MSA Engineering Journal
MSA Engineering Journal (ekb.eg)
ISSN 2812-5339(print); ISSN 2812-4928(online)
E-mail: jzus@msa.edu.eg

Exoskeleton Supporting Back and Shoulders

Shehab Kishta[a], Zeina Khalil[b], Ahmed Badawy[c], Olfat Diab[d]

[a] October University for Modern Sciences and Arts, MSA, Egypt, shehab.abdelghany@msa.edu.eg
[b] October University for Modern Sciences and Arts, MSA, Egypt, zeina.mahmoud@msa.edu.eg
[c] Prof. In Mechatronics Department, October University for Modern Sciences and Arts, MSA, Egypt, ahbadawy@msa.edu.eg
[d] Dean of Faculty of Physical Therapy, October University for Modern Sciences and Arts, MSA, Egypt, olfdiab@msa.edu.eg
Corresponding Author’s Email: ahbadawy@msa.edu.eg

Abstract

Musculoskeletal disorders (MSDs) are the most common diseases in industrialized countries today and have a significant impact on the lives of workers. They are one of the primary causes of work-related injuries in the construction sector. Furthermore, MSDs affect worker productivity and company productivity. Studies have found a notably high prevalence of this disorder among workers in Egypt. The lower back, neck, and shoulders are the areas most affected by this disorder. Lower back pain is the most affected area, often resulting from lifting heavy weights with incorrect postures. Conversely, shoulder fatigue is caused by repetitive tasks in inappropriate positions over extended periods of time.

This paper presents a quasi-passive exoskeleton, as a possible solution to MSDs. The proposed design aims to reduce a major health problem for workers, to correct wrong human postures, to reduce muscle fatigue, to decrease heart rate.

It has been identified after testing and having real data that exoskeleton implemented supports lumbar which enables participants to lift more weight while being comfortable without any injuries or pain. Furthermore, the proposed design can support the shoulder and reduce muscle activity while enhancing heart rate, and oxygen consumption.

Keywords: Anybody Modeling System, Posture misalignment, Quasi-passive exoskeleton, repetitive tasks.

1 Introduction

An exoskeleton is a wearable, powered machine that mimics the human body's form and function. It acts as an extension of the wearer's limbs and shoulders. Exoskeletons can be used for both medical and industrial purposes. In medicine, they can help people with weakened or injured muscles, joints, or bones due to disease or neurological conditions. These machines combine human intelligence with machine power, making them more intelligent and powerful tools for the user. Exoskeletons work mechanically alongside the human body and can be either passive or active.

In recent years, work related injury, and pain gain many attentions because of increasing number of workers complains. MSDs are a group of disorders that affect the soft parts of the muscles, tendons, or nerves resulting from sudden or continuous repetitive movement in inappropriate positions. It was found that 43% of workers in the European Union complain of back problems and pain due to MSDs[1]. This problem has various ethical and economical aspects. These work-related issues lead to some limitations, with 50% of workers experiencing an inability to conduct daily activities, and another 22% facing major limitations in their lives resulting in 62% of people suffering from work-related health problems one day. At least one month of sick leave has been taken in the last twelve months, and 22% of people take at least one month of sick leave [2].

Exoskeleton is a wearable device, which helps its user physically in aid through structural support or adaptive torques. According to the actuation types, it is classified due to whether external power is used or not. These types are active, passive, and quasi-passive. Active exoskeletons have additional energy from external resources, passive exoskeletons use springs or powered actuators, while quasi-passive utilize passive components with the aid of external power [3], [4]. When it comes to kinematic structure and attachment, exoskeletons are categorized as soft or rigid. Soft exoskeletons are known as exosuits or soft back-support exoskeletons. However, rigid ones are rigidly connected with hard structures, which are called SKEL. Figure 1 presents a range of exoskeletons depending on their kinematic structures.

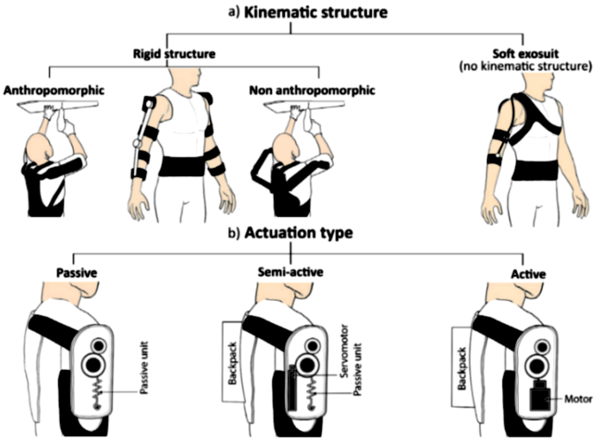


Figure 1: Exoskeletons Classification Depends on Kinematic Structures [3]

Varieties of exoskeletons were presented Ranging active, passive, and quasi-passive. Active exoskeletons have actuators that assist and move the human body [4]. Passive exoskeletons are lighter than active exoskeletons as they do not require external power like motors or batteries; they only rely on mechanical elements [5]. Quasi-passive exoskeletons utilize active and passive components [6]. In quasi-passive exoskeletons, the mechanical properties that are in the passive devices and coupling are modulated automatically during the operation. Soft exoskeletons, also known as exosuits, aid without the rigid, articulated structures found in traditional exoskeletons. In rigid exoskeletons, hard structures are used to attach the actuators to the user's garments [7].

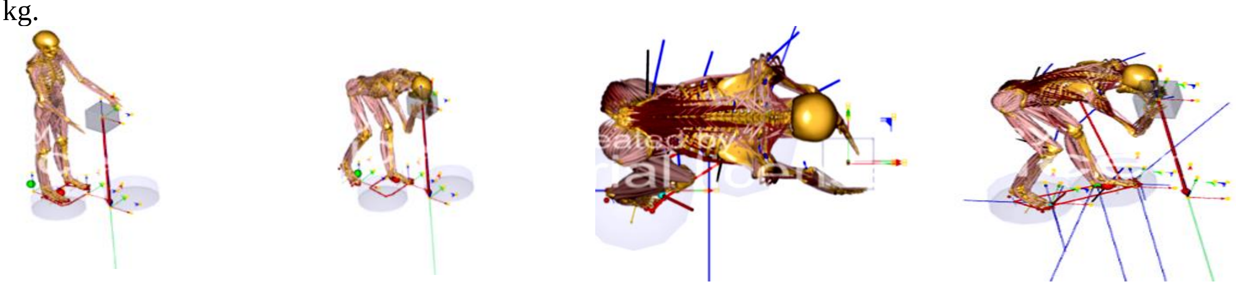
2 Modeling and Simulation of Human Body

The simulation of the musculoskeletal system investigates mechanical functions like dynamic and kinematic analysis [8,9]. There are some special simulation features, using the Anybody Modeling System (AMS). This modeling and simulation software which has a lot of aiding tools to help in setting a full simulation tool chain that has an open code model library where users can use, alter, and submit new models to the *Anybody* Managed Model Repository (AMMR) for certain uses, but only with a specified AMMR license. The software also takes input motion data as input to the modeling system and the output is body loads (muscle forces, joints moments, and joint reaction forces). Furthermore, this musculoskeletal software system is used to find out the mechanical functions of the living human body. Simulation is then used to make a certified estimation of properties inside the body, which are typically impossible and unethical to measure, Fig. 2.

Figure 2: Human Body

The musculoskeletal simulation offers countless benefits, including a comprehensive understanding of the human body and its interactions with the surroundings, all without the requirement of extra equipment. When performing thorax flexion, this software enables the measurement of spinal disc forces without depending on motion capture data.

The model predicts posture in response to applied hand loads. This is carried out by reducing joint torques and using balance drives to consider externally applied loads. Fig. 3 shows analysis results for a human model-lifting box of 5 kg.



(a)normal position **(b) model bending** **(c) forces on a model** **(d) Side view of model**

Figure 3: Posture Prediction

Tables 1-3, present the parameters used of the human model in Anybody simulation platform, segment masses, and segment parameters. The human body is represented in its entirety, encompassing major anatomical regions like the upper and lower extremities, a trunk model featuring accurate representations of the lumbar spine, and the abdominal cavity.

Every component is then derived from measurements taken from bodies or medical imaging investigations of specific individuals. This model covers all the major physiological muscle complexes found in the human body, including 63 segments and around 1000 muscle branches.

Table 1: Human Model Parameters

Body mass	Density	BMI	Body height	Fat percentage	Right arm mass	Left arm mass
75 kg	1000 kg/m^3	24.49	1.75 m	22.09 %	4.74 kg	4.74 kg

Table 2: Segment Masses [kg]

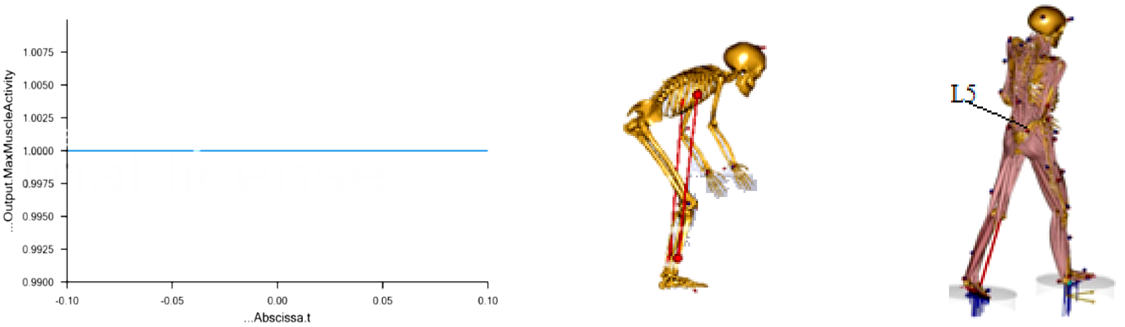
Lumbar	Thorax	Pelvis	Head
10.425	14.205	10.65	6.075

Table 3: Segment Parameters

Specific muscle tension spine	90 N/cm^2
specific muscle tension arm	90 N/cm^2
strength index leg	1.0
force magnitude	100 N
Force direction {X, Y, Z}	{0.0, 0.01, -1.0}
Muscle max stress	1.5 MPa

Applying our model first for the case without exoskeleton, meanwhile the spine was not in neutral position muscle activity of 100 %, Fig 4-a. This conceptual simulation is to evaluate the effect of the exoskeleton on the human body, how reactions and forces vary with and without the exoskeleton, Fig. 4-b.

It is found that in lumbar spine compression the proximo-distal force reaches the peak when human is lifting weight. The study in AMS software shows that the compression load in the spine when a human is standing not doing activity is less than the compression load when human is doing tasks like lifting by a factor of four. This proves the effectiveness of the presence of exoskeleton. In Fig. 4-c, the joint reaction force, L5 sacrum distal-proximo peak force approximately is 805 N. In actual working task the joint reaction force, L5 sacrum distal-proximo peak force is 3475.947 N.



(a) Muscle Activity (b) Human's Posture (c) Human Gait

Figure 4: AnyBody Modeling

Moreover, this design uses extensible rods with forces as unrealistic support for knees, hips, and lumbar spine. Therefore, there is a comparison made with and without the rods to examine the effect on joint reaction, L5 sacrum distal force from L5 to S1. This is the exact spot where the lumbar spine ends and the sacral spine begins. Without the exoskeleton each sacrum distal forces reach peak force of 3 KN, however with exoskeleton the force decreases by 20% which is approximately 150 N.

Joint reaction force is the resultant of forces of the joint, it occurs to estimate the stress that the joint tolerates during activities. The resultant of forces is higher than the weight lifted by a human body and the weight of the muscle. The joint reaction forces and resultant stress play a huge role in the pain occurred in the joint because as the joint reaction forces increases the usage of muscles and joints will also increase leading to increasing pain. In conceptual exoskeleton design, the output of joint reaction forces is low which an advantage as the joint is and muscle pain is low, these forces are illustrated in Table 4. This Table depicts that the conceptual design of exoskeleton achieved good stability of the human body. That is because the Medio lateral and Antero posterior forces, that handle stability, are low as they are in negative. Furthermore, the force that handles taking actions is proximo distal force which is high across all the joints in the lumbar region, which is a good measure to use this force in calculations including rod stiffness [10].

The joint reaction forces that act on the shoulder that result from the simulation of conceptual design are Medio lateral force, Inferior superior force, and anterior posterior force. The results from the simulation of the joint reaction forces are listed in Table 5.

Table 4: Joint Reaction Forces of Lumbar Spine

L5-sacrum Medio Lateral force	-49.1761 N	L3-L4 Antero posterior force	495.6725 N
L5-Sacrum proximo-Distal force	3475.947 N	L2-L3 Medio Lateral force	-52.0098 N
L5-Sacrum Antero posterior force	1162.654 N	L2-L3 proximo-Distal force	3768.788 N
L4-L5 Medio Lateral force	-101.181 N	L2-L3 Antero posterior force	-581.6746 N
L4-L5 proximo-Distal force	3579.095 N	L1-L2 Medio Lateral force	-18.36693 N
L4-L5 Antero posterior force	1011.393 N	L1-L2 proximo-Distal force	3960.076 N
L3-L4 Medio Lateral force	-153.377 N	L1-L2 Antero posterior force	-1146.044 N
L3-L4 proximo-Distal force	3796.858 N		

Table 5: Joint Reaction Forces of Shoulder, JRF

SC Medio lateral force	175.24 N	AC anterior posterior force	-1040.00 N
SC inferior superior force	332.05 N	GH Medio lateral force	-1705.86 N
SC anterior posterior force	255.85 N	GH inferior superior force	1505.95 N
AC Medio lateral force	520.04 N	GH anterior posterior force	378.52 N
AC inferior superior force	-893.72 N		

The Glenohumeral spherical joint reaction force, GH-JRF, is demonstrated in three orthogonal directions of the glenoid reference system. It is the opposing vector of eight pushing forces that are normal to the glenoid surface, directed towards the middle of the humeral head, and are positioned around the glenoid rim. These pushing pressures guarantee the GH-JRF's retention within the glenoid cavity, Fig. 5[11].

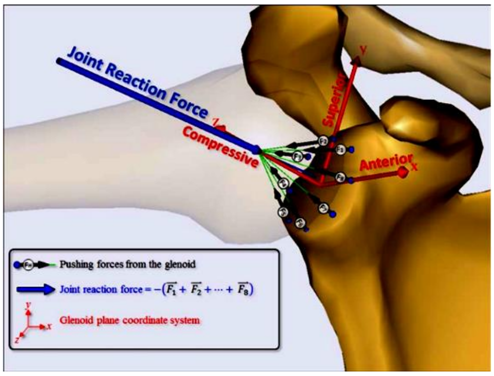


Figure 5: Computation of GH-JRF [11]

The rod faces bending as an artificial spine, Fig. 6. This rod is fixed from one end only, so it is considered as a cantilever beam. When the wearer is bending the rod also bends to support the spinal cord.

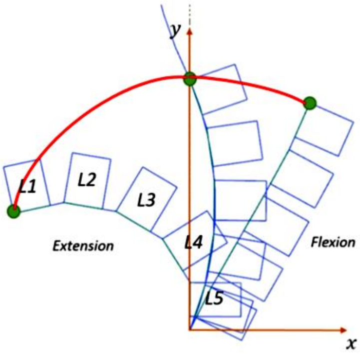


Figure 6: Rod Deformation

The force acting on the artificial spine is the total weight of the carried parts: box mass (M1), mass of the human's trunk (M2), mass of hands, arms, and shoulders (M3), mass of the head (M4). These give a total mass of M5. The parameters used are given in Table 6. The result of this part of simulation gives the rod deformation of 9.2 cm. This deformation, along with rod length is then used to determine the required rod diameter and material.

Table 6: Model Masses [kg]

M1	M2	M3	M4	M5
10	41.95	10.5078	6.723	69.1808

3 Control Algorithm

Triggering for the control system comes from the shoulder movement. When the shoulder starts to rotate, a rotary encoder attached to the system senses this rotation. Consequently, it sends a signal to the microcontroller, which in turn sends the proper command to the motor. The rotary encoder has an SW button, this button programmed to move the servomotor to its home position. Fig. 7 illustrates the working algorithm of the shoulder part of the exoskeleton.

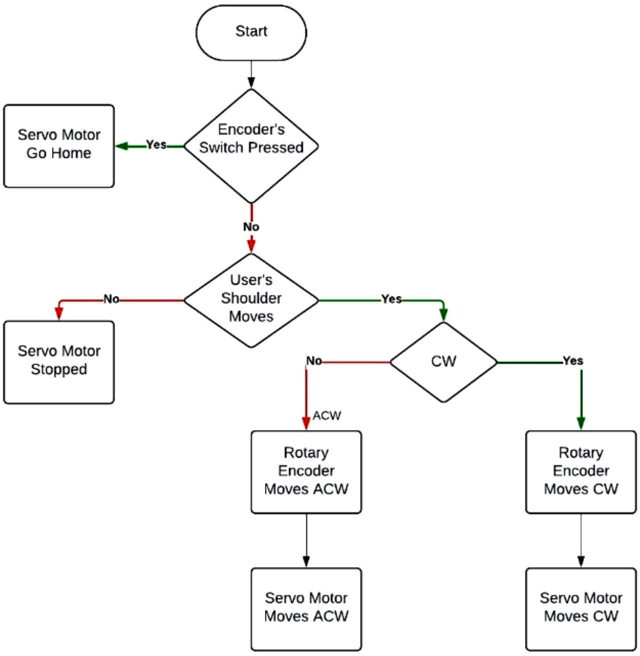


Figure 7: Control Flowchart

4 Tests Setup

Numerous tests were carried out after implementation of the exoskeleton, Fig. 8. Testing has been done to figure out the exoskeleton's efficiency in aiding shoulder movement and supporting back muscles during lifting activity. This section compares the performance of some tasks applied with and without the user wearing the exoskeleton. Measuring the efficiency of the exoskeleton is divided into two parts, the effectiveness of the servomotor in helping the shoulder movement from 0 to 90 degrees and the effectiveness of the rod in supporting back muscles during lifting activity.

Figure 8: Manufactured Exoskeleton

Testing has been carried out for 18 participants. Female percentage is 20 %, while male percentage is 80 %. Sample ages from 19 to 25 years old with a mean of 22 years and median of 23 years. Sample body weight's range is from 46 to 96 kg with a mean of 71 kg and median of 71 kg. Their height is in the range between 157 cm to 195 cm with a mean of 176 cm and median of 176 cm. Moreover, the weight and height of the participants have been used to calculate their BMI to figure out if the participant is suffering from obese or having a healthy body. BMI has been calculated for the 18 participants, Fig. 9.

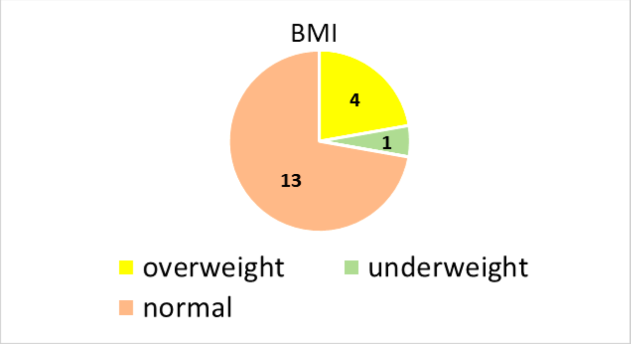


Figure 9: Participant's BMI

However, more data about the participants have been collected which was utterly crucial to be taken into consideration like their physical fitness, lifestyle, gender, disorders, and pain, Table 7.

\

Table 7: Participants Statistical Data

Description	Number of Participants	Description	Number of Participants
Female	4	Male	14
Non-athletes	13	Athletes	5
Smokers	13	Non-smokers	5
Musculoskeletal disorder	6	No musculoskeletal disorder	12
Felt pain	8	No pain felt	10
Took medication	2	No medication	16

Before the testing procedure, participants have been aware of all the steps they are going to go through. The experiment is about lifting weights by using a device like the one the dead lift found in the gym known as back-leg-chest dynamometers, Fig. 10-a. While wearing the exoskeleton and figure out how effective the exoskeleton is and how it influences the participant's heart rate, oxygen saturation and respiration rate. Oxygen consumption, respiration, and heart rate have been measured while lifting weight using this device and they have been measured again while wearing exoskeleton repeating the task carried out using the same device.

Oxygen saturation and heart rate have been measured using an Oximeter illustrated through the fingertip, Fig. 10-b. Respiration is measured using a respirometer, Fig. 10-c. It measures the rate of respiration of the human body by measuring the rate of exchange of oxygen and carbon dioxide; it has three readings, which are 600 cc/sec, 900 cc/sec and 1200 cc/sec. All these parameters have been measured for the 18 participants during lifting task with and without wearing the exoskeleton.

(a)Dynamometer **(b) Oximeter** **(c) Respirometer**

Figure 10: Measurement devices

Other tests are carried out using electromyography signals, EMG. The EMG signal is a biomedical signal that estimates electrical currents generated in muscles during its contraction standing for neuromuscular activities. Detection of EMG signals with powerful and advanced methodologies is becoming a particularly important requirement in biomedical engineering. The EMG test is a diagnostic procedure designed to assess the well-being of muscles and the nerves that govern their functioning. It is chosen to determine the effectiveness of the shoulder part of the exoskeleton because of its ability to evaluate shoulder muscle performance and detect muscle fatigue.

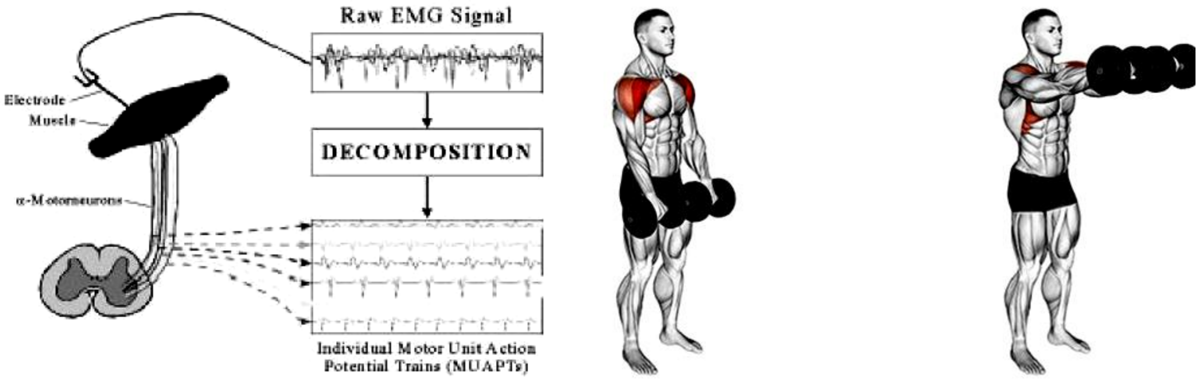
The EMG test for the shoulder procedure is implemented through insertion of thin needles with electrodes into several muscles in the shoulder. The needles pick up the electrical signals produced by the shoulder muscles. These signals are then displayed on a screen or heard as a sound.

The EMG signal output is a biomedical signal specifically designed to measure the electrical currents generated in muscles during contraction, thereby capturing and evaluating neuromuscular activities. The nervous system always controls muscle activity (contraction/ relaxation). The EMG signal output is the train of Motor Unit Action Potentials (MUAPs) showing the muscle response to neural stimulation. In the EMG signal acquisition process, the signal is detected by an electrode and then amplified. A common approach is to use a differential amplifier. Prior to being displayed or stored, the signal undergoes processing to remove undesirable low-frequency or high-frequency noise, as well as other potential artifacts. Often, the user's focus lies in determining the signal's amplitude. Consequently, the signal is often rectified and averaged in some format to indicate EMG amplitude as shown in Fig. 11-a.

The second set of testing was carried out for shoulders. All the participants were awarded for the tasks and the test steps that will be taken. All the users do all the tests once with and once without wearing the exoskeleton, respectively. The user will perform the same exercise throughout all the shoulder tests. The exercise is about doing a front raise exercise by raising a 3 kg dumbbell in the front plane until reaching muscle fatigue, Fig. 11-b.

The experiment investigates the impact of an exoskeleton on muscle activity during front raises. Two male participants performed four sets of front raises:

1. Free Shoulder Front Raise (without exoskeleton)
2. Free Shoulder Front Raise (with exoskeleton)
3. 3Kg Dumbbell Front Raise (without exoskeleton)
4. 3Kg Dumbbell Front Raise (with exoskeleton)

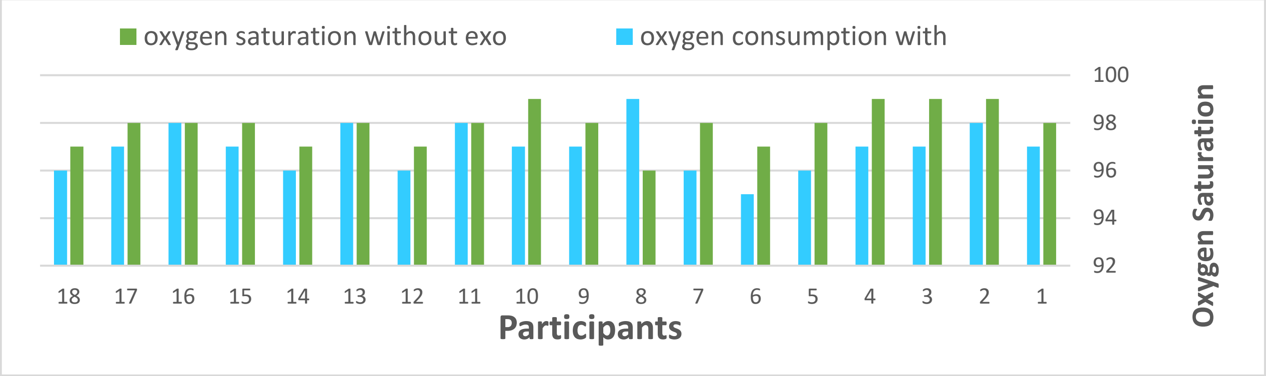


(a)EMG and decomposition of MUAPs [12] **(b)Dumbbell Front Raise**

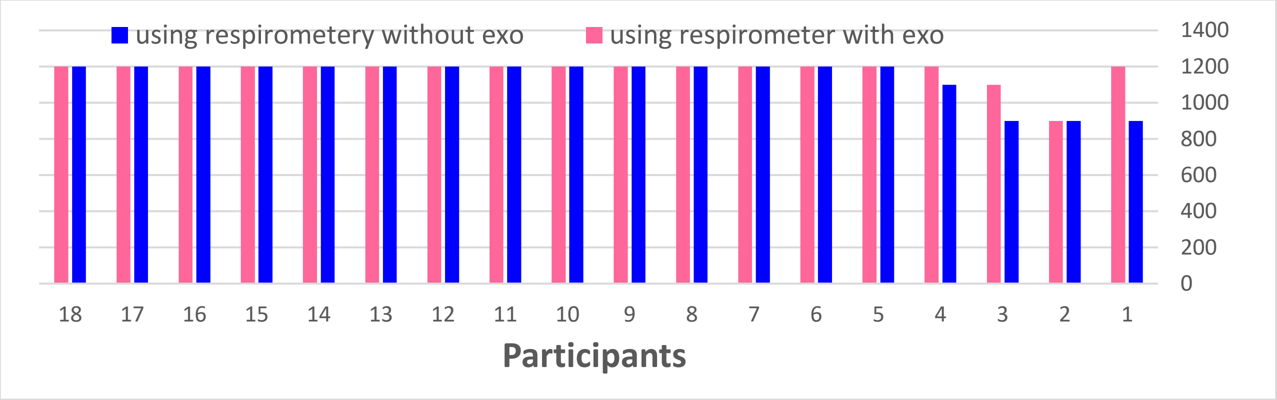
Figure 11: Experiments Setup

5 Results and Discussions

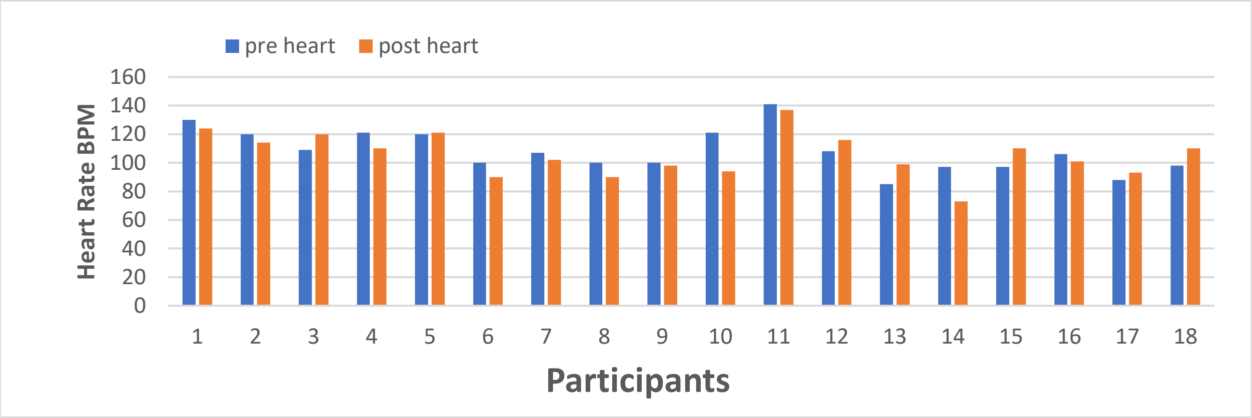
Results are divided into two parts: spine and shoulder tests. Spine tests are proved in Fig. 12. It demonstrates pre and post average rates of oxygen saturation, rate of respiration, heart rate and mass of load lifted by the 18 participants. It shows a comparison between the collected date with and without wearing the exoskeleton. It has been concluded that the oxygen saturation consumption has decreased by 0.96 % that is almost 1%. The rate of respiration increased by 2.9 %, which means that the exoskeleton is utterly effective as it, keeps the participant's spine in neutral position that reduces hunched and rounded postures so there is no pressure on the lungs leading to respire freely and decreasing the amount of oxygen consumed. Furthermore, the participant's lifting ability increased by 22 %, it means that the exoskeleton made them more capable of lifting more weight than they lifted without wearing the exoskeleton so that the exoskeleton did its function with push and pull strategy which supports the spine. Lastly, the heart rate decreased by 2.3 % that depicts that the participant’s effort to do the task is less than the effort exerted they did without wearing the exoskeleton.



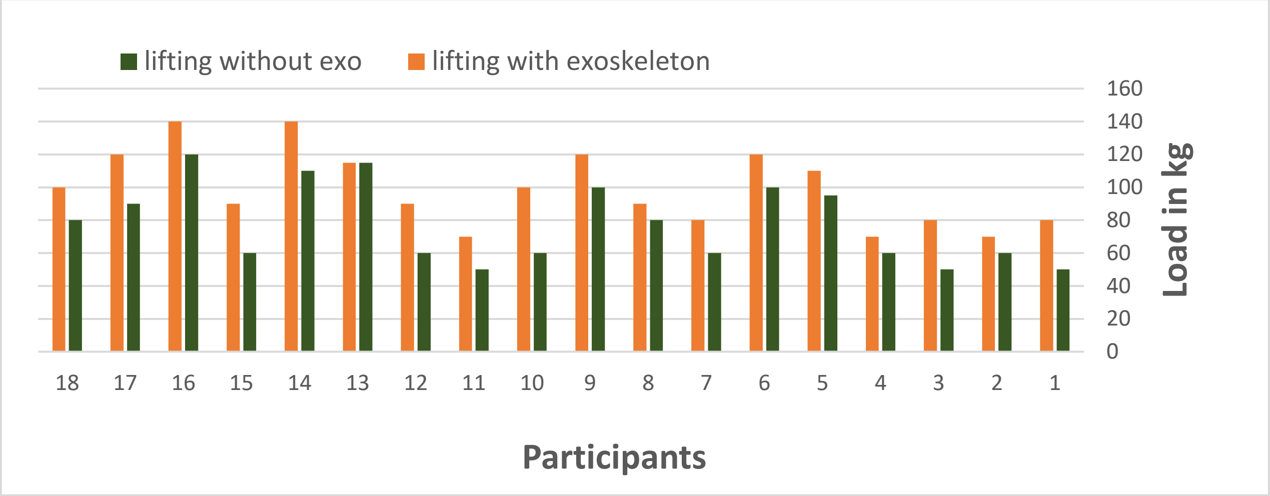
(a): Oxygen Saturation with vs. without Exoskeleton Results



(b): Respiration Rate with vs. Without Exoskeleton Results



(c): Pre Vs Post Heart Rate Test Results



(d): Lifting with vs. without Exoskeleton Results
Figure 12: Measured Data with and without Exoskeleton

During each set, EMG is used to measure muscle activity. The results show that wearing the exoskeleton reduced muscle activity by 14.45% during free shoulder raises, Fig. 13.

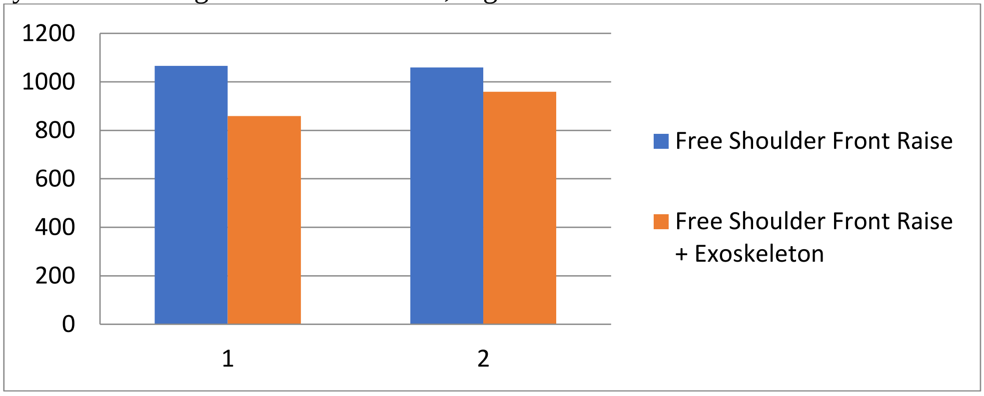


Figure 43: Free Shoulder Front Raise EMG Results

Comparable results were obtained during front raises with 3kg dumbbells. A 10.66% reduction in muscle activity was observed when wearing the exoskeleton, Fig. 14.

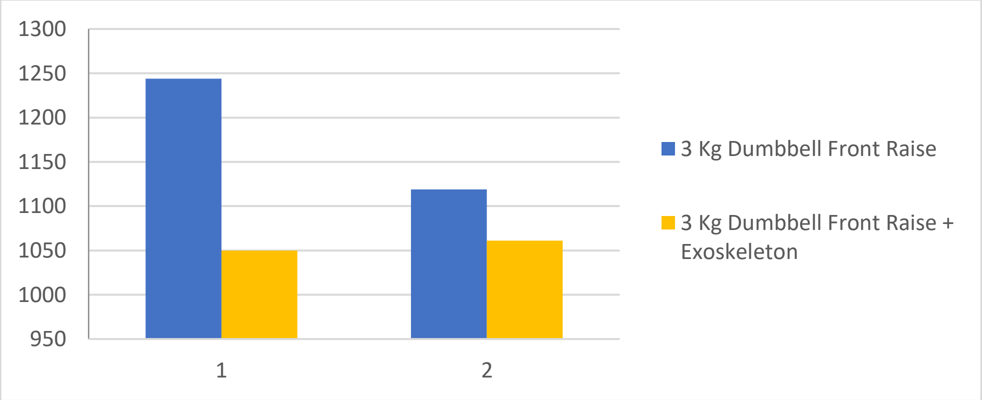


Figure 5: 3 kg Shoulder Front Raise EMG Results

The last part of all experiments is to ensure Participant Response, whether using exoskeleton is comfortable or not. Participants were asked to provide their feedback about the comfortability of using exoskeleton. It was found that 16 participants were comfortable, and two participants were moderate about comfortability. As the participants have different body types, mass, and height they were asked about the size of the exoskeleton as it was designed to fit more than one body type, and they did not add any comment about the sizes as it fit all the participants perfectly.

Participants were pleased with the easiness and assistance that the exoskeleton offered while doing specific tasks with no pain or exerting their maximum effort to lift heavy weights, Fig. 15.

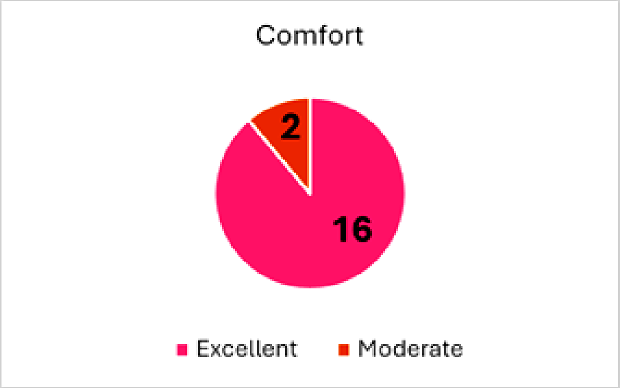


Figure 6: Participant's Comfort

6 Conclusions

The main aspiration of the proposed exoskeleton is to assist workers lift objects and perform tasks involving the shoulders. To ensure its effectiveness, the exoskeleton has undergone methodical design and testing processes. Using AnyBody software, simulations have shown that when the model performs lifting tasks, muscle activity reaches 100% as all muscles are used to exert maximum effort.

Significantly, it is observed that while wearing the exoskeleton during tasks, the Medio lateral force acting on joint L5 - which is responsible for shear force - decreases, resulting in a reduction in the model's instability. Wearing the exoskeleton enhances the wearer's stability, especially during activities involving bending to lift weights. Additionally, the proximo-distal force shows a significantly positive value, aiding in task execution and increasing the model's ability to perform actions while wearing the exoskeleton.

An analysis conducted using AnyBody software indicates that the deflection of the spine assisting rod measures 0.092 meters. The manufactured exoskeleton has a total mass of 2.6 kilograms. Utilizing the exoskeleton leads to a 22% increase in lifting ability, a 2.9% rise in respiration rate, a 0.96% decrease in oxygen consumption, and a 2.3% reduction in heart rate.

Electromyography (EMG) tests have shown that the exoskeleton assists the shoulders by 14.5% and 10.7% during shoulder front raise exercises with and without a 3-kilogram dumbbell, respectively. Notably, 80% of the participants expressed a significant sense of comfort while wearing the exoskeleton.

List of Abbreviations

AC	ACROMIOCLAVICULAR SPHERICAL JOINT
AI	SCAPULA THORACIC GLIDING PLANE, ELLIPSOID.
AMS	ANYBODY MODELING SYSTEM
BNDR	BENDING AND NOT DEMANDING RETURN.
CEMS	CONTEXTUAL ERGONOMICS MODELS
FIN	FORCE IN.
FOUT	FORCE OUT.
GH	GLENOHUMERAL SPHERICAL JOINT
JRF	JOINT REACTION FORCE
MMH	MANUAL MATERIAL HANDLING
MSDS	MUSCULOSKELETAL DISORDER.
SC	STERNOCLAVICULAR SPHERICAL JOINT
TS	SCAPULA THORACIC GLIDING PLANE, ELLIPSOID

7 Declarations

Availability of data and materials

The data used in this research can be found via the corresponding author.

Competing interests

The authors declare that they have no competing interests.

Funding

No funding was obtained for this study.

Authors' contributions

SK and ZK 1st author and 2nd author drafted the paper, designed the models, and analyzed the results using *SolidWorks* and Anybody. AB and OD the 3rd and the 4th authors helped in analyzing results, suggested modifications to the models and then approved the paper.

Acknowledgements

Not Applicable

8 References

[1] Jan De Kok et al., "Work-related musculoskeletal disorders: prevalence, costs and demographics in the EU," EU-OSHA, 2019.

[2] Eurostat, *Health and safety at work in Europe*. Luxembourg: Eurostat Statistical books, 2010.

[3] Stefano Toxiri et al., "Back-Support Exoskeletons for Occupational," *IISE Transactions on Occupational Ergonomics and*, vol. 7, no. 3-4: Occupational Exoskeletons, Guest Editors: Maury A. Nussbaum, Brian D. Lowe, Michiel de Looze, Carisa Harris-Adamson, Marty Smets, pp. 237-249, 2019.

[4] Julia Riemer and Sascha Wischniewski, "Long-term effects and user acceptance of back-support exoskeletons in the workplace," *Zeitschrift für Arbeitswissenschaft*, vol. 77, pp. 658-691, Nov. 2023.

[5] Aida , Nozaki , and Kobayashi , "Development of muscle suit and application to factory laborers.," , Changchun, 2009.

[6] M Hasegawa and Muramatsu, "Wearable lower-limb assistive device for physical load reduction of caregiver on transferring support," , 2013.

[7] Yang AJ and Zelik KE Lamers EP, "Feasibility of a biomechanically-assistive garment to reduce low back loading during leaning and lifting," , 2017.

[8] Francesco Missiroli et al., "Rigid, Soft, Passive, and Active: A Hybrid Occupational Exoskeleton for," *IEEE Robotics and Automation Letters*, vol. 7 no.2, no. 10.1109/LRA.2022.3142447., pp. 2557-2564, 2022.

[9] Simon Auer et al., "Biomechanical assessment of the design and efficiency of occupational," *Wissenschaftliche Beiträge*, vol. 76, no. December 2022, pp. 440–449, November 2022.

[10] Jonas Schiebl et al., "Model-Based Biomechanical Exoskeleton Concept," *Internationak Jornal of Enviroment Reseacrh and Public Health*, vol. 23, no. Occupational Ergonomics: Design, Development, and Usability Evaluation of Ergonomic Products for Application in Various Industries, pp. 19-23, 2022.

[11] Michael Damsgaard, John Rasmussen, Søren Tørholm Christensen, Egidijus Surma, and Mark de Zee, "Analysis of musculoskeletal systems in the AnyBody Modeling System," *Simulation Modelling Practice and Theory*, vol. 14, no. 8, pp. 1100-1111, 2006.

[12] P. O. Lemieux, N. Hagemeister, P. Tétreault, and N. Nuño, "Influence of the medical offset of the proximal humerus on the glenohumeral destabilising forces during arm elevation: A nummerical sensitivity study," *Computer Methods in Biomechanics and Biomedical Engineering*, pp. 1476-8259, February 2012.

[13] M B Raez, M S Hussain, and Mohd-Yasin, "Techniques of EMG signal analysis: detection, processing, classification and applications," *The National Center for Biotechnology Information advances science and health by providing access to biomedical and genomic information.*, vol. 8, no. 11, p. 163, 2006.