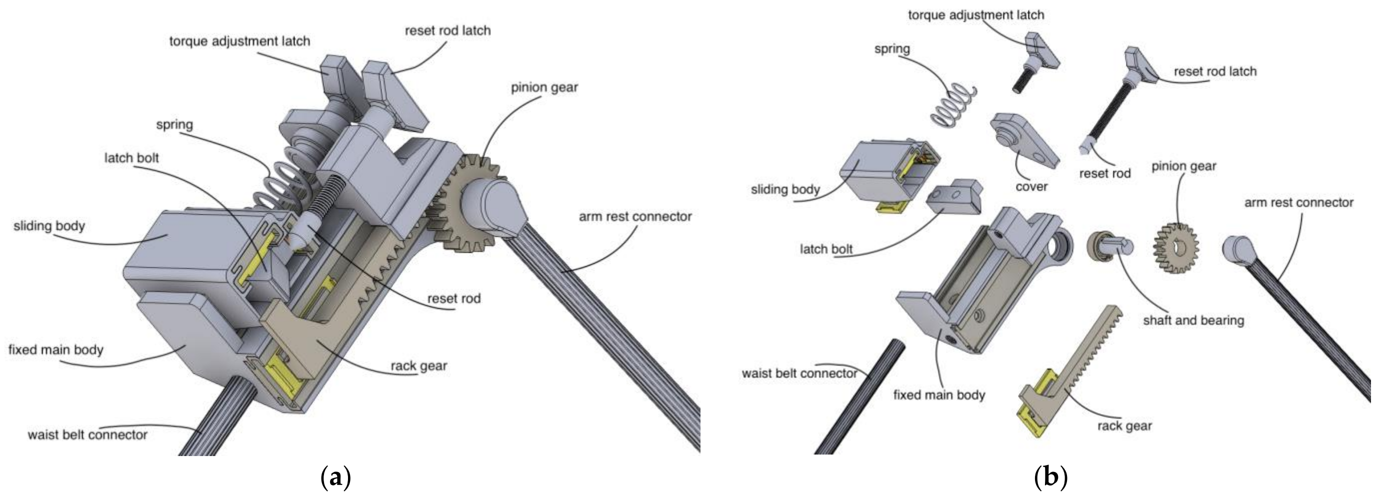


Figure 4. Mechanism inside torque generator: (**a**) assembled view; and (**b**) exploded view.

The exoskeleton system is to provide torque support to the arm as shown in the Figure 5. The design question of the mechanism is: what is the necessary torque generated by the mechanism that can transfer the torque calculated in Equations (6) and (7) to the shoulder via the exoskeleton? The design is set such that mechanism stands 0.07 m behind the shoulder; therefore, the required exoskeleton torques for both tasks can be given as

$$M_{exo,t1} = F_{exo,t1} \times [(H \times 0.186 \times 0.85) + 0.07] \tag{8}$$

$$M_{exo,t2} = F_{exo,t2} \times [(H \times 0.186 \times 0.85) + 0.07] \tag{9}$$

By obtaining the exoskeleton moment, one can calculate the rack forces (see Figure 6) that directly represent the force on the spring; therefore, the spring constant can be chosen such that it provides the required torque.

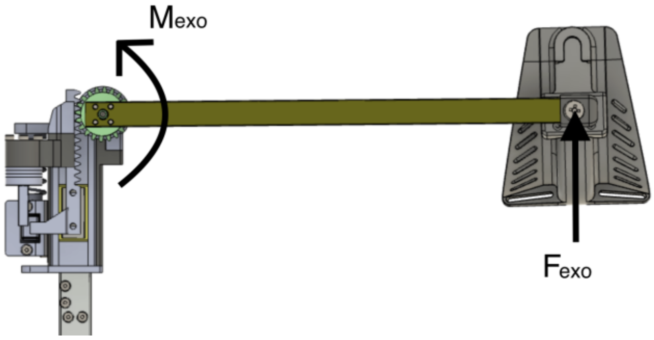


Figure 5. View that shows the mechanism's main torque-providing solution.

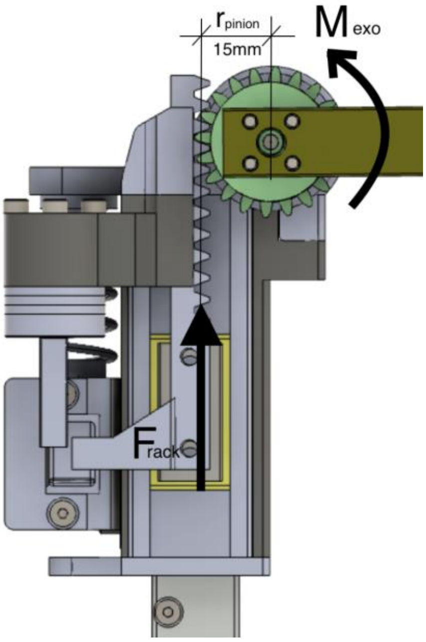


Figure 6. Mechanism side view that shows force transmission.

2.3. Verification of the Design: Interventions and Measurements

Three healthy, right-handed volunteers participated in the interventions. The age, sex, weight, and height of the participants are provided in Table 1. None of the participants reported any musculoskeletal disorders. The participants were informed about the exoskeleton, testing procedure, and scope of the test. Written consent was taken from all the participants after the procedure was explained to them.

Table 1. Participants information.

Age	Sex	Height (cm)	Weight (kg)
33	female	176	62
33	male	176	75
34	male	185	78

There were two tasks defined for the measurements. The first task was named "Task 1", in which the participants were asked to perform flexions of their upper arm of up to 120 degrees (to activate the exoskeleton first), then to perform an extension back to 90 degrees (upper arm was aligned parallel to the ground), and wait at this position for one minute. While moving their upper arms, their forearms were also flexed by 90 degrees (forearm was aligned vertical to the ground), and they held a tool with their hand (see Figure 7a,b).

(a) (b) (c) (d)

Figure 7. Views from tests: (**a**) Task 1 without exoskeleton; (**b**) Task 1 with exoskeleton; (**c**) Task 2 without exoskeleton; and (**d**) Task 2 with exoskeleton.

In the second task, named "Task 2", the participants were asked to perform flexions of their upper arms of up to 120 degrees again, then to perform an extension to 90 degrees from the anatomical position, and hold this position for one minute. However, their forearms were kept in line with their upper arms and their hands were positioned forward while holding the same tool (see Figure 7c,d). Before recording the data, they wore the exoskeleton and pretended to perform tasks to get familiar with the exoskeleton and its motions. After this, they performed the tasks as defined to them and rested 15 min between each session. They carried out both tasks three times with and without the exoskeleton. Task 1 was defined to simulate overhead assembly work and Task 2 was defined to simulate shoulder-level assembly, welding, and similar works.

The activation patterns of the muscles that alter the gleno-humeral (shoulder), scapula-thoracal (scapula-ribs), scapula-vertebral (scapula-spine), thoracal-vertebrae (back vertebrae), and lumbar vertebrae arthrokinematics were evaluated to prove the efficiency of the exoskeleton. Therefore, the EMG signals for the muscle activity were measured for the following ten muscles (see Figure 8): triceps brachii (TB), biceps brachii (BB), pectoralis major (PM), anterior deltoid (AD), middle deltoid (MD), posterior deltoid (PD), upper trapezius (UT), middle trapezius (MT), lower trapezius (LT), and latissimus dorsi (LD).

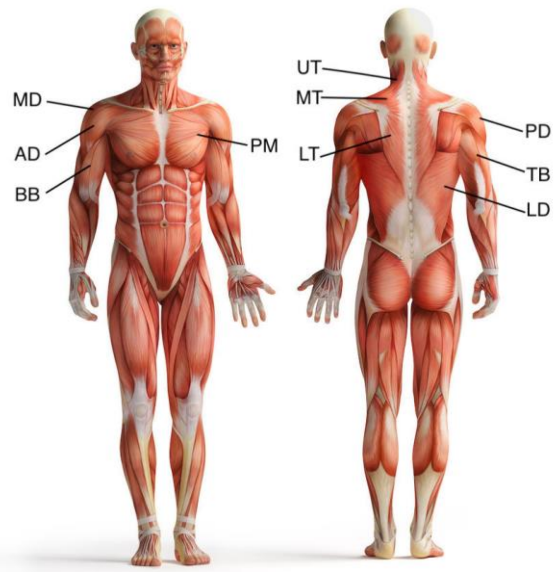


Figure 8. Muscles that measured EMG activation during tests: triceps brachii (TB), biceps brachii (BB), pectoralis major (PM), anterior deltoid (AD), middle deltoid (MD), posterior deltoid (PD), upper trapezius (UT), middle trapezius (MT), lower trapezius (LT), and latissimus dorsi (LD) [21].

NORAXON Ultium measurement hardware and myoMOTION analysis software (version MR 3 3.14.52) were used to measure and analyze the intramuscular electro potentials. The EMGs of the muscles were recorded at 2000 Hz using wireless sensors. The main technical specifications of the device are given in Table 2. The measurements were taken for one minute. The Root Mean Square (RMS) values over the entire period were calculated with the mean amplitude and peak values for each muscle separately. As an advantage of the passive exoskeleton design, there was not any electric or electromagnetic signal that may have interfered with the muscle signals.

Table 2. EMG device specifications.

Specs	Value
EMG sampling rate	Up to 4000 Hz
EMG internal sampling resolution	24-bit
EMG baseline noise	<1 μV

The participants were asked if they sensed any abnormal feelings with the exoskeleton after they performed some basic movements during the tests. None of them reported any abnormal discomfort. There was no abnormal posture observed during the tests by the laboratory staff also.

3. Results

The anthropometric body segment weights and center of gravity locations in the anatomic positions were taken from Neumann's book [20]. The anthropometric segment lengths of the human body, as a function of the human height, were taken from Winter's book [22]. The tool weight used during the tests was 1.6 kg and considered the same for the calculations.

The moments around the shoulder joints for Task 1 and Task 2, calculated with Equations (1) and (2), were 13.26 Nm and 21.69 Nm, respectively, with a 179 cm height and 72 kg weight representing the mean height and weight values of the test participants. The deltoid muscle forces from Equations (4) and (5) were 1293 N and 2114 N for Task 1 and Task 2, respectively. The exoskeleton forces from Equations (6) and (7) were 23.42 N and 38.32 N and the exoskeleton moments from Equations (8) and (9) were 8.26 Nm and 13.52 Nm for Task 1 and Task 2, respectively. Finally, the rack forces were calculated as 550 N and 901 N, respectively, for Task 1 and Task 2. These rack forces directly apply to the compression spring. The spring was selected to provide the forces between these values. In practice, the user can pre-compress this to provide less or more force.

The muscle activities for Task 1 and Task 2, defined in the previous section, are shown in Figures 9 and 10, respectively. The primary muscles doing the work for Task 1 were the AD and MD responsible for the shoulder flexion, the UT responsible for the elevation of the scapula, the MT and LT responsible for the scapular adductor (retractor), and the BB responsible for the elbow flexion. The other muscles were supportive in this task. Wearing the exoskeleton decreased the activity of the AD by 27%, the MD by 55%, and the PD by 37%. The other muscles were not much affected in comparison to the deltoid. However, the lower trapezius muscle activity was increased slightly, by around 4%, with the exoskeleton.

For Task 2, the primary and supporting muscles were the same as those in Task 1, but all the muscles' activities increased. This was an anticipated result, because the tool was held further from the moment point of the shoulder in Task 2. The AD activity decreased by 38%, MD decreased by 48%, and PD decreased by 20% when wearing the exoskeleton. In addition, the UT and MT activity were also decreased by 37% and 27%, respectively. Since there was a greater moment around the shoulders for Task 2, the trapezius muscles actively participated in performing such posture. Unlike the UT and MT, the LT is located around the spinal cord and lower back. Therefore, the LT was also responsible for stabilizing the torso posture in Task 2. Consequently, the LT activity increased by 22% when the human arms were reached forth to help the torso stand still. This could be attributed to the complicated dynamic motion of the scapula for shoulder-complex-related motions. The BB activity is slightly increased by 4% in Task 2.

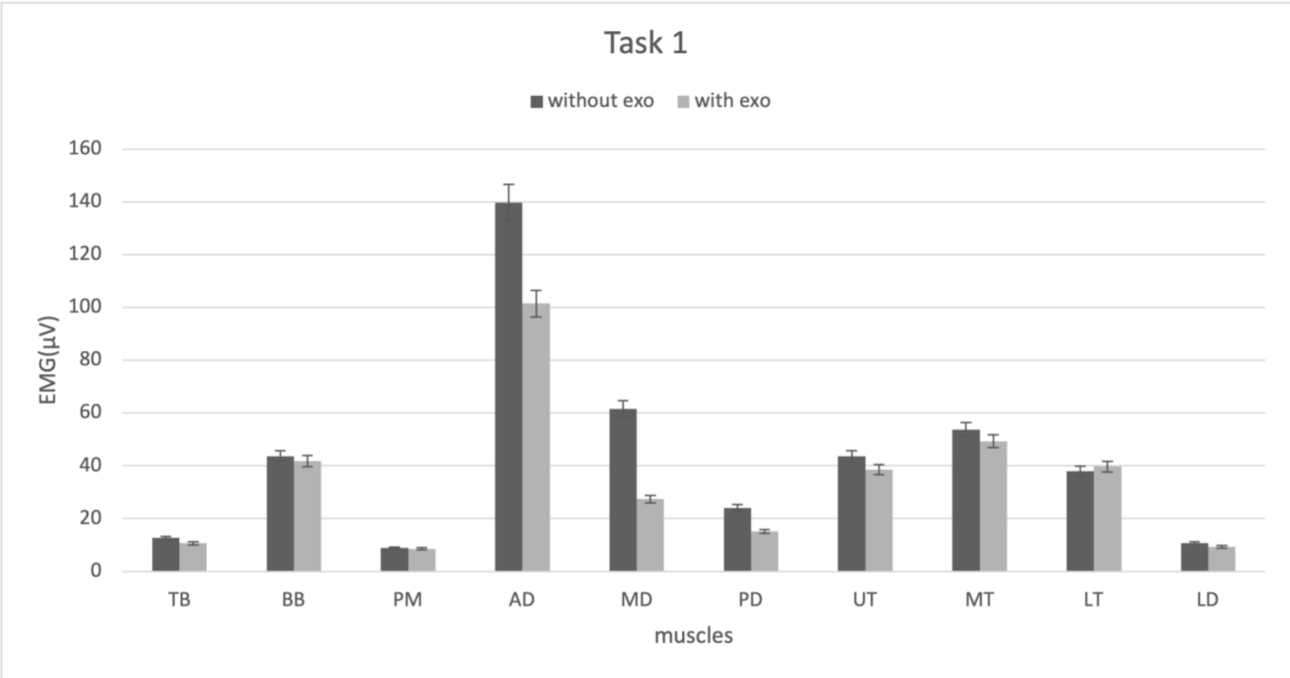


Figure 9. Comparing muscle activities without and with exoskeleton for Task 1.

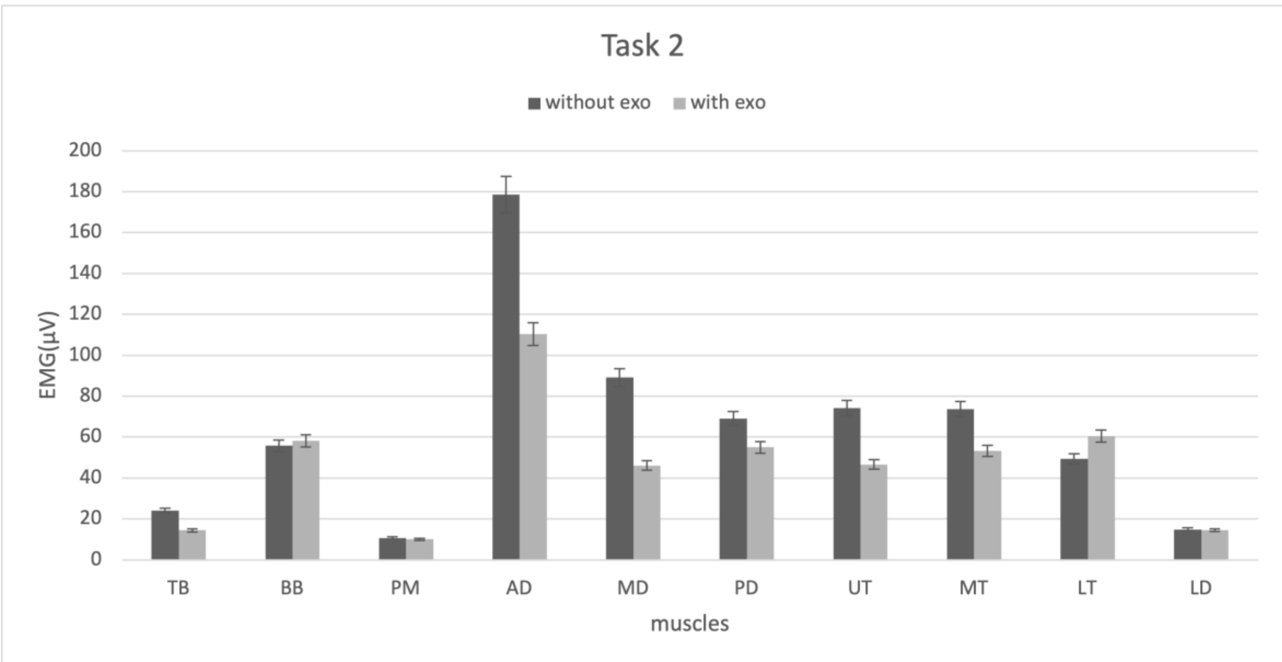


Figure 10. Comparing muscle activities without and with exoskeleton for Task 2.

Muscle activity is considered to be a direct measure of muscle force. However, metabolic cost is not only related to the force generated in the muscles, but also to how fast they contract, and exoskeletons may alter the speed of these muscle contractions. When raising the upper arm, there is no resistance up to 120 degrees, because the arm rests are extremely light and connectors are attached to the wrist band with ball-and-socket joints, where no moment reactions occur. Therefore, no contraction velocity change and additional metabolic cost is expected for just wearing the exoskeleton when raising arm up to 120 degrees. For flexion angles higher than 120 degrees, the mechanism becomes active, but resistance is felt only when the upper arm is pushed down against the arm supports. For isometric contractions, resting the upper arm does not create any additional metabolic cost, because there is no velocity in the muscle. For lowering the upper arm, there is a resistance on the arm rest and this causes lower velocity contractions. Lower velocity means lower muscle force generation for eccentric contractions and higher force generation for concentric contractions. The most active deltoid muscles contact eccentrically with the balance moment created by the arm and the arm rest slows down this movement. Therefore, it is anticipated that the exoskeleton will not create additional metabolic cost, even though there is a resistance on the arm rest up to 89 degrees. When occupational tasks are considered, lowering the arm is mostly a translational phase, rather than a main movement required by the task. Thus, no additional metabolic cost is expected that can be attributed to the exoskeleton. On the other hand, occupational tasks are not similar to sport-related activities and therefore heat generation is not as significant as that in sport movements. This is another point avoiding unanticipated metabolic costs.

4. Discussion

Repetitive muscle activity around the shoulder for over-the-head tasks is the main source of fatigue and resulting discomfort for workers. Exoskeletons are one of the most promising devices that prevent WMSDs [23]. Exoskeletons have also been introduced to reduce the physical strain on workers [24]. It has been shown, in detail, that occupational exoskeletons can significantly reduce the muscle activity for these tasks. Passive exoskeletons with lightweight designs also avoid the drawbacks of active exoskeletons and a trade-off between benefits and costs can be achieved with almost no problem if the psychological barriers can be removed for workers. Passive exoskeletons also enable the load to be evenly distributed across the shoulder joints [25]. In this study, a very lightweight passive exoskeleton was presented and the efficiency of the design was measured via muscle activities for over-the-head and forearm-stretched tasks. Compared to the readily available exoskeletons known to the authors, the original design in this work provides more freedom when wearing an exoskeleton, especially during breaks, because its support mechanism is set to be activated after a 120-degree flexion and released for an 89-degree extension back. In addition, no work known to the authors has shown efficacy for tasks where the forearm is completely stretched with a tool held still (Task 2).

The muscle activity measurements for the two main tasks prove that the exoskeleton helped to reduce discomfort around the shoulder, because the deltoid muscles' activity decreased significantly. These deltoid muscles are mainly responsible for performing tasks and WMSDs can be prevented or delayed thanks to reduced muscle activity. The design presented an adjustable resistance for the arm rest and this also provides extra comfort, because the muscle history of workers may vary significantly. A reduction in the all the main muscles was shown, except for a negligible increase in the BB activity in Task 2 and a slight increase in the LT activity. However, it can be said that the metabolic cost will be significantly reduced because of less overall muscle activity.

McFarland and Fischer [26] claimed that the available passive exoskeleton designs help in reducing metabolic costs, especially for overhead tasks, in their extensive review. The design presented in this work supports their findings; however, the original design with an adjustable mechanism presented in Figure 4 is expected to lead to even more reduced metabolic costs. They also criticized the work in the literature focusing on overhead tasks without providing data proving a reduction in the back or core muscles. LD and LT muscle activities can be considered as sources of potential back pain created by an exoskeleton. The muscle activity for LD is very small compared to other muscles and there was no increase for both tasks when the exoskeleton was on; however, there was an increase in LT, and this increase was more prominent for Task 2. Any contraction velocity change in these muscles was not expected due to wearing the exoskeleton; therefore, additional costs can be evaluated based only on muscle force. Due to reductions in the main muscle activities around the shoulder, there was an obvious comfort provided by the exoskeleton for the over-the-head occupational task. The increase in the LT was very small compared to the decrease in the deltoid muscles; however, a worker with present back issues may feel uncomfortable due to the exoskeleton after prolonged use.

An investigation into the effects of an exoskeleton on the muscles has been performed under two static tasks for 1 min. Overhead tasks vary and task times could take more or less than 1 min according to the task. Thus, further investigations should be performed for more or less than 1 min. Muscle fatigue develops with time, so different time period scenarios would be interesting to take into account, in order to evaluate such exoskeletons in real conditions. On the other hand, both tasks were performed with 90-degree flexions of the upper arm. Test scenarios for different arm angles could be investigated in future works.

A completely new and unique mechanism was developed in this study. Additionally, this mechanism also has new features. This presented mechanism allowed for free movement when the mechanism was not activated and significantly reduced the muscle activation when it was activated. The involuntary activation problem of other exoskeletons was solved. In addition, the operators could adjust the support angle degree according to the task they perform. This feature was developed for the first time.

It can be concluded that the exoskeleton design in this work helped to reduce muscle activities, especially the main muscles contributing to movements, which were significantly reduced with the exoskeleton. The muscle activity for Task 1 was reduced by 55% for the middle deltoid, 37% for the posterior deltoid, and 27% for the anterior deltoid muscles in comparison to no exoskeleton. For Task 2, the muscle activity was reduced by 48% for the middle deltoid, 20% for the posterior deltoid, and 38% for the anterior deltoid. There was slight increase in the activity for some muscles. This additional muscle activity due to carrying the exoskeleton can be neglected thanks to its passive structure and lightweight design. Furthermore, the exoskeleton weight was also shared by the muscles that were not active in the tasks.

Muscle-fatigue-related problems for workers can be avoided with the help of an exoskeleton. There is no unexpected metabolic cost stemming from wearing an exoskeleton, and this is very unlikely due to the nature of occupational work tasks.

5. Patents

The mechanism introduced in this article is patent pending. Its international application number to WIPO is PCT/TR2022/050361 and local application patent number to Turkish Patent is 2022/003083.

Author Contributions: Conceptualization, A.E.Ö.; methodology, A.E.Ö., H.L. and S.T.Ç.; validation, A.E.Ö., H.L. and S.T.Ç.; investigation, A.E.Ö.; resources, A.E.Ö. and H.L.; writing—original draft preparation, A.E.Ö. and H.L.; writing—review and editing, H.L. and S.T.Ç.; visualization, A.E.Ö.; supervision, H.L. and S.T.Ç.; project administration, A.E.Ö.; funding acquisition, A.E.Ö. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by TÜBİTAK (The Scientific and Technological Research Council of Turkey) under 1512 programme, grant number 2200035.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of Bursa Uludag University (2020-3 and 2 June 2020).

Informed Consent Statement: Informed consent was obtained from all subjects (test participants) involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to it is commercial product.

Conflicts of Interest: The authors declare no conflict of interest.

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