TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Electrical Power Engineering and Mechatronics

DESIGN AND BIOMECHANICAL ANALYSIS OF UPPER LIMB EXOSKELETON FOR INDUSTRIAL APPLICATIONS

TÖÖSTUSLIKULT KASUTATAVA ÜLAJÄSEMETE EKSOSKELETI DISAIN JA BIOMEHAANILINE ANALÜÜS

MASTER THESIS

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(*On the reverse side of title page*)

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THESIS TASK

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Thesis main objectives:

1. Developing an exoskeleton design
2. Performing biomechanical analysis to guide design decisions
3. Taking a human-centred approach towards exoskeleton development process

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Review of relevant standards for industrial applications, Study of relevant biomechanical parameters and research	05.03.20
2.	Construction of CAD model, Biomechanical analysis , Optimization of designed components based on analysis results	20.10.20
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PREFACE

This Thesis was initiated at Tallinn University of Technology, Department of Electrical Power Engineering And Mechatronics, where the majority of the work took place, under direct supervision of Scientist Toivo Tähemaa, and consultation with Programme Head, Professor Mart Tamre.

The topic of this thesis is to take a human-centred approach towards the design process of an active upper-body exoskeleton for industrial applications, specifically load handling. The task in point is lifting a load (25 kg) from a set height of 30 mm, walking for a certain distance and placing the load at a different height (800 mm). This was achieved by researching and following the most recent and relevant engineering standards, followed by a biomechanical analysis of the human upper body and several load lifting techniques, with assessing their effects on different body parts and parameters, and using this information as an additional guideline to create a computer-aided design that is able to achieve a required range of motion.

This Thesis is dedicated to my parents, without whom I would not have been able to be here, to Moustafa, who have supported and encouraged me unconditionally, and to Farah and Ahmed, who were always there to raise my morale and cheer me on. I would like to thank scientist Toivo Tähemaa for his guidance and help throughout this year, and Professor Mart Tamre, for his continued help and support throughout my study time.

Keywords: Exoskeleton, Computer-Aided Design, Upper-body, Biomechanics, Master Thesis

List of abbreviations and symbols

ADL	Activities of Daily Living
CAD	Computer Aided Design
CG	Centre of Gravity
COR	Centre of rotation
DH	Denavit–Hartenberg
EODS	European Occupational Disease Statistics
GNP	Gross National Product
MSD	Musculoskeletal Disorders
PPA	Personal Protective Equipment
ROM	Range of Motion
WMSDs	Work-related Musculoskeletal disorders

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1 INTRODUCTION

Automation is the use of technology to carry out different tasks with minimal or no human assistance. Over the past decades, there has been major development in the industrial sector, thanks to automation. One main aspect that automation helped with is reducing physical effort on the human body and increasing mobility; through its introduction to assistive devices [1], such as wheelchairs, walkers, cranes and prosthetic devices. This helped alleviate their features from passive to active; where electric motors are used to facilitate their usage, thus reducing human motor power required to use them. This affects all aspects, from daily chores, to industrial settings where workers have to spend long hours standing or performing physically demanding tasks, which affects their overall health and performance.

Exoskeletons are considered an example of automated assistive devices. They are Defined as Physical assistant robots, which in turn are defined as personal care robots that physically assist a user to carry out required tasks, by providing supplementation or augmentation of personal capabilities [2]. They can be classified into full-body, lower-body and upper-body exoskeletons.

Active exoskeletons use motors to perform assistive motion, reducing loads and effort exerted by users, compared to passive exoskeletons, which provide support to bodies, thus only relieving stress or providing support to motion. Active exoskeletons provide a form of performance augmentation, if motors are placed in suitable locations, where they are proven to work efficiently and not act as an additional load to the user. In order to find these locations, a study of the human musculoskeletal construction must be performed, to test the effects this exoskeleton has on different muscles/joints, in order to make informed design decisions.

In medical fields, exoskeletons were initially developed to facilitate and accelerate patients' recovery; by introducing the possibility to perform repetitions of exercises with higher consistency [3], and in movability aid; to compensate for injuries or disabilities. Extensive research was performed to solve problems and improve current exoskeleton solutions used in these fields. However, in industrial applications, exoskeletons remain rather unexplored and underdeveloped, when compared to those used in medical applications. In principle, performance augmentation exoskeletons can be used in both fields, however, there are additional considerations and studies that need to be performed to adapt the exoskeleton to the industrial setup, including but not limited to operating hours, the type of performed motion and the exoskeleton material, as it will handle different loads.

Workers' wellbeing is an important aspect to both personal and institutional levels; therefore, reducing physical and mental stresses is considered a priority. Further studies should be directed towards this goal, in order to benefit in the safest way possible from automation in industrial sector. This directly reflects on workers' productivity, which in turn reflects on economy as a whole.

Thesis problem and objectives:

The focus of this thesis is the development of a CAD model of an upper-body exoskeleton, in a human-centered approach that designs based on the biomechanics of the designated task. Current exoskeletons are governed by the task they are intended to achieve (subject-specific), directly affecting their complexity and creating heavy structures for specific tasks. This thesis sets out to create a versatile yet simple design. The biomechanical analysis is intended to observe how the activated musculoskeletal parts act during lifting motion in general, and using the most suitable technique as a guideline for the design. This is based on the specific task of lifting a load of 25 kg, and move it then place it in a specified location. Since each motion is produced by different sets of muscles, reactions are different as well. This study can be further used in specifying and comparing different locations for motors, choosing the most optimal results, subsequently, making informed design modifications and recommendations, hence the need to perform biomechanical analysis as an essential step towards production. This can be considered one of several sub-projects towards the prototyping of a final exoskeleton.

Biomechanical analysis is essential to the overall mechanical exoskeleton design, as the latter has a direct effect on the hours a user can wear the device. This results in design challenges presented in the need to careful alignment of human joint axes and robot joint axes [4], which in turn results in complex designs, hence the need to use biomechanical analysis, integrated in the design process, to overcome similar issues and offer wider opportunities to solve design problems.

	Task description	**Deadline**
1.	• Available constructions, products and technologies • Review of relevant standards for industrial and medical applications • Study of relevant biomechanical parameters and research • Limitations and disadvantages overview	05.03.20
2.	• Construction of CAD model • Biomechanical analysis • Optimization of designed components based on analysis results	20.10.20
3.	• Finalizing of documentation.	10.12.20
4.	• Printing and binding of thesis.	10.01.21

The thesis starts by reviewing available upper-body exoskeleton models, with special focus on those used in industrial applications, followed by a review of the most recent studies in the fields of biomechanical simulation, lab experiments and exoskeletons prototypes for different purposes. This is followed by an overview of the most current limitations and disadvantages that face the research and development process of exoskeletons, which comprises the main literature review. This is followed by studying relative engineering standards, work-related MSDs, biomechanical analysis of different lifting techniques, detailing the work on the developed CAD model, results and subsequent recommendations.

2 LITERATURE AND INDUSTRY REVIEW

Exoskeletons were first used in the medical filed as assistive devices, to help in rehabilitation processes. For example, post-stroke rehabilitation benefited from exoskeletons through their ability to help with exercises; in terms of repetition and providing customized assistance [4]. Later, exoskeletons were introduced to different fields, military and industrial applications for example, for performance augmentation purposes. These applications include helping soldiers and workers carry heavy loads and performing different movements (walking for long distances or lifting) and reduce loads by transferring the weight of the carried load to the ground, through the exoskeleton frame, in the case of full body exoskeletons.

The scientific definition of exoskeletons developed along their usage in different fields. Standards were developed initially for medical applications. Afterwards, definitions were set as exoskeletons expanded into other applications, where they were categorized under personal care robots [2]; service robots that perform actions contributing directly towards improvement in the quality of life of humans, excluding medical applications. This is further categorized into Mobile Servant Robots, Physical Assistant Robots and Person Carrier Robot. Physical assistant robots are personal care robots that physically assist a user to perform required tasks, by providing supplementation or augmentation of personal capabilities [2].

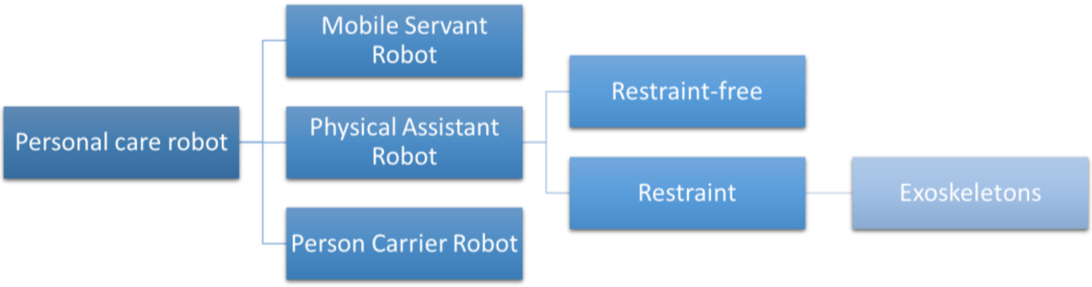


Figure 2.1 Classification of Personal Care Robots

2.1 Existing solutions (products)

Exoskeletons were recently introduced to industrial applications in 2014-2015, however, they were mostly passive exoskeletons that only reduce stress off workers' bodies, not augment their performance. For example, in 2018 FORD [5] announced that it would start using EksoVest, a passive upper-body exoskeleton, to reduce injury risk in some plants and help reduce physical effort. According to research [6] using passive exoskeleton in assembly line tasks can reduce lower back muscle activity by 35:38%, resulting in increasing endurance time for static holding by three folds.

Ekso Bionics is the manufacturer of the aforementioned EksoVest [7], which offers lift assist of 2.5 to 6.5 kg per arm, adjustable to fit operator and application, and the vest weighs 4.3 kg. It is customizable to fit a wide range of operator heights between 15.2:19.3 m, using durable and flexible material to withstand wear and tear. EksoVest reduces fatigue and increases endurance if operators, making it easier for them to operate for longer hours and improving their overall health.

Ottobock is a German artificial limb manufacturer that designed a passive upper-body exoskeleton; Paexo Shoulder [8], to reduce physical strain, on shoulder joints and upper arms, from repetitive overhead assembly work. It weighs 1.9 kg, adapts to heights from 1.6 to 1.9 m and can be worn for more than eight hours. In addition, it offers full freedom of movement and easy to put-on and take-off. It focuses on transferring the arm weight to the hips, not to the back, through a pelvic belt. Paexo proved good results when tested on 30 workers at Volkswagen manufacturing plant in Bratislava. Ottobock conducted and published two studies on the effect of an industrial exoskeleton on overhead work [9, 10] proving a notable reduction in muscle size (deltoid and bicepts brachii between 40% and 48%, segments of trapezius muscle between 18% and 34%). Moreover, Muscle Fatigue Index was compared without and with an exoskeleton and was proven to be lowered significantly. Another passive upper-body exoskeleton produced by Laevo [11], and carries the company's name, is Laevo V2. It weighs 2.8 kg, available for different heights [12] from 1.56 m to 1.96 m and provides a combined torque of 30 Nm.

Active exoskeletons use actuation (electrical, hydraulic, pneumatic, etc.) to help augment workers' performance, as a result, reducing fatigue. However, active exoskeletons are more popular in rehabilitation applications. Ekso Bionics produce an active exoskeleton under their Ekso Health project [13] to help with stroke recovery gait training. It is a lower body exoskeleton that uses motors to assist patients in walking motion to help accelerate their recovery process. Another solution is developed by a Japanese company, Cyberdyne, defined as a "robotic remedial device that lead to the possibility to walk" [14], also known as HAL for Medical Use. It moves the user's legs in accordance with their intention through verbal commands, which enables timely feelings' feedback; accelerating brain learning.

An example of active exoskeletons used in industrial applications is Guardian XO; a battery-powered, full body exoskeleton produced by SARCOS. It offloads 100% of the exoskeleton's weight (68 kg) [15] during usage and is able to manipulate weights from 15 kg to 90 kg. It amplifies user's strength by 20x and can dynamically compensate for gravity and inertia [9] through a torque that peaks at 450 Nm.

2.2 Research fields and progress

Biomechanical analysis and experimentation are proving to be an essential part in the development of exoskeletons for different purposes. Experimental studies on overhead work on the human body proved that passive exoskeletons can reduce work-related strain [9] and improve comfort. This is obtained through monitoring metabolic and electromyographic parameters during experimental lab studies using the aforementioned Paexo passive exoskeleton. The study showed reduction in the user’s metabolic energy consumption and a measurable reduction in shoulder strain.

Similar studies are applied on different motion types; for example, experimental studies on forward-bending tasks using passive upper–body exoskeleton [6] considering muscle activity, discomfort and endurance time, showed a reduction in muscle activity (35:38%) and lower discomfort in lower back. Other studies focus on different parameters; such as oxygen consumption and energy demand [16] during continuous lifting task and proving that using a personal lift assistive device (PLAD) does not justify increasing workloads. Moreover, different versions of PLADs have different effects on body muscles’ activity, for example, the version used in this study achieved a 14% reduction in biceps femoris activity during lifting, while a different study [17] found an additional reduction in gluteus maximus’ activity during lifts but not squats. This, in addition to an increase in compressive spinal loads for exoskeleton compared to no exoskeleton, with the effects being more pronounced for the heavier tool used in the experiment. The study concludes that while exoskeletons are used to eliminate or reduce specific muscle stress (arms, torso in this case), they affect other muscles (lower back) indirectly and negatively, when closely investigated.

The variations in study focus of biomedical analyses provides insight to the way exoskeleton affect different body parts in different movements, as this study [18] that focuses on the effect of biomechanical loading on lower back as a result of wearing an exoskeleton to assist in occupational work. This is achieved through a lab study wear a mechanical arm is connected to an exoskeleton vest to support overhead work, while observing muscle forces for two different tools with and without the exoskeleton and arm. Results of this study included an increase in muscle forces in torso muscles, for both tools by significant percentages, however, they remain inconsistent for both. While an increase in torso muscles activities is predictable, the study found an increase in flexor muscle forces, which requires further investigation. Moreover, muscle forces on the left side of the body were higher than those on the right side (peak and mean values).

Another lab study performed an assessment of an active industrial exoskeleton used for aiding dynamic lifting and lowering of handling tasks, in terms of its effect on muscle activity, perceived musculoskeletal effort, measured and perceived contact pressure at the trunk, thighs and shoulders, in addition to subjective usability for simple sagittal plane lifting and lowering conditions [19]. The study included lowering two different box weights (7.5 kg and 15 kg) from mid-shin to waist height, with and without exoskeleton. The exoskeleton reduced back muscle activity (12:15%) and biceps (5%), in addition to a total reduction of musculoskeletal effort in the trunk (9.5:11.4%), with the highest contact pressure being on the thighs and least on the shoulders.

Biomechanical analysis can be tested before lab experimentation using simulation software, which reduces the need to build prototypes and facilitates fast and repeatable testing. An additional benefit in the case of biomechanical analysis of the human body is that it allows deep and non-invasive muscle analysis, which helps in providing more valuable information. This is shown in this study [20] to determine the metabolic cost of running of an Ideal, lower-body assistive device, where the average metabolic consumption was computed for 10 subjects running at 2 and 5 m/s. The study proved a notable power consumption reduction for the two running speeds tested. Higher reduction in metabolic power was recorded at higher speeds however the speed to metabolic power consumption ratio was equal when compared to lower speed.

Another simulation-based study looked into Reducing the metabolic cost of walking with heavy loads using ideal wearable assistive devices to reduce injury risk for people who carry heavy loads [21] such as firefighters and soldiers. The study is based on simultaneous optimization and prediction of muscle activity changes in response to applied device torques, at regular intervals throughout the motion, for all 7 devices in the study. The devices were found to only partially reduce the metabolic rate of their associated joint motion and many of them affected the metabolic rate related to joint motions rather than the metabolic rate of the joint act actuated by the device itself.

another study [22] is concerned with the effect of exoskeletons on the human musculoskeletal system and physiological interaction of the device with the body. The study looks at 3 main biomechanical discomfort aspects; muscle activation effort, representative joint reaction force and total metabolic cost, and compare cases of assisted and unassisted movements; box-lifting and sit to stand, using AnyBody Software. For the sit to stand movement, a notable reduction in knee joint reaction forces (9%) was recorded compared to unassisted motion, with higher values for muscle activation effort and total metabolic cost. However, more consistent values were recorded for the three parameters (49.2%, 48.8% and 49.6%) in the box-lifting task, proving that a device gain is not proven using one task only.

Analysis can be used to validate mechanical designs prior to prototyping and manufacturing, as the case in this study [23] to validate a hand exoskeleton, with focus on examining any change in finger kinematics, by creating user-specific musculoskeletal models through motion capture, while performing two industrial tasks (hammer and screwdriver usage). The study found that the exoskeleton does not affect joint angles, with a coefficient of determination between models with and without exoskeleton = (0.93), which is considered an ideal value.

Biomechanical simulation can be combined with other software as MATLAB to construct a dynamic model that obtain its characters from a CAD model. Design model is used to compute independent join trajectories for the exoskeleton [24], which further helps in the development of the control mechanism of the exoskeleton. This is considered as a further analysis of the results of biomechanical simulation. The entire process is completed using virtual tools, which facilitates the construction of personalized devices according to the needs of each user.

2.3 Challenges, current and future solutions

Early 2000's challenges were related to balance difficulties and high metabolisms [25], which required solutions related to developing flexible, muscle-like actuators, which in turn had their own challenges; actuators' durability at high performance and meeting the required force and stroke. These problems had little development over time, in fact, metabolic cost remains a topic that is still being developed and applied for different types of motion [26]. This, in addition to challenges that remains unsolved to this day, such as weight, especially for active exoskeletons, and range of motion, which directly relates to the exoskeleton's complexity, which directly affects the exoskeleton's mobility; all making it difficult to use in rehabilitation of paralyzed patients.

A large portion of the performance and development of exoskeletons lies in actuators. Current actuators are a part of the problem imposed by the weight of exoskeletons. Lightweight actuators should be used, with high power and efficient transmission, to help provide the required motion while reducing the overall weight. This, in addition to, improving the actuators' durability and lifetime at high performance levels [27]. Pneumatic actuators are the most suitable; especially those that have similar principles to muscles, and limited maximum contraction.

Performing accurate motion requires more degrees of freedom (DOF), which in turn requires more complex controllers and more parts, making the exoskeleton heavier for the user, and in cases of upper body exoskeleton, it limits the options to transmit stress from lower back or targeted body parts. Moreover, the lack of direct information exchange between the nervous system and wearable device further limits the latter's development [28].

Exoskeletons for rehabilitation purposes are linked to skin surface EMG signals, as they reflect the user's intention, however, EMG signals are not consistent in the sense that they are different for the same motion in the same person; therefore, they remain complex to fully understand and rely on as the main control signal. Moreover, human motion is more complex than a robot motion, making it impossible to match the kinematics for both of them and obtain optimal accuracy and alignment. In fact, current mechanical design of many exoskeleton prototypes alters the biomechanics of normal human gait, causing discomfort and a large metabolic cost. This, in addition to the existing misalignment resulting from the slippage between the robot and human body during motion, which adds to the list of problems resulting from the differences between the human and the exoskeleton [29].

3 ENGINEERING STANDARDS

Following a correct engineering design approach, a research was performed to find the design and safety standards, relevant to Exoskeletons. Since exoskeletons were first developed in the realm of medical applications; to be used in personal support and rehabilitation, the first encountered set of standards was relevant to medical devices. This standard is ISO 13485:2016 Medical devices - Quality management systems [30], which is applied to all medical devices exclusively. Such standards were used by researchers, while developing exoskeletons, due to the lack of standards to be applied on exoskeletons generally as a structure, therefore, medical applications standards were the next best thing, even though they do not completely apply to industrial exoskeletons.

Further research resulted in finding other standards related to exoskeletons specifically, however, still within medical fields. These standards are known as “ISO 13482:2014 Robots and robotic devices - Safety requirements for personal care robots” [2] and they comprise the main part of this chapter, since they have been developed for a while and contain large specifications and details.

In addition to ISO standards, there are new and separate sets of standards that applies to exoskeleton applications within the industrial field. These standards are being developed by ASTM, Committee F48 [31] on Exoskeletons and Exosuits. However, this committee was recently established (2017), with initial standards relevant to terminology [32] and labeling [33]. This chapter contains a description of the standards used directly in the design process; the full standards documentation is available in Appendices B and C.

3.1 ASTM standards

3.1.1 Standard practices for exoskeleton wearing, care, and maintenance instructions

Recent publications (2020) from this committee contain additional details, such as ASTM F3392 “Standard Practices for Exoskeleton Wearing, Care and Maintenance Instructions” [34] that describes the minimum written information that should be provided by exoskeleton manufacturers to end users, in relation to wearing, care and maintenance of exoskeleton. It specifies that the information be written in a manner easily understood by user, however, it does not include information on how or when to use the exoskeleton.

3.1.2 Documenting environmental conditions for utilization with exoskeleton test methods

Environmental conditions play an important role in assessing exoskeletons performance, since they are meant to operate in different conditions, it is essential to consider the effects of these conditions on exoskeletons' operation, and how they affect each other [35]. The designer must describe the conditions in which the exoskeleton is permitted to operate. These conditions are Environment Consistency, Ground Surface, Temperature, Humidity, Atmospheric Pressure, Lighting, Air Flow and Quality, External Sensor Emission, Electrical Interference and Boundaries.

3.1.3 Load handling practices

This standard [36] provides example test procedure for common load handling tasks, along with a method to record load and test parameters, for replication purposes. It provides different examples of load shapes, along with their design details, to allow replication. The user requests the load-handling test and these guidelines demonstrate to perform the test and document the results, as shown in flowchart from figure 3.1.

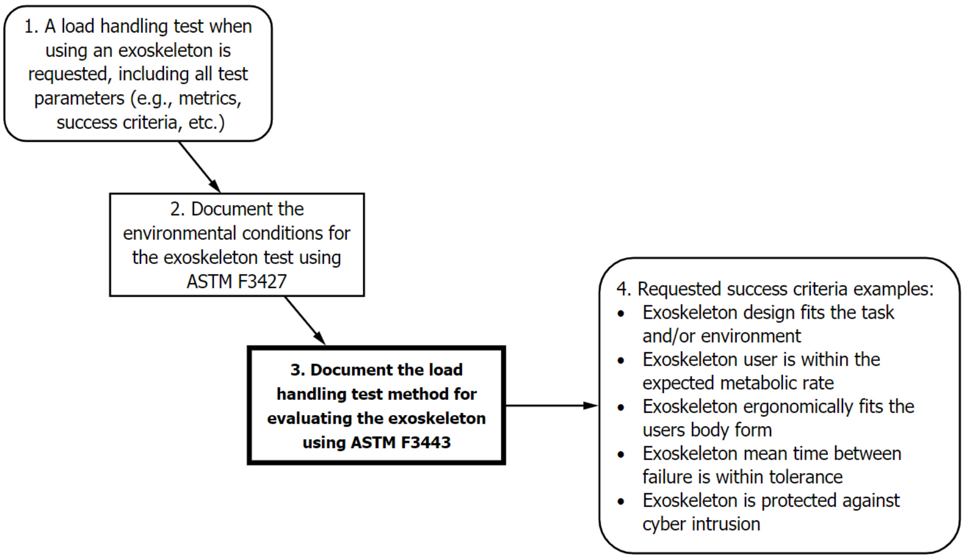


Figure 3.1 Flow Chart for Performing Load Handling Test Methods [36]

A classification of load type per sector (industrial, medical, military, response and entertainment) is provided for specific load shapes (box, back load, human dummy, cylinder, flexible cylinder, bar and various), as examples to be followed for similar shapes or altered accordingly.

A description is provided with steps for the complete procedure, for example, lifting a box load, starting with where to grip the box, where to hold it upright, all the way to the steps taken away from the origin point to box destination. After describing the procedure, photos of the process should be attached, along with metrics documentation. Tests are repeated 29 times, or as instructed by client. Further modifications are added to each simple trial to make it more complex and ensure a variety of basic movements that can be combined across different experiments.

3.1.4 Drafted standards

There are other drafted standards in development phase, such as ASTM WK68719 "New Guide for System Usefulness and Usability", with a scope to identify and develop tools (e.g., relevant attributes, questionnaires, and observation methods) for assessing usefulness and usability of exoskeleton usage [37]. This is intended to help increase user acceptance by demonstrating how a person interfaces and integrates with exoskeleton, on physical and cognitive levels.

Another set of drafted standards is ASTM WK73074 "New Guide for the Prevention of Ergonomic Hazards and Injuries from Exoskeleton Use", which aims to provide ergonomic guidelines to reduce or prevent risk of injuries or illnesses [38], resulting from repeated motions attributed to exoskeletons usage.

The last set being drafted is ASTM WK65347 "New Guide for Utilization of Digital Human Modeling", which is very important to the subject of this thesis. It aims to identify and develop methods to be used in human modeling tools to help understand the physiological and biomechanical effects on the body, resulting from using exoskeletons, for both static and dynamic conditions. It states that ideal exoskeleton development will use digital modelling tools and human in the loop testing to ensure constant consideration of internal forces, torques and pressures on the user's body [39]. It is intended to be used in evaluating current exoskeleton designs and eliminate the need to build prototypes for all prospective designs and avoid unsafe testing [40].

3.2 ISO standards

This part of the research will focus on explaining all relevant sections of the currently used standard; ISO 13482, which is implemented in almost all exoskeleton research studies, for medical and industrial fields. The following sections are an adaptation of the published standards by ISO [2][41], and have been partially developed during the course of a previous course project [42] (spring 2019).

3.2.1 Mechanical design

3.2.1.1 Hazards due to robot shape

According to ISO 12100, sharp edges and points shall be avoided in the design of a personal care robot. Holes or gaps shall be designed in a way that prevents insertion of any part of the human body, in compliance with ISO 13845 & ISO 15534.

Joints shall be designed in a way that prevents crushing parts of human body, while performing its intended movement; by choosing geometry and restricting joint limits.

Moreover, cushioning sharp edges and points shall be applied, in addition to using fixed or movable guards to cover hazardous moving parts.

3.2.1.2 Hazards due to contact with moving components

It is recommended that personal care robot be designed to reduce risks of hazards resulting from exposure to moving components to an acceptable level.

Design considerations include designing personal care robot with a minimum number of accessible moving parts, however, components such as motors, shafts, gears shall not be exposed.

Protective measures; fixed and movable guards, are subject to specific regulations. For fixed guards; they shall be installed so that they are opened/closed only using tools, and they shall not be capable of remaining in place without their fixings. As for movable parts, they shall be designed so that they cannot be easily removed, and once they are removed, they shall remain attached to the personal care robot.

3.2.1.3 Electrostatic potential

Design considerations related to Electrostatic discharge include using conductive materials, discharging outer surfaces by earthing and using other techniques to prevent electrostatic charge build-up on touchable surfaces. Moreover, covers of electrical equipment shall comply with IEC 60204-1 to avoid contact with live parts.

3.2.2 Hazards due to stress, posture and usage

3.2.2.1 Physical stress and posture hazards

Design of personal care robot should consider minimizing physical stress or strain to its user, resulting from continuous usage. Moreover, design shall take into consideration the typical body size of intended population, to avoid physically demanding body postures.

Safe design measures include designing and locating manual control devices, that are detachable and/or hand-held, instead of being permanently attached to the personal care robot. Protective measures include using shock absorbing mechanisms and posture supports.

3.2.2.2 Mechanical instability

Personal carrier robot shall be designed to minimize mechanical instability due to failure. Mechanical stability shall be maintained against static and dynamic forces from any moving parts and loads of the personal care robots.

Design measures include designing the center of gravity of the personal care robot to be as low as practicably possible, to ensure that mechanical resonance effects cannot lead to instability, and to reduce the masses of the moving parts to be as low as reasonably practicable.

3.2.2.3 Instability while carrying loads

Risk assessment shall consider consequences of dropped loads, and any actions required by personal care robot following such actions. Further safety measures shall be applied as; the use of form fitting designs, using passive means of securing loads (screws), limiting devices to avoid handling of loads that exceed its maximum rated payload.

Other protective measures include tying or locking loads by means of bolting or latching devices. In addition, the device should include a protective or emergency stop for normal operation.

3.3 Key takeaways

The current state of engineering standards has evolved over the past years and is in a better status than it has ever been. The aforementioned standards have helped in guiding the exoskeleton design process and making calculated design decisions. Regulations pertaining to robot shape (item 3.2.1.1) have been followed and the developed design avoided having sharp edges, cushioning exoskeleton parts in contact with body parts, as well as restricting joint limits to avoid trapping body parts. Moreover, regulations in item (3.2.1.2) have been applied to the motor housing unit, where it is isolated from direct contact with the human body, at the same time accessible for maintenance.

The design process considered regulations in item (3.2.2.1) where the design must take into account the typical body size of intended population (male and female measurements), with the additional adjustability to size option. This, in addition to limiting the designated load to be handled by this specific design, as recommended in item (3.2.2.3)

ASTM standards specify (item 3.1.2) that the designer set forth the environmental conditions where the exoskeleton can optimally operate, and include specific factors of how the designer can document the conditions. This is considered a prerequisite for the description and validation of subsequent load handling tasks, to be replicated by the user or by other developers. A designer must provide instructions and recommendation for the user that describes all operations pertaining to the exoskeleton (item 3.1.3, 3.1.1), which was followed in this thesis by studying the motion techniques used in the lifting motion and making a recommendation for two techniques based on the load’s location, which takes into consideration item (3.2.2.1) of the provided ISO standard to reduce or minimize physical stress to the user.

Pertaining to this topic is a drafted standard [39], which will develop standardized methods to be used in physiological and biomechanical simulations to understand their effects on the body. It is expected to provide better framework and more insights to the process. This guideline will specifically state that human in the loop modeling is essential for the development of exoskeletons.

4 WORKPLACE ERGONOMICS

According to the International Ergonomics Association, ergonomics is "the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance" [43]. Given the importance of an integrated approach that takes into consideration environmental factors during the exoskeleton development process, this part will discuss common workplace injuries related to load handling, the cost of these injuries, material handling, prevention and reduction methods of these injuries and respective recommendations.

4.1 Workplace injuries

Musculoskeletal disorders (MSD) are one of the most common workplace injuries. According to the CDC [44] they are "injuries or disorders of the muscles, nerves, tendons, joints, cartilage, and spinal discs". Work-related MSDs are conditions where the work environment and work contribute or worsen the condition.

According to the European Agency for Safety and Health at Work [45], 24.7% of European workers suffer with backache, 22.8% with muscular pain, 45.5% work in painful positions and 35% handle heavy loads. MSDs make up about 39% of total occupational diseases in Europe in 2005 [45]. Moreover, recent trends point out the increase of MSDs in younger working populations [45], with a great effect on service workers, some of which are unrecognized as women and younger workers. For example, load handling, mostly dominated by men, affects 5.8% of workers, compared to 43.4% of workers in female-dominated health care sector. Similarly, for younger workers, they are focused in specific sectors that are under-studied and require more inspection to get a clear representation of their percentage in this study. Generally, blue-collar and service workers are the most exposed to continuous risks arising from load-handling and vibrations. Service sector, agriculture and construction workers are subject to prolonged standing and walking, each of which has their own risks and subject workers to different MSDs.

Musculoskeletal disorders include a wide range of locomotor system diseases [45], such as tendons inflammation (forearm, wrist, elbow and shoulder), pain and functional impairment of muscles, nerves compression (wrist and forearm) and spine degenerative disorders related to manual handling or heavy work. EODS complied a table of MSDs incidence rate per 100 000 workers, shown in table 4.1.

Table 4.1 Incidence rate (per 100 000 workers) of occupational diseases, EODS obligatory list, 2001-2005 [45]

	2001	**2002**	**2003**	**2004**	**2005**
Infections	0.5	0.6	0.6	0.5	0.4
Cancers	2.4	3	2.7	3.8	4
Neurological diseases	8.5	12.1	13.5	13.8	16.5
Of which Carpal tunnel syndrome	8.4	12.1	13.5	13.8	16.5
Diseases of sensory organs	4.5	8.9	10.2	10	10.1
Raynaud’s syndrome	3.1	2.5	1.7	1.1	1
Respiratory diseases	7.7	9.3	10.6	11.3	11.3
Skin diseases	5.3	7.5	7.9	5.8	5.6
Musculoskeletal diseases	15.2	23.7	2.5	26.4	30
Total	47.1	67.7	73.8	72.8	78.8

Accroding to European Working Conditions Surveys [45], risk factors for MSDs include reptitive work, painful/tiring positions, carrying heavy loads, exposure to vibrations, lifting/moving people and prolonged standing/walking. Other factors include speed of work, forceful movements and direct mechanical pressure on tissues.

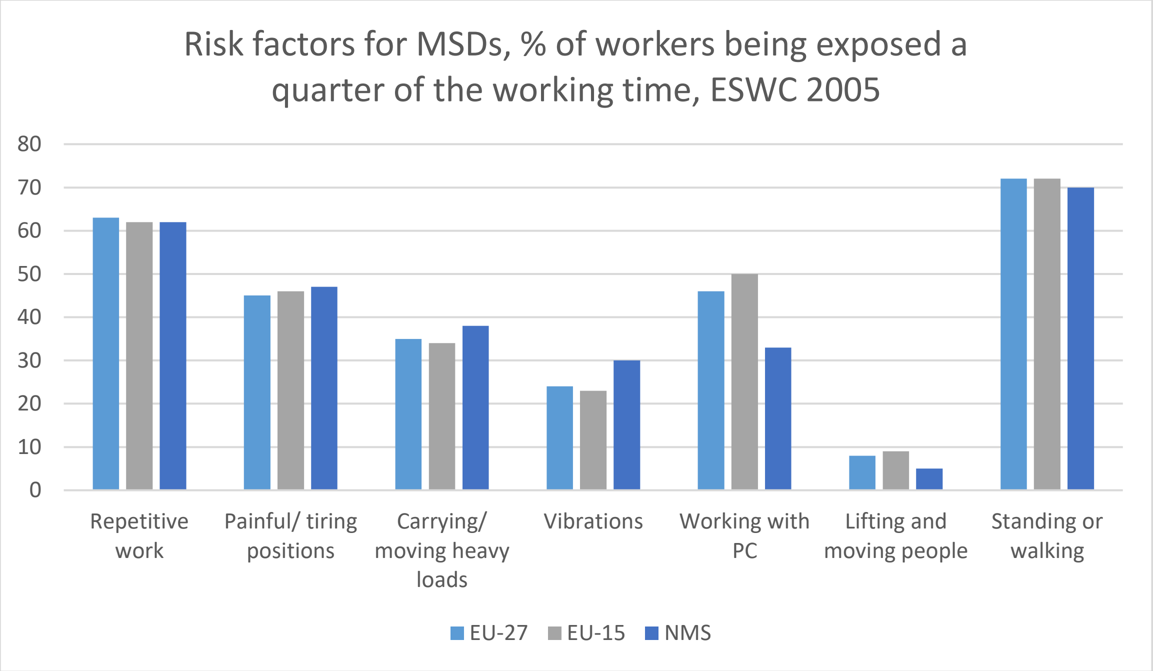


Figure 4.1 Risk factors for MSDs, exposed workers percentage per quarter of working time [45]

4.2 Cost of MSDs

Besides their health effects on workers, MSDs have an apparent economic impact due to their commonality. The costs are divided to direct and indirect costs. Direct costs include insurance, compensation, medical and administrative costs [45]. Indirect costs are sick leave costs, hiring and training of new employees, reduced productivity and effects on production and its quality. The actual cost across EU states is difficult to assess, however, a report published by the European Agency for Safety and Health at Work in 200 estimates the cost to be 0.5% to 2% of GNP.

In France, according to the national Plan on Health and Safety at Work (Plan Santé Travail 2005-2009), there was 31000 compensated diseases that led to a loss of 6.5 million workdays, with a cost of 650 million euros [46], without considering indirect costs. In 2006 [45], MSDs contributed to loss of 7 million workdays and 710 million euros of companies' contributions. Indirect costs are estimated [45] to be 10 to 30 times higher than direct costs.

In Austria [47], a labour inspection estimated costs impacts from MSDs. The inspection found that MSDs attributed to 38% of work-related absenteeism cost. Direct costs on the employer were 164.7 million Euros in the form of continued salary payment; state economy effect was 29.6 million Euros in the form of paid sick leave, 300.4 million euros in medical treatment costs, rehabilitation and disability pensions, and a worker contribution of 135 million euros in treatment costs. Indirect costs for the employer were represented in Non-wage costs, production loss, worker-replacement costs, while the state economy suffered 236 – 315 million Euros in lost productivity and 103.8 million euros in disability pensions, on the other hand, workers lost income and had reduced employment chances.

In Germany, according to The German Federal Institute for Occupational Safety and Health (BAuA) [45][48], MSDs accounted for 95.2 million sick leave days, out of 401.4 million days total (23.7%). This resulted in a cost of productivity of 8.5 Billion Euros (total 36 billion) and a percentage of 0.4% of GNP, and an added cost of 15.4 Billion Euros (0.7% of GNP).

4.3 Material handling

According to U.S. Department of Labor, load handling is defined as "Seizing, holding, grasping, turning, or otherwise working with the hand or hands. Fingers are involved only to the extent that they are an extension of the hand, such as to turn a switch or to shift automobile gears".

During this process, workers are exposed to injuries resulting from handling (in our case, lifting) repetitive loads, which can be reduced by improving how workers and their environment fit together. Introducing a device to reduce loads on the worker is one step towards that direction, however, it imposes its own variables to be taken into consideration during this fitting process.

Possible health effects from load handling include fractures caused by sudden incidents, as well as damage to muscles, tendons, ligaments and joints caused by repetitive tasks over long time. Most common MSDs related to material handling are low-back pain and injuries.

The human spine contains four natural curves that are maintained in their neutral position during upright stand. Material handling results in changes in these curves based on the handling technique chosen by the worker. For example, using stoop lifting technique changes these curves drastically, and by repeating this motion, a person is more subject to sustaining injuries as a result.

According to the European Agency for Safety and Health at Work [48] there are four main factors to be taken into consideration while assessing the dangers of manual handling, these are; load, task, environment and worker.

The load can be too heavy for one individual worker, however, a weight of 20 to 25 kg is considered heavy for most people. Taking into account the frequency of handling this load, puts the load into better perspective. Moreover, the size of the load is essential to reduce or increase the ease of handling; it is arguably easier to handle a small but heavy load, than to handle a large load of medium size. In addition to size, the shape of the load plays an important role in a worker’s ability to handle it, where providing handles to loads can help in having a better grip and stability to the worker. The load location is essential as loads far-to-reach can pose an additional strain to arm muscles to be moved closer to the worker’s body to be better handled, as recommended.

The nature of the task is a direct contributor to the amount of harm it does to the worker’s body. The duration and frequency of the task, combined with performing it without taking a break can cause more damage over time. Moreover, the worker’s posture over prolonged periods of time should be avoided to reduce strain on lower back (seated tasks) or legs and lower back (standing tasks).

The work environment can add more restrictions to the worker’s movement, if it was small or irregular, it adds more strain to the aforementioned factors. Moreover, irregular or slippery floors can pose more threats to the worker’s movement, in addition to climate conditions in the work place, that can harm both the worker and the equipment.

There are several factors that can increase the worker’s chance to workplace incidents; experience and familiarity to the job are important to avoid such results. Moreover, older workers are more susceptible to injury than younger workers, just as smaller workers are more susceptible than those with bigger physique are. Individual differences include personal physical history of back disorders, and workers’ preference to using assistive devices or PPA.

4.4 Prevention

There exists an agreed-upon, comprehensive approach to address and eliminate workplace hazards and injuries. It is addressed through three different sectors; use of engineering controls, use of administrative controls and use of Personal protective equipment [44]. Even though the recommendations are for individual sectors, combining methods from all of them yields better results.

The engineering controls take into consideration the technicalities of the workplace; transferring raw material, assisting with lifting loads, modifying loads to be easier to handle, adjusting work environment to be more adaptable to different conditions to address individual physical attributes, and ergonomic design of the work space with respect to the task being performed.

Administrative controls are not as effective as engineering controls, however, when combined they are proven to provide better overall results in preventing workplace injuries. These include reduction of shift length, scheduling more breaks, providing education and training on several tasks that they can swap between to avoid prolonged exposure to one posture.

The traditional definition of PPE is a device that provides a barrier between worker and hazard source. These include earplugs, safety goggles, safety shoes and hard hats. Other devices that are considered assistive devices such as braces, back belts and even exoskeleton can offer more help and reduce loads, reducing risks of injuries. However, the latter devices are not widely adapted or completely considered as PPE, given their complex nature compared to earplugs and similar devices. Moreover, these devices are not universal, and are very task-specific, making them less popular and arguably less effective on a wider scale of industries.

4.5 Recommendation

The European Agency for Safety and Health at Work [49] lists what is agreed upon as the “correct handling techniques” that form a preliminary guideline, to be taken into consideration as the bare minimum for lifting loads. This includes recommendations before attempting to lift the load and they are:

1. Knowing your destination
2. Clearing your surroundings of obstacles
3. Pre-opening doors and clearing floor of obstacles
4. Having a good grip on the load
5. Not having slippery hands or load handles
6. In case of lifting with another person, it is essential that both people know what they are doing before proceeding

As for the lifting technique, the following is recommended:

1. The feet should be put around the load, and the body on top of it, or keeping the body as close to the load as possible
2. Utilizing leg muscles in the lifting motion
3. Keeping the back straight, preferably upright, if possible
4. Lifting the load as closely as possible to the body
5. Lifting and moving the load with straight arms.

Figure 4.2 squat lifting technique [50]

Additional considerations are addressed by UNC [51] concerning carrying the load from one location to another. It is recommended that a person does not twist their body (hips, shoulders, trunk) but try to move to destination with their body keeping the same direction, while keeping elbows close to the side of the body. Moreover, setting the load down should be performed in the same manner of lifting it up, only in reverse, while maintaining the previous recommendation of not twisting the body, as well as steady and slow motion (as tolerated).

5 BIOMECHANICAL ANALYSIS

Biomechanical analysis of the human joints related to the movement assisted by the exoskeleton is arguably one of the most important aspects related to the development process of exoskeletons. However, it was shown recently [52] in a study of relevant design metrics to exoskeletons, that biomechanics is the least considered metric, according to 40 field experts. Biomechanics ranked last of 50 metrics, including cost, manufacturability, weight, comfort, ease of use, degrees of freedom and social impact. This is a result of the lack of a solid design approach of exoskeletons, due to their recent introduction to the industrial field from the medical field, which makes them relatively new to a different area of application, with different purposes and considerations. This chapter contains an analysis of upper body biomechanics, an analysis of different lifting techniques, their metabolic costs and a subsequent recommendation for the users to incorporate during usage of exoskeleton.

5.1 Upper limb biomechanics

5.1.1 Anatomy

Upper limb refers to the collection of shoulder, arm, elbow, forearm and hand joints and the attached bones and muscles, as shown in figure 5.1. These parts, along with the hip and back, are responsible for generating the lifting movement. For simplification, this part will include only bone structure of the upper body.

The shoulder is comprised of one main joint known as “Glenohumeral Joint” (a ball-and-socket-like joint) which in turn is made of the combination of the scapula and clavicle. It is linked to the back through the scapula, to the thorax through the clavicle, and to the arm through the humerus, which in turn is considered a part of the Glenohumeral Joint. The humerus is linked to the elbow through the radius and ulna, which in turn comprise the forearm. The humerus, radius and ulna comprise what is known as the elbow, with the major part of the joint being a part of the ulna, while the radius comprises the main part of the wrist joint.

Different combinations of movements from each of the aforementioned parts comprise a specific movement the places the hand in the final location. Moreover, they are responsible for holding and stabilizing the arm while the hand performs a specific action.

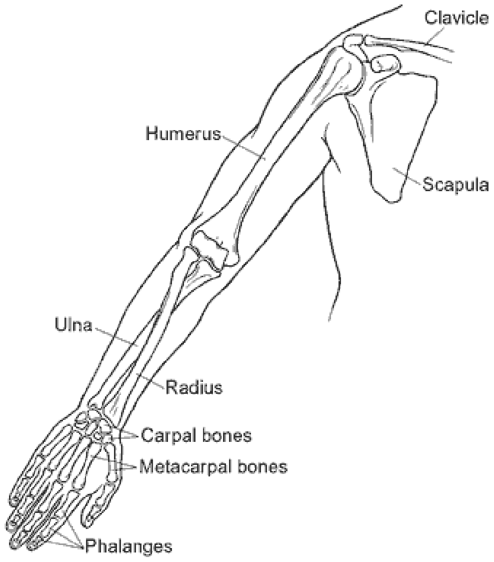


Figure 5.1 Skeletal structure of human arm [53]

5.1.2 Biomechanics

The movement of limbs in different directions lies within three planes, known as anatomical planes, and these planes are sagittal (lateral) plane, coronal (frontal) plane and transverse (axial) plane, shown in figure 5.2. The sagittal plane divides the body into left and right, the coronal plane divides it into front and back, and the transverse plane divides the body to upper and lower.

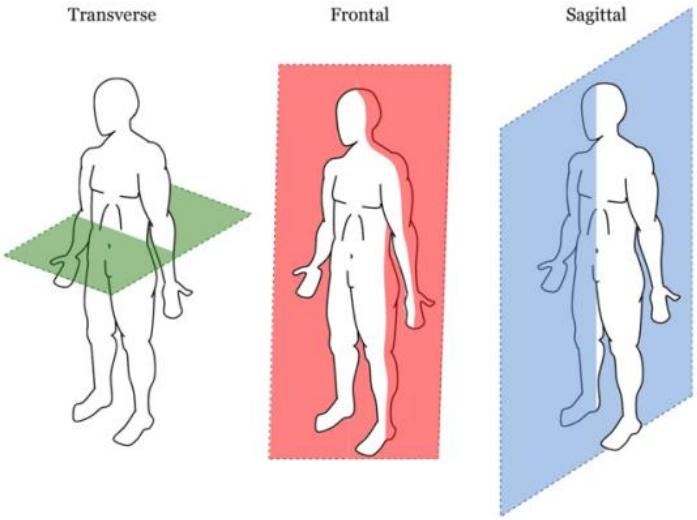


Figure 5.2 anatomical planes of motion [54]

Given its ball-and-socket-like nature, the shoulder joint can perform 7 movements in the aforementioned planes. These movements, shown in figure 5.3, are shoulder flexion and extension in the sagittal plane, abduction and adduction in the frontal plane, as well as horizontal abduction and adduction in the transverse plane, medial and lateral rotation, and circumduction; which is a combination of flexion/extension and abduction/adduction.

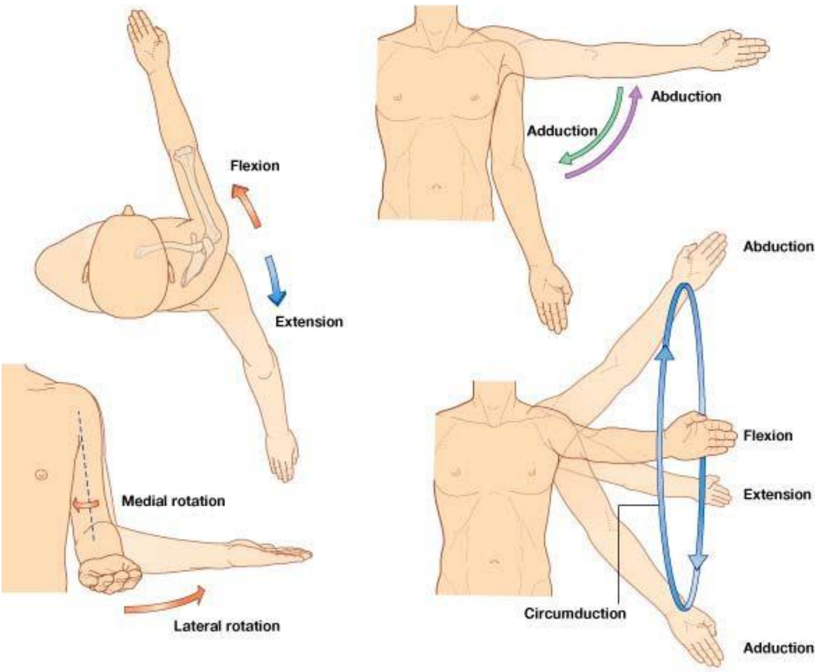


Figure 5.3 Different shoulder motions [55]

The range of motion for each of the aforementioned movements is essential in the development of exoskeletons. Neither can the exoskeleton perform a movement that it out of the body’s normal range, nor is it safe for the body to exceed the exoskeleton’s limits. However, in this case, it is more important to focus on the body’s limits, known as range of motion, for the relevant joints to the performed motion.

According to the American Academy for Orthopaedic Surgeons [56], the ROM for horizontal flexion is 180 degrees, and 60 degrees for horizontal extension. ROM for abduction/adduction is 180 degrees. ROM for forward flexion is 180 degrees, and 60 degrees for backward extension. ROM for medial (internal) rotation is 70 degrees and for lateral (external) rotation is 90 degrees. The values are summarized in table 5.1.

Table 5.1 Range of motion for Shoulder movements

Motion	**Plane**	**ROM**
abduction/adduction	Frontal	180°
Horizontal flexion	transverse	180°
Horizontal extension		60°
Forward flexion	Sagittal	180°
Backward extension		60°
Medial rotation	transverse	70°
Lateral rotation		90°

5.2 Back biomechanics

5.2.1 Anatomy

The second essential part responsible for the lifting motion is the back, specifically lower back and pelvis bones. The bone structure of the back is comprised of the vertebral column (spine), whose inner part forms the spinal cord, and attaches to the back muscles. The spine is responsible for transferring loads from the head and trunk to the pelvis [57].

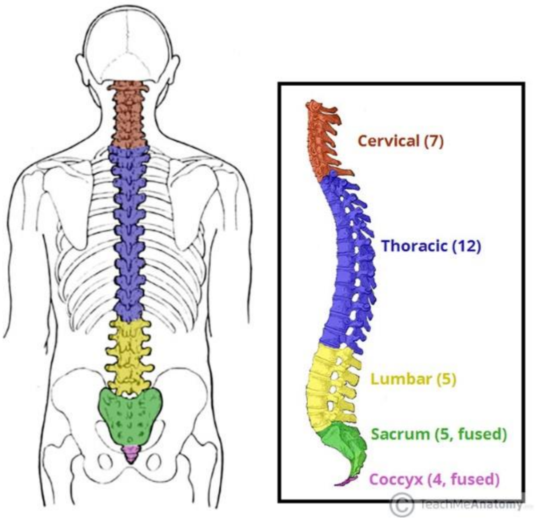


Figure 5.4 Human vertebral column (spine) [58]

The spine is comprised of 33 vertebrae, the upper 24 of which are articulating and separated by intervertebral disks. These 24 vertebrae are divided into three sections: the upper seven form the cervical vertebrae, the following twelve form thoracic vertebrae and the last five are the lumbar vertebrae. The lower nine vertebrae are fused together, forming two groups: sacrum (upper five vertebrae) and coccyx (lower four vertebrae), as shown in figure 5.4.

Vertebrae vary in size depending on their location [59], which in turn defines their purpose. The cervical vertebrae are the smallest in size, given their location at the back of the neck and considering the relatively low weight (skull) they support. Thoracic vertebrae are larger than cervical vertebrae. They are longer and have an angle to overlap with the lower vertebrae. Lumbar vertebrae are the largest; however, they are shorter and the thicker than thoracic vertebrae. They carry most of the body weight, due to their location at the lower back. The sacrum is triangular, has a wide upper part that bears loads, and a small lower part that connects to the coccyx. This last part does not bear weight during standing motion, but can hold some weight during sitting.

5.2.2 Biomechanics

The spine movement lies within the same three aforementioned planes; sagittal (lateral) plane, coronal (frontal) plane and transverse (axial) plane. The spine can perform extension/flexion in the sagittal plane, left and right lateral flexion in the frontal plane, as well as right and left rotation in the transverse plane, as shown in figures [60] 5.5, 5.6 & 5.7.

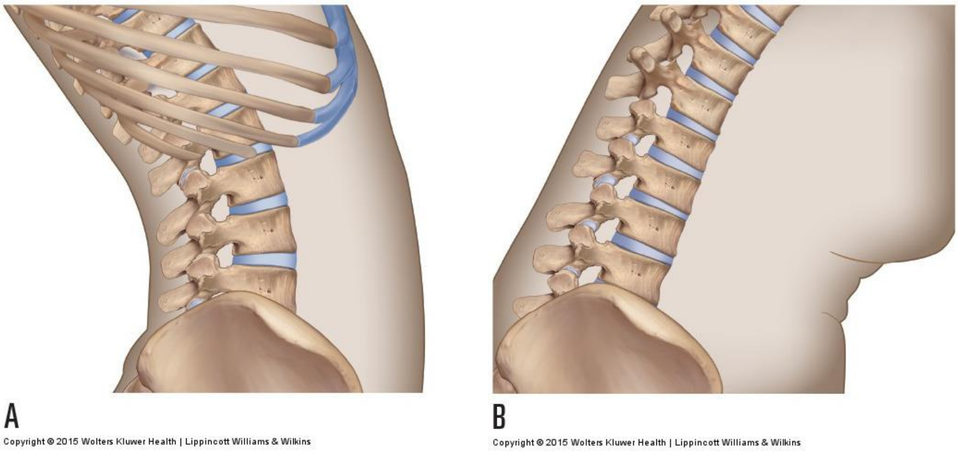


Figure 5.5 Back extension (A) and flexion (B) [60]

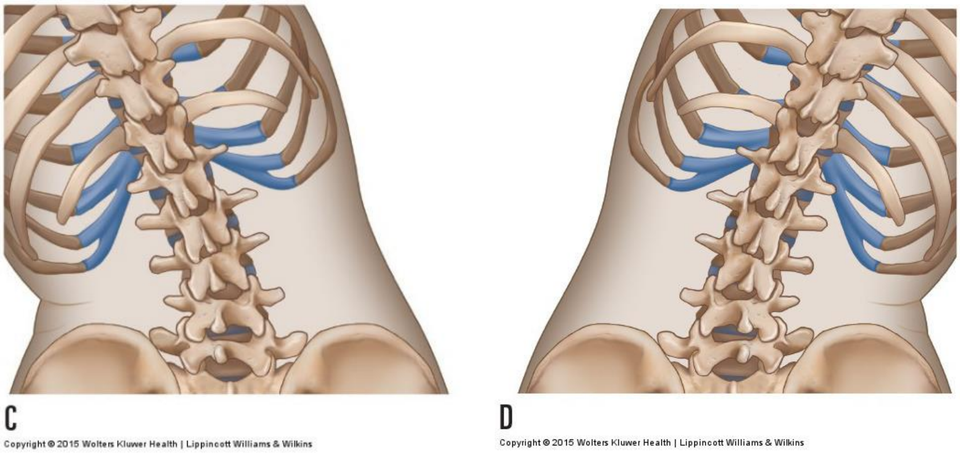


Figure 5.6 spine left (C) and right (D) lateral flexion [60]

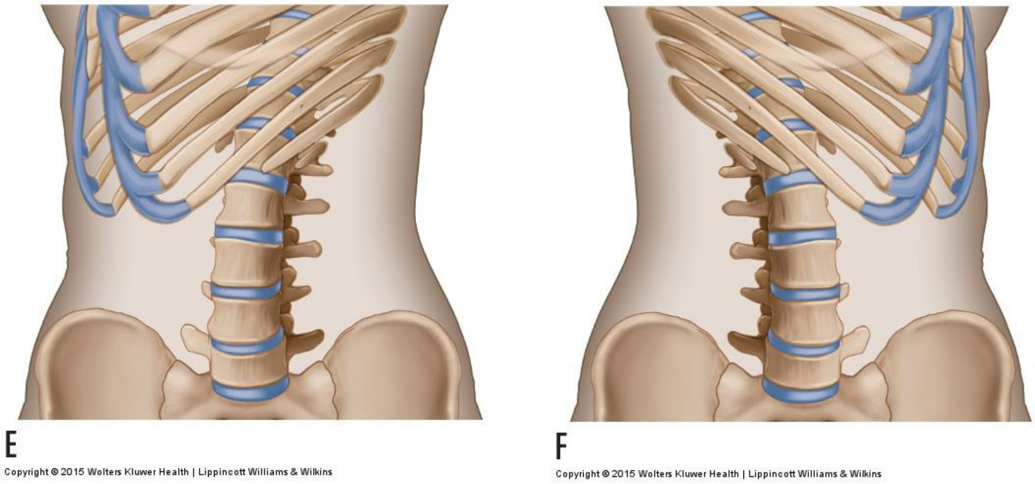


Figure 5.7 spine left (E) and right (F) rotation [60]

The average range of motion differs for the aforementioned movements according to different measurements and studies [61]. There exists different ROM for the 3 areas of the spine; Cervical, Thoracic and Lumbar. Since different studies give out different values, these were combined statistically and the average values were presented as follows, and summarized table 5.2.

For the cervical spine, maximum flexion is 64 degrees, and maximum extension is 64 degrees (total ROM = 127 degrees). Lateral bending for cervical spine is equally 49 degrees for left and right direction. Axial rotation for cervical spine is identical as well for left and right sides at 85 degrees.

For Thoracic spine, ROM for maximum flexion is 26 degrees, and 22 degrees for maximum extension, with a total ROM of 48 degrees. For lateral bending, the maximum ROM for both left and right directions in 30 degrees. For Axial rotation, the maximum ROM is equal for left and right directions at 47 degrees.

For lumbar spine, maximum ROM for flexion from neutral position is 65 degrees, while ROM for extension is 31 degrees, with a total ROM of 96 degrees. For lateral bending, the maximum ROM is 30 degrees for each of left and right lateral bending. For axial rotation, the maximum ROM is equal for both left and right directions at 15.3 degrees.

Table 5.2 Range of motion for different sections of the spine

Spine	**Motion**	**Plane**	**ROM**
Cervical	Extension/flexion	Sagittal	127°
	Axial rotation	Transverse	170°
	Lateral bending	Frontal	98°
Thoracic	Extension/flexion	Sagittal	48°
	Axial rotation	Transverse	94°
	Lateral bending	Frontal	60°
Lumbar	Extension/flexion	Sagittal	96°
	Axial rotation	Transverse	30.6°
	Lateral bending	Frontal	60°

5.3 Metabolic cost

Metabolic cost is a term used to describe basal metabolic rate or rate of energy expenditure exerted during the performance of a specific motion. It is considered a standard way of comparing differences between different motions; walking, running, jogging, etc., and is often used within the context of biomechanical analysis. For these motions, the factors affecting metabolic rate are walking speed, step length to frequency, step width and vertical movement of the human's center of mass.

As explained in [62] metabolic cost can be measured directly through the heat production of the body, or indirectly by measuring the volume of oxygen and carbon dioxide inspired and expired, respectively. These are the practical methods of obtaining metabolic costs of activities. More recently biomechanical analyses software have enabled these measurements through musculoskeletal modeling of a specific motion and calculating the metabolic cost based on a metabolic energy expenditure model.

Metabolic cost is a very useful parameter to be used in comparing and choosing between different lifting techniques.

5.4 Lifting motion

There exist several techniques for lifting a load off the floor, all of which have different effects on different body parts. This section will discuss and analyze three of them; stoop lifting, squat lifting and semi squat lifting. Moreover, this analysis will result in a recommendation of a movement to be used alongside the exoskeleton developed, as recommended in item 2.1.3 of exoskeleton development standards by ASME.

5.4.1 Stoop lifting

Stoop motion is comprised of a straight leg with a flexed trunk. It involved spinal flexion, with trunk flexion of 90 degrees and fully extended knees. This position exerts higher intradiskal pressure, compared to other techniques, and higher quadriceps femoris group activity at the start and end of the lift movement, while hamstrings are moderately used only at the middle of the lift motion [63][61].

Due to its lower usage of muscles, stoop method is shown to require lower oxygen consumption [63][65], with an Oxygen volume of 32.9 ml/kg/min compared to 38.7 ml/kg/min for squat lifting [63][66].

In general, the difference in lumbar moment between stoop and squat is 5% of their values [63][67], however, stoop motion is generally recommended for smaller loads with more frequency [63][68]. Stoop is generally preferred by workers, due to its lower physical demand, compared to squat lift [63][69]. Moreover, there is a great concern related to stability during stoop lifting, caused by exposure to static postures involving stoop positions, which causes tissue creep affecting stabilizing ligaments, which can increase injury likelihood [63][70].

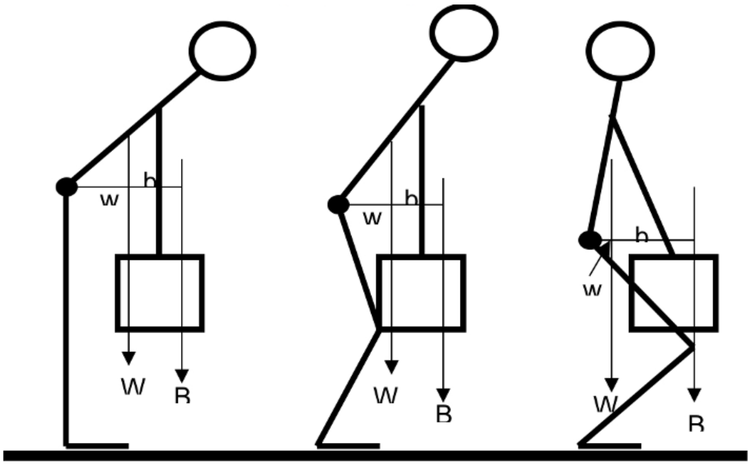


Figure 5.8 Diagram of stoop, semi-squat and squat lifting techniques [71]

5.4.2 Squat lifting

Compared to stoop lifting, which is fully dependent on a flexed trunk/lumbar spine, the squat lifting maintains a straight or slightly tilted spine, with flexed hips and knees. This results in a reduction of intradiscal pressure, in addition to a change of knee movement from flexion to extension through the movement. As outlined before, squat lifting has more oxygen consumption compared to stoop lifting, because it engages more muscles. Moreover, studies [69] showed that it requires bigger lung capacity, indicating the need for healthier workers to be considered better than stoop lifting.

The main merit of squat lifting is avoiding spinal flexion, reducing injury risks from overloading intervertebral column. Moreover, it was shown [72] that shear forces on spine in stoop lifting can reach 1000 N, compared to 200 N in squat lifting, where the tolerance for spine shear forces is at 2000-2800 N range.

5.4.3 Semi-squat lifting

Semi-squat is considered a "natural" or "intuitive" approach to lifting loads. It is a middle stage between squat and stoop techniques, where the spine is more tilted but not entirely flexed nor straight, with partially flexed knees and hips.

Studies [73] revealed that semi-squat lifting has lower oxygen consumption than squat lifting; however, it is still higher than stoop lifting. Moreover, compared to squat lifting, semi-squat avoids motion extremes represented in high knee flexion, and compared to stoop lifting, it avoids spine flexion. Therefore, it is less likely to cause injuries to knees and lumbar ligaments, and enables longer working times for workers performing lifting motion.

5.5 Recommendation

In addition to the aforementioned analysis of the lifting techniques, other factors can be taken into consideration to recommend a technique for load handling using the exoskeleton. One study [74] regards foot placement during lifting and location of the load. It describes a version of semi-squat lifting, with a “moderate knee flexion and a straight but not upright trunk”, and feet being widely separated, similar to weight lifting. This technique resulted in a 20% reduction of compression forces compared to squat and stoop lifting.

Another study [75] proposes placing one leg next to the object being lifted (20 kg) and compares lumbar compression forces between stoop, squat, straddle and kneeling rom two different heights. For the bigger height (290 mm), squat resulted in the least compression forces (3980 N), while for the smaller height (50 mm), the stoop technique resulted in the smaller compression force (5926N). In the light of this variance, it was concluded that it is not possible to recommend one technique for all lifting conditions.

The location of the load was the center of another study [76] that focused on lower back loads within this context. The comparison was established between one load (20 kg) in front of the body and two loads (10 kg each) beside the body. The study used stoop, straddle, squat and kneeling techniques to measure reaction forces and estimate low-back load. The study found that splitting the load caused a reduction (8-32%) of peak compression forces. Moreover, based on load analysis, it is recommended to keep the load as close to the user’s body as possible, to keep the center of gravity for both bodies closer for more stabilization.

This points out the importance of combining the aforementioned techniques with feet and load location, to provide a more accurate recommendation of the technique within the context of the specific study. However, given the results from previous studies, this study’s load (25 kg), the addition of an exoskeleton, the work setting (factory), workers’ body and health conditions (mostly middle-aged men), it is reasonable to recommend testing with the semi-squat technique to lift the load. Afterwards, an experimental study needs to be performed and measurements of the reaction forces on knees and spine be recorded, then the results can be used to validate or discredit this recommendation.

6 CAD MODEL

The main problem with active exoskeletons is that they are subject-specific; meaning that every exoskeleton is designed within a specific context, to perform a specific task, and have more obstruction performing tasks with different movements. Versatility is a highly desired goal, which is unfortunately difficult to achieve given the complexity of exoskeletons in general. Most recent innovations [77] in exoskeleton design focus on specific joints, to create more versatile and simple mechanisms to address the aforementioned problem.

The second problem is weight; as exoskeletons get more complex, they become heavier. It is a compromise between both factors depending on the purpose of the exoskeleton and the maximum load effect on the user. Most active exoskeletons require rigid structures, so they require using heavier materials that are not easy to deform.

The proposed design attempts to address the universality problem, while having some constrictions for simplification's sake. It is essentially designed to perform lifting task from a low height, and has sufficient ROM to place to the load approximately at the user's eyesight level. This chapter discusses the geometry of the proposed CAD models, static load analysis, kinematics conformity with human body, limitations and final results.

Main design considerations:

1. Adjustability for different user lengths (males)
2. Conformity to the ROM for a specified task
3. Adding additional ROM for future expandability and user comfort

6.1 Review of current designs

Exoskeleton design is based on a compromise between weight and complexity, the more complex the design, the more ROM it offers, the heavier it becomes. A review of relevant designs is conducted to help point out the disadvantages, trends and advantages.

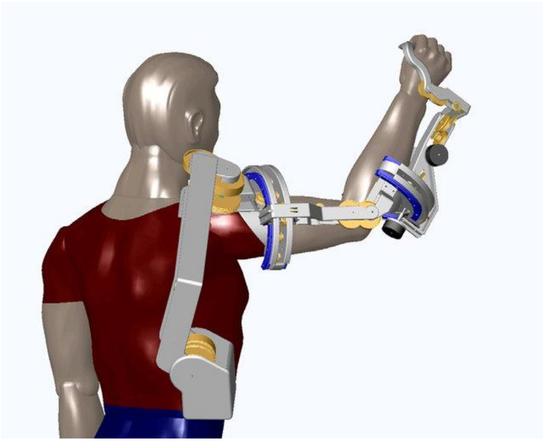
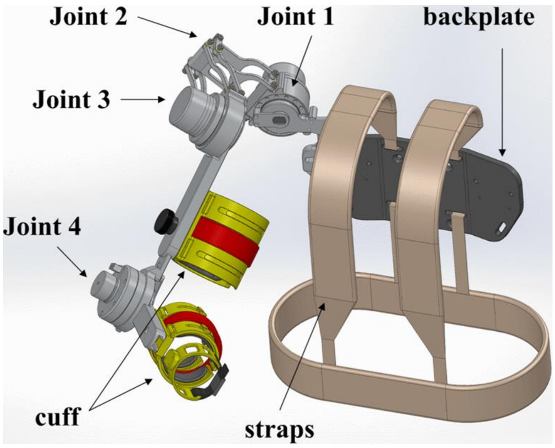
One example of complexity compared to the desired task and practicality is a 7 DOF powered upper-body exoskeleton [78] shown in figure 6.1. The relatively high ROM, and variety of tasks that can be accomplished using the exoskeleton (24 tasks) grant the structure its complexity and weight. However, it is arguably inflexible, heavy and immobile (not attached to user).

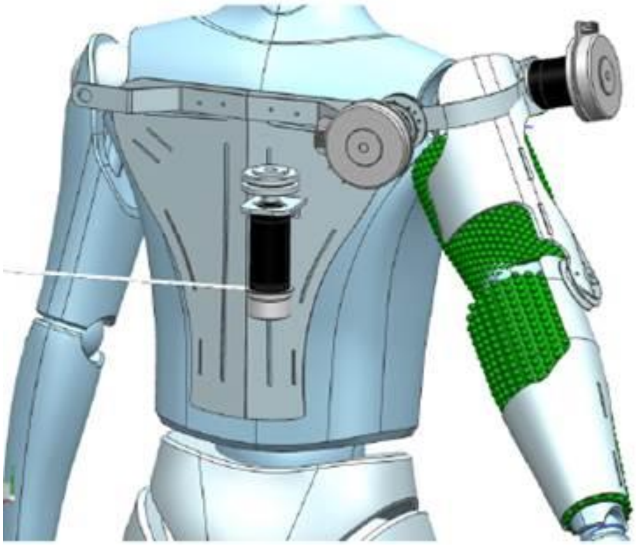
Another example is a 5 DOF mechanism [79] for assistive applications that has a rather complex workaround for the shoulder joint. The study demonstrates the exoskeleton being used in a fixed state, which can help for rehabilitation purposes, however, the study mentions powered motion assistance, in which case the exoskeleton's rather complex design will add more weight to the user.

Another design [24] is intended to assist in rehabilitation and ADL, implements a hinge-like link to join the shoulder with the back support. This, in addition to rotary degrees of freedom for arm and forearm attachments, which further complicates the design. However, this is justified considering the purpose of the design.

The last design [80] has a simpler 3 DOF mechanism, resulting in a simple and presumably light structure (mass not explicitly stated in publication) of 2 kg per arm. The mechanisms are simplified and shown in table 6.1.

Table 6.1 Different exoskeleton models with their respective tasks and DOF

ROM	**Purpose**	**Design**
7 DOF	Assistance in ADL	 Figure 6.1 7 DOF exoskeleton [78]
5 DOF	Powered motion assistance	 Figure 6.2 5 DOF exoskeleton [24]

8 DOF	Assistance in ADL, rehabilitation	 Figure 6.3 8 DOF exoskeleton [79]
3 DOF	Generic performance augmentation	 Figure 6.4 3 DOF exoskeleton [80]

6.2 Dimensions for Geometry

Since the exoskeleton is directly mounted on a human, the design dimensions are derived from average European human measurements published by the German Federal Institute for Occupational Safety and Health (BAuA) [81]. The data was collected so that median (P50) values were collected across all European countries, while the upper (P95) and lower (P5) percentiles were collected from countries with higher (Norway) and lower (Italy) measurement averages. Moreover, these countries would provide average measurements from both males and females. The used measurements are shown in table 6.2, as it appears in the publication [81]. Values are given in mm.

The default length of adjustable segments in the proposed design is taken around the median to lower values, with the adjustability increasing towards the upper measurement averages. This is chosen given that the design is mainly developed for male workers, and since these measurements include both males and females, it is more feasible to design towards larger averages.

Table 6.2 Human body measurements for upper body

No. (figure 6.5)	**Description of Measurement**	**Percentile**		
		5% (mm)	**50% (mm)**	**95% (mm)**
9	Sitting height	790	905	985
10	Eye height	680	790	860
11	Shoulder height	510	623	695
12	Shoulder-elbow length	288	346	410
13	Elbow height	190	243	280
14	Thigh clearance	112	146	170
15	Elbow-wrist length	240	279	318
16	Elbow to elbow breadth	390	478	540
17	Shoulder bi-breadth, bi-deltoid	395	474	485
18	Shoulder bi-breadth, bi-acromial	320	380	425
19	Hip breadth	333	368	440
20	Lower leg length (popliteal height)	380	444	495
21	Abdominal depth	195	237	350
22	Knee height	460	530	602

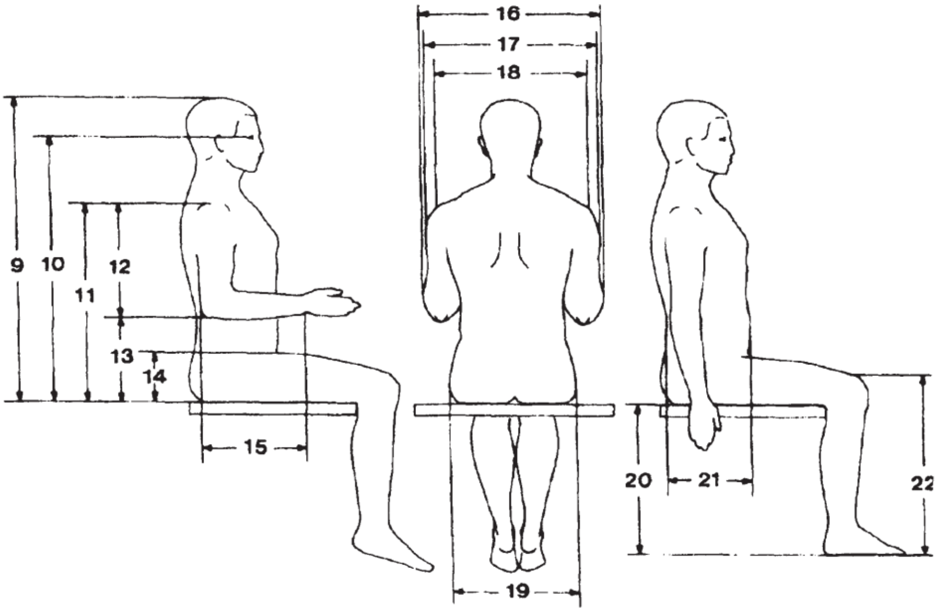


Figure 6.5 indicators for body measurements in table 4.4

6.3 Geometry

The preliminary direction for the design was set to follow the kinematics of the human upper body, taking into consideration the required task. It is comprised of four active rotational joints, for the rotation of shoulders and elbows in the sagittal (lateral) plane, passive back-to-shoulder link, with a flexible ball-and-socket link to the back support, which is curved and padded for user's comfort. The design has 5 DOF for each arm; elbow extension-flexion (active), shoulder flexion/extension (active), shoulder abduction/adduction (passive), shoulder horizontal flexion/extension (passive, defined range), and shoulder circumduction.

6.3.1 Forearm link

The forearm is comprised of two interlocking parts that allow length adjustment to fit different users (280:330mm). Moreover, given the unique cross-section recommended from the results of a previous study [82]; with circular outer cross-section and elliptical inner cross-section shown in figure 6.6, having two interlocking parts increases the strength of the forearm assembly. This cross-section selection resulted in a lighter assembly and provided for a surface of smooth transition for adjustment purposes. The assembly is comprised of the elbow link and the wrist link, shown in figure 6.6. The total length of the elbow link is 215mm, and for the wrist link, it is 168mm.

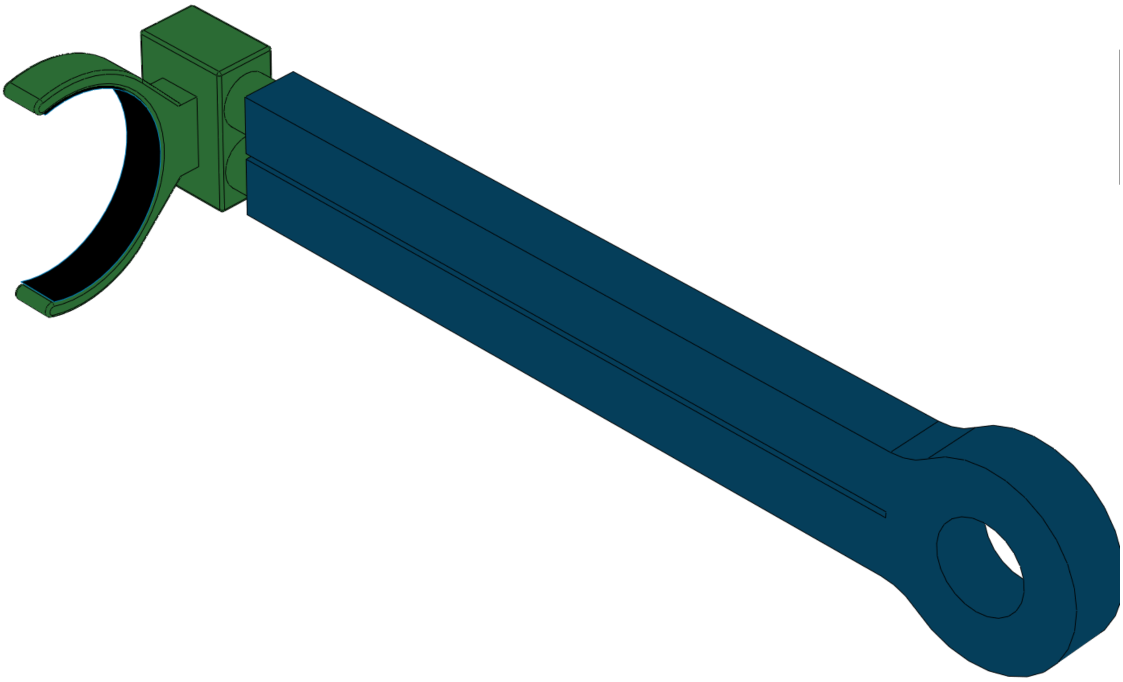


Figure 6.6 Forearm link geometry

The cross-section for the forearm link is based on a previous study [82] that was concerned on studying different cross-sections proposals for industrial exoskeleton applications. In the study [82], multiple cross-sections were evaluated, with different inner and outer shapes. These shapes included Circular Inner Shape and Circular Outer Shape (CISCOS), Circular Inner Shape and Elliptical Outer Shape (CISEOS), Circular Inner Shape and Rectangular Outer Shape (CISROS), Elliptical Inner Shape and Elliptical Outer Shape (EISEOS), Elliptical Inner Shape and Circular Outer Shape (EISCOS) and Elliptical Inner Shape and Rectangular Outer Shape (EISROS). Specific dimensions were set, and material was chosen to be Aluminium alloy 6262. The aforementioned cross-sections were then subjected to loading based on their location in the exoskeleton, and recommendations were made based on the best result for location and type of loading.

The results used in this study are a combination between ideal results; for example, the forearm design in this thesis is comprised of two concentric pipes, to allow for length adjustment. The most optimal part for the forearm was Circular Inner Shape and Rectangular Outer Shape, and it was combined by the second-best choice for forearm, which was Elliptical Inner Shape and Circular Outer Shape, shown in figure 6.7, with the dimensions shown in table 5.1. The same result was applied for the arm cross-section, since the only difference for Circular Inner Shape and Rectangular Outer Shape was negligible.

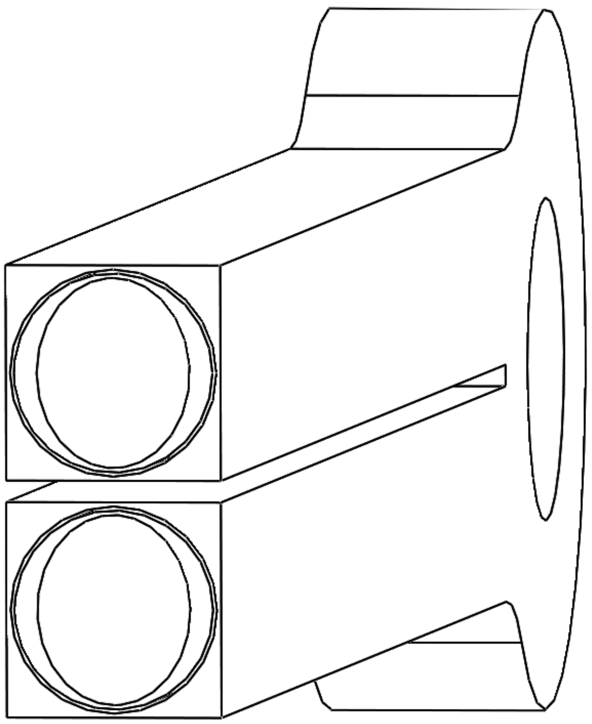


Figure 6.7 Forearm cross-section

Table 6.3 Dimensions for inner and outer pipe cross-sections for forearm link

Inner pipe dimensions		**Outer pipe dimensions**	
Ellipse	Circle	Circle	Rectangle
b = 7.14 mm a = 8.83 mm	D = 18.5 mm	D = 19.5 mm	L = 20 mm W = 19.24 mm

6.3.2 Arm link

The arm link is more complex than the forearm, in terms of ends connection, since both ends will house the motors (at shoulder and elbow). The same cross-section recommendations were applied to the arm link; a Circular Inner Shape and Rectangular Outer Shape, and it was combined by the second-best choice, which was Elliptical Inner Shape and Circular Outer Shape. This, in addition to the length adjustment option, with length range from 315 mm to 406 mm. The forearm link linked to motion transmission from the shoulder to the elbow, however the elbow joint is attached to the bracket that houses the motor and other components directly, for additional stability. The arm link is joined with the shoulder-to-back link concentrically, and this joint adds an additional degree of freedom responsible for shoulder flexion/extension motion.

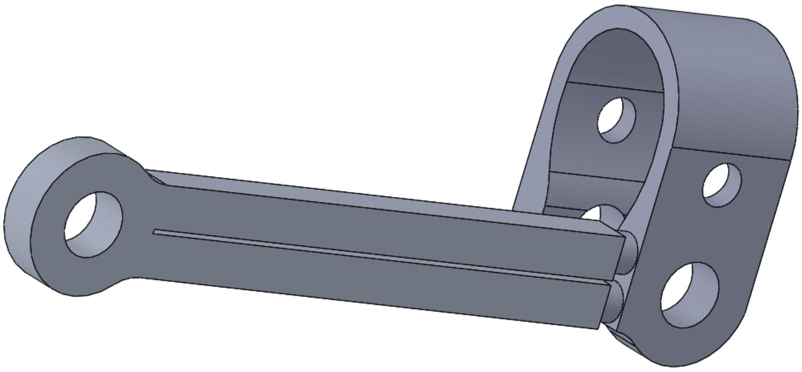


Figure 6.8 Arm link geometry

6.3.3 Shoulder-to-back link

The shoulder-to-back link is attached to the shoulder motor housing through a flexible link. The initial design for this link was a rigid link that can only rotate laterally on the back (1 DOF) at the back-support link. However, the design was later modified to include a slot in one half, and a tab in the other half that can move through it, enabling additional horizontal shoulder flexion. Moreover, it is joined to the back support through ball and socket mechanism, allowing for more ROM for the shoulder joint through the shoulder-to-back link (additional range for shoulder flexion, approx. 30°). Given the complexity of the task and the required ROM, this option can be restricted from motion and act as a fixed part. This proposed technique is an initial direction to be tested, with the goal of adding flexibility to the shoulder-to-back link, without jeopardizing the required rigidity to transfer motions and loads.

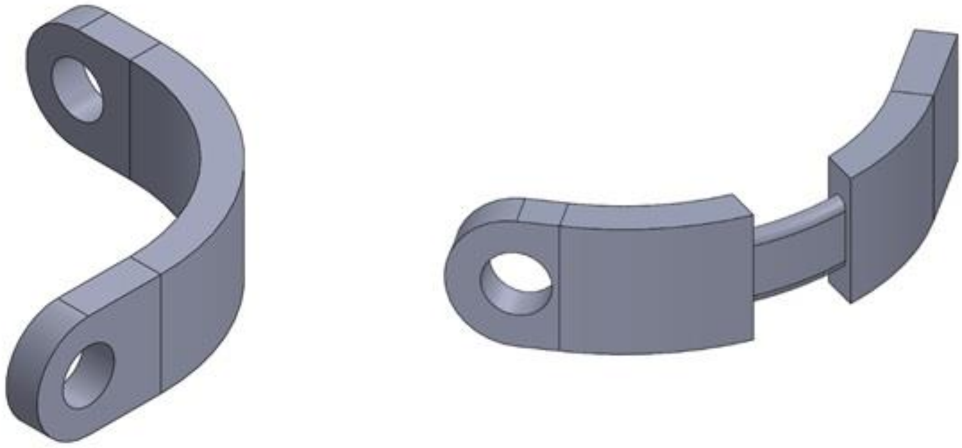


Figure 6.9 Initial shoulder-to-back link (left), final shoulder-to-arm-link (right)

The linking mechanism between the shoulder and back was developed from a flexible rotational link, to offer more flexibility. Since the lifting motion did not require additional frontal DOF across the back due to the fixed handling heights, however, it would offer more flexibility with added DOF in the sagittal plane, to specifically extend the range for horizontal shoulder flexion. Based on this information, a hinge-like mechanism was first proposed to attach the shoulder-to-back joint to the back support. Afterwards, it was decided to combine both options through the introduction of a ball-and-socket mechanism to join the parts and offer both frontal and sagittal ROM.

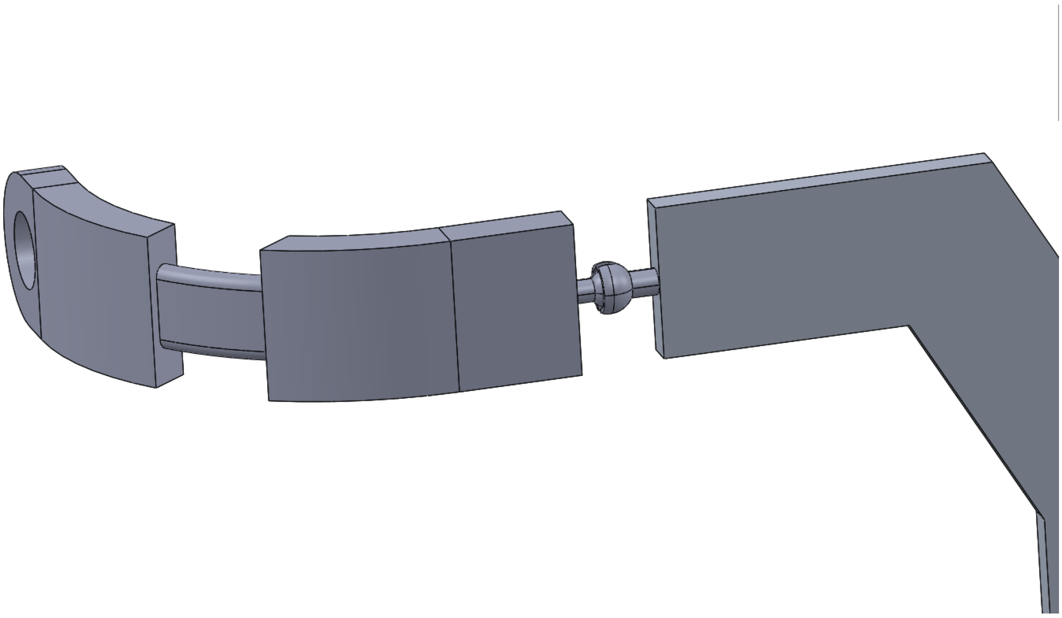


Figure 6.10 Complete shoulder-to-back attachment

6.3.4 Back-support

The initial direction for the back support was to use a flat metal piece that supports the back alignment and help transmit the loads from the upper body to the pelvis. For comfort purposes, the current design does not lay flat on the back; however, there is an angle of 165 degrees between the two halves, as shown in figure 6.11. The lower back support has more tilt (170 degrees from first tilt) as it goes outwards to the sides, to fit the human dimensions. Moreover, rubber padding is added to avoid rigid contact between the back-support and the user’s back. The structure is to be mounted on the human body using flexible fabric fastening, fixed on the lower part of the back support, to the sides and run across the user’s chest and over the shoulders, to avoid adding additional weight and offer flexibility for different trunk lengths and thicknesses.

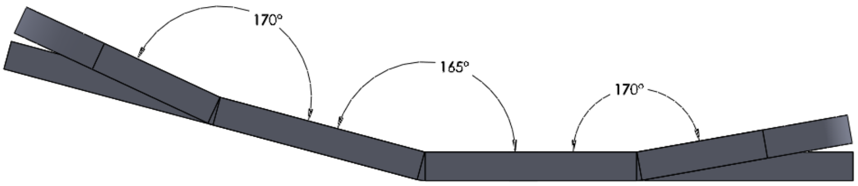


Figure 6.11 lower projection of the back support

6.3.5 Complete design

The final design has a total mass of 4.5 kg, with links lengths conforming to that of human limbs. The length range for forearm is 280 mm to 300 mm, for the arm the range is 315 mm to 400 mm, the shoulder-to-shoulder breadth is 440 mm with extended shoulder-to-back joint, and 400 mm non-extended, as for back support height, it is 370 mm resting from the shoudler scapula towards the lower back.

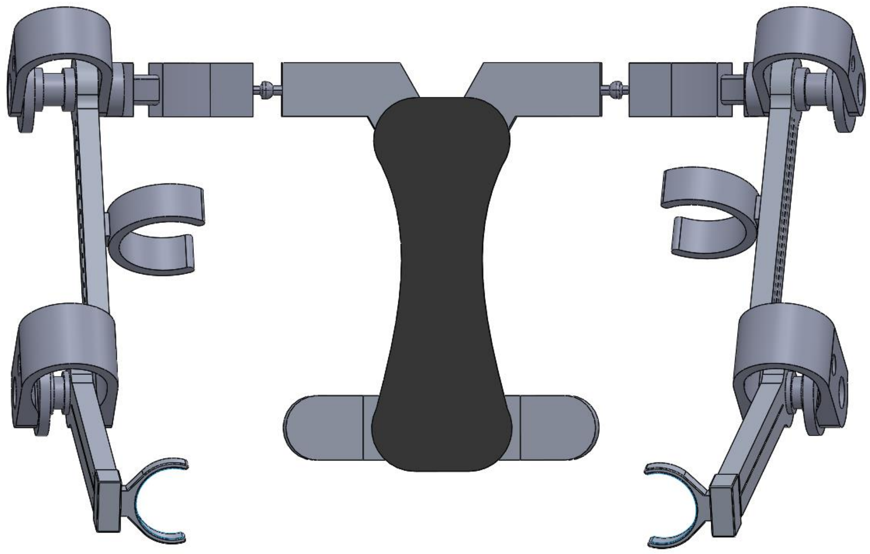


Figure 6.12 front projection of the complete design

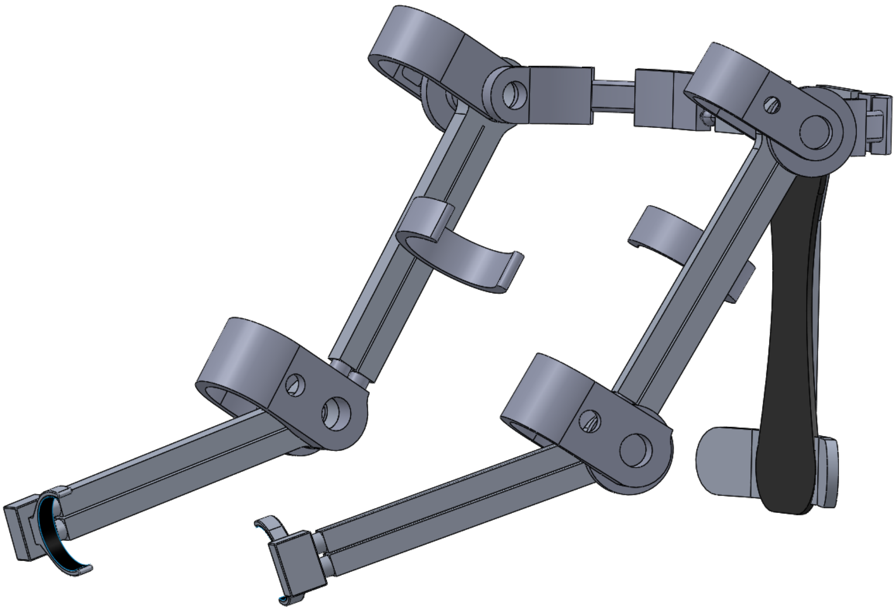


Figure 6.13 side projection of the complete design

6.4 Load analysis

The main task to be achieved, as described in the initial proposal, is lowering the body and lifting a load (25 kg) from a set height (200 mm) and getting up and moving the load to another location (5 m away from original location) at a different height (800 mm). Given the relatively stable nature of the human gait, and the short distance between the initial and final locations (5 m), the loading is considered to be acting in a static manner. This, in addition to the constant load throughout the process, does not change direction, and the inertial and damping force being neglected. Loads are studied on the forearm and arm links only, as they are the most directly affected parts by the load.

The load is studied at approximate positions of highly loaded orientations. For the forearm, the most affected part by the load, bending is the most apparent stress. The orientation of the forearm link while carrying the load varies from 60° to 80° from the resting position at the vertical axis, therefore the analysis fixes the load vertically (90°) for simplification purposes. For the arm, given its orientation range between 30° and 45°, the loading is performed at a 30° angle from the vertical axis, where the loading effect is more prominent.

The material used is Aluminium 1060 alloy with the assumption of uniformity, to allow for equal material distribution across the entire joint to simplify and reduce simulation time. Material properties are Elastic Modulus $6.9\text{x}10^{10}$ N/m^2, Poisson's ratio 0.33, Shear modulus 2.7 x10^{10} N/m2, Mass density 2700 Kg/m^3, tensile strength $9.8\text{x}10^7$ N/m^2 and Yield strength $2.7\text{x}10^7$ N/m^2.

6.4.1 Static loading for arm and forearm

As mentioned before the arm link is fixed in a specific orientation, deemed as the highest loaded orientation of the link. A reaction forces analysis was performed, taking into consideration both the masses of the attached load (12.5 kg) and the links (0.5 kg for forearm, 0.55 kg for arm). The reaction force, from the 12.5 kg load, was added at the elbow joint.

The two links; forearm and arm, were modeled and analyzes separately in the aforementioned orientations, to have a more controlled simulation environment and obtain more accurate and specific results.

Load analysis was performed using Solidworks simulation interface, where material was set to be Aluminium alloy 1060, connection sets were defined between the interconnected slots for both arm and forearm links, with global bonded contact for each part separately, and non-penetrative component contact for the two interconnected links. This is applied for both arm and forearm separately. For simplification purposes, the forearm link was set to have fixed geometry on one end (the elbow location) and the 12.5 kg load added on the other side, while for the arm link; fixed geometry was added to the inclined link at the upper end, with reaction forces from the load was added at the elbow end. Only one arm was subjected to load analysis given the symmetrical nature of the design.

Meshing some of the parts proved to be a little difficult, due to the predominantly circular structures in the design, especially around the joints (elbow, shoulder). General meshing was applied to almost all straight parts of the design, except for the circular joints and the motor housing attached to shoulder and elbow joints, where smaller mesh dimensions were applied (3 mm width and a/b ratio of 1.5). This added to the overall simulation time, taking additional trial and error attempts to modify the overall setup to obtain a reasonable solution.

6.4.2 Results of Static loading tests

The forearm link was subjected to the aforementioned loads, on the load attachment ring at the wrist; a force of 122 N (25 kg x 9.8 m/s^2). The obtained results for von Mises Stress were well below the material's yield strength (2.57x10^7 N/m^2), with the highest possible stress value recorded at 1.6x10^7 N/m^2. The high values were expected to be found around circular edges and connection points between two different parts, which was validated by the analysis results. Moreover, the attachment ring to the wrist sustained the highest stress values, given its relatively thin structure compared to the attached load. As for deformation, the highest value recorded amounted for 0.09 mm and was mainly concentrated at load attachment point at the wrist, and prominent at the lower part of the wrist attachment link to the human arm.

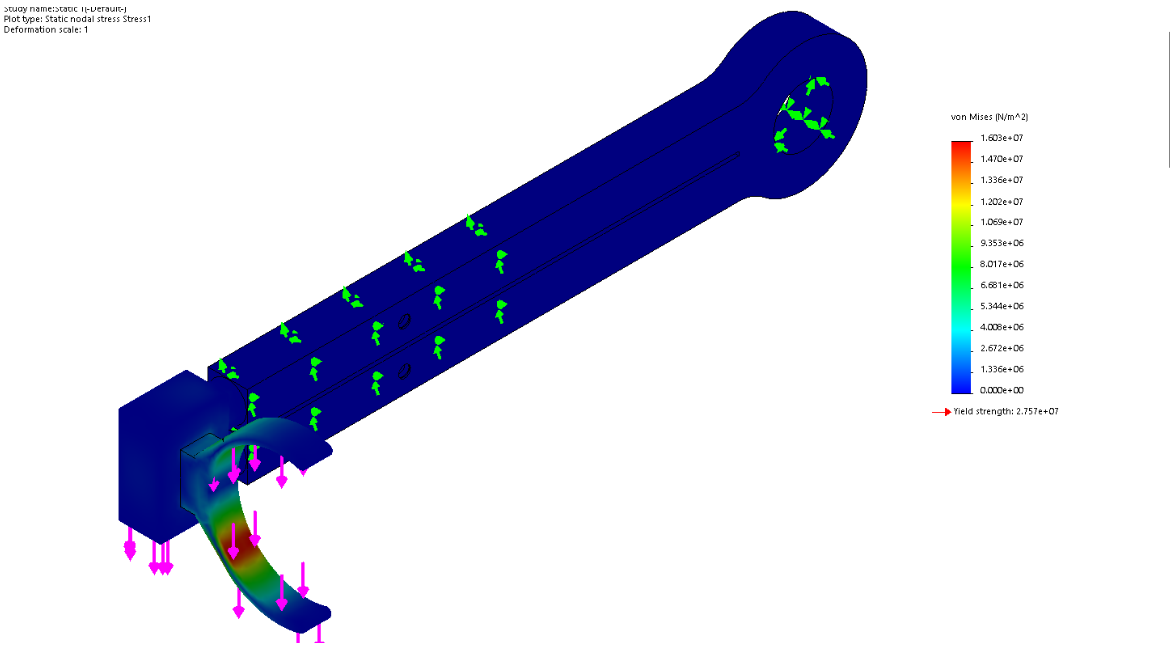


Figure 6.14 von Mises stress results on forearm link

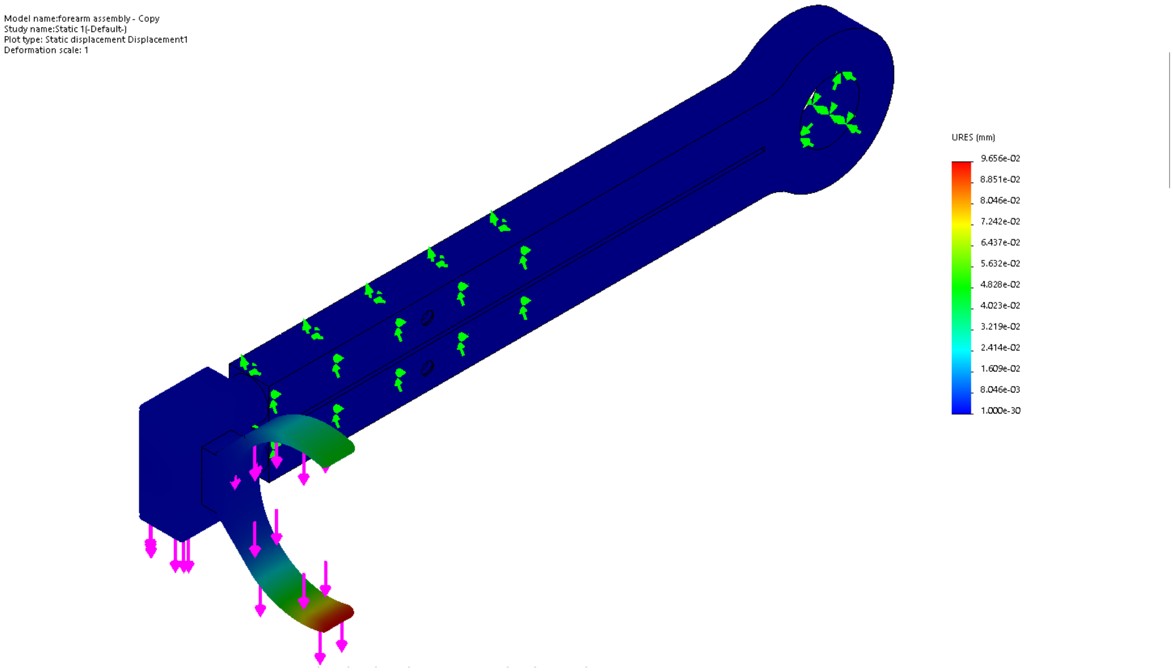


Figure 6.15 deformation results on forearm link

The arm link contains a more complex elbow joint, as it contains the motor housing unit, with more round edges, which required smaller meshing. On the joint connection point at the elbow; a force of 127 N was added acting downwards, as a direct reaction to the attached load. The highest von Mises stress value obtained was 7.6×10^6 N/m^2, which lies below the material's yield strength of 2.57×10^7 N/m^2.

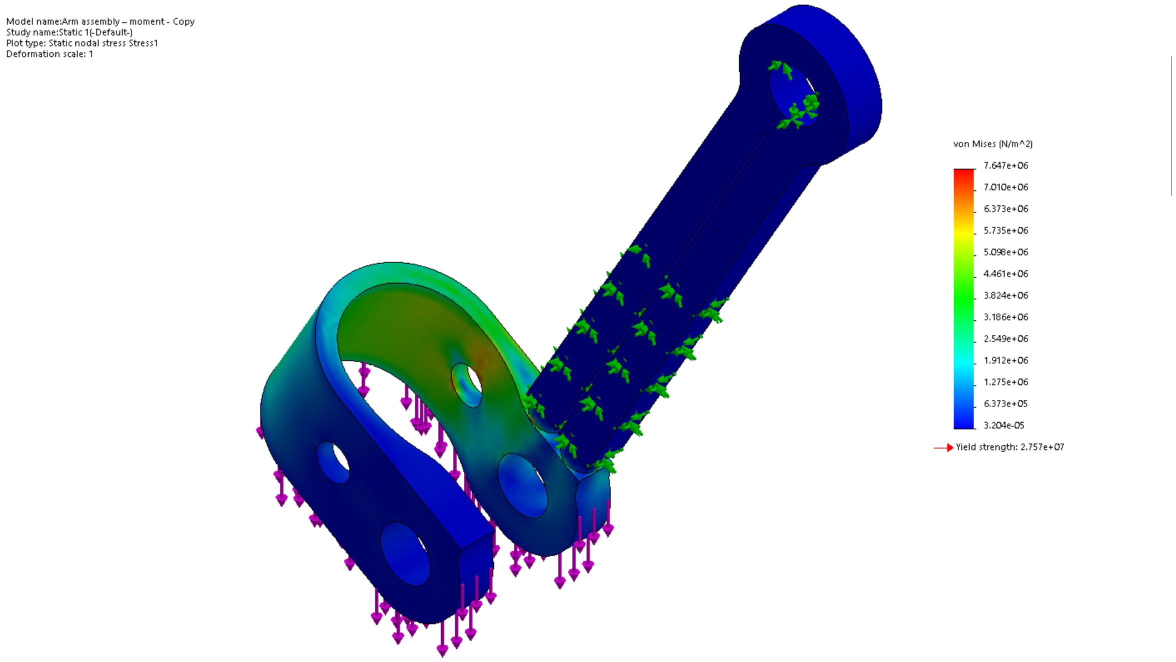


Figure 6.16 von Mises stress results on arm link

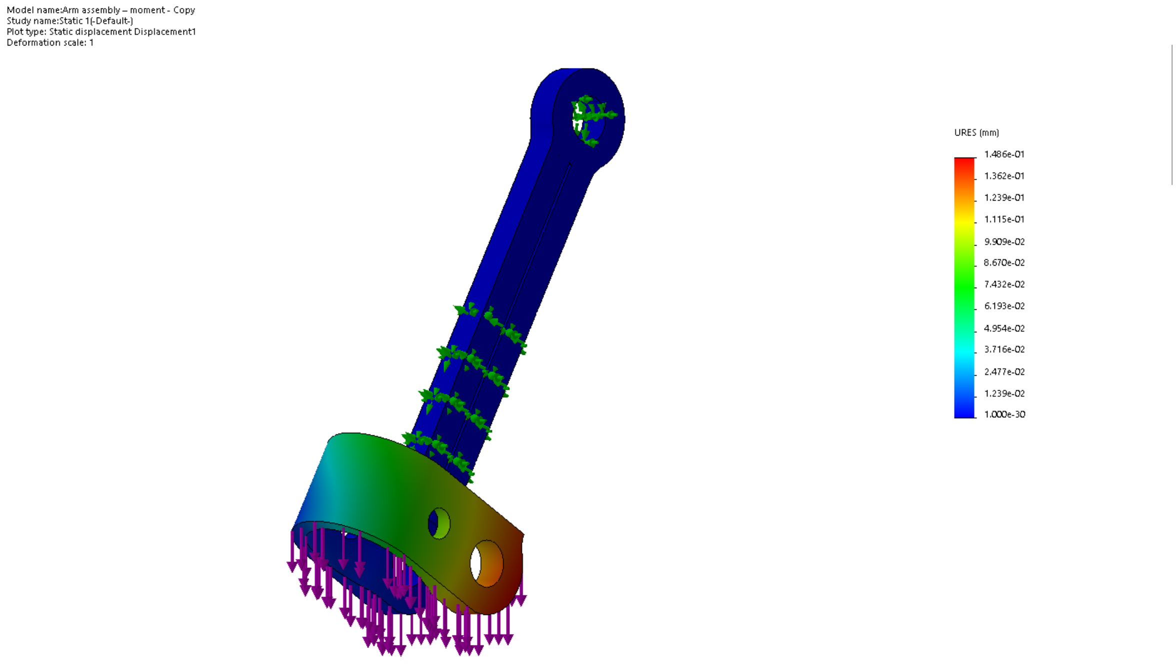


Figure 6.17 Deformation results on arm link

The high values were expected to be found around circular edges and connection points between two different parts, which was clearly shown in the elbow motor housing at the right-side circular outlets, which can be attributed to the pipe attached to this side, providing less stability compared to the left-hand side. As for deformation, the highest value recorded amounted for 0.14 mm and was mainly concentrated at the left-hand side of the motor housing unit at the elbow, prominent at the arched lower area where the load is added and where are no other parts (pipes, etc.) are supporting the structure.

The obtained results conform to load, weight, reaction forces and most importantly geometry expectations. It offers insights to further design modifications, however, given the problems that these "hot" areas encountered during meshing and having to apply mesh controls on them, it is most likely an exaggerated result that can be studied and eliminated with applying further mesh controls and having smaller mesh dimensions. Moreover, this can be further enhanced by applying fillets, in case of sharp edges, that can increase the area over which the stress is distributed; reducing its effect.

6.4.3 Static loading to determine fixture points in forearm

Given the adjustable structure of the forearm and arm links, the small thickness and the unique cross-section; their fixture mechanism should be taken into consideration for further analysis. Given the small thickness of the links, it is critical that they act stable under loading. This is essential as any type of fixture would require creating holes in the pipes, which makes them less rigid and subsequently less stable under loading. Proposing bolting as fixture method, different locations were considered for the forearm piece; 15 mm, 30 mm, 45 mm and 55 mm away from the joint's edge, and the link was loaded in the same methods and locations implemented in the aforementioned sections. The results were significantly different for each condition. The fixed geometry on the inner parts of the tube were replaced by Pin-connector fixtures in Solidworks, which gave out completely different results.

Stresses are expected to be higher around the bolting location due to its circular shape, however, for different locations, overall stress values in the link have changed. It is worth noting that the relatively high results for maximum stress values are concentrated around the pin connections, attributing to their failure, however, the stress variation across the entire link has very similar values.

For the first condition; 15 mm from the edge, shown in figure 6.18, the highest von Mises stress values existed around the bolt cavities, and amounted to 5.08×10^{8} N/m^{2}, shown in figure 6.18, compared to material's yield strength at 2.57×10^{7} N/m^{2}. The highest deformation existed at the load attachment ring with value of 2.8 mm, shown in figure 6.19.

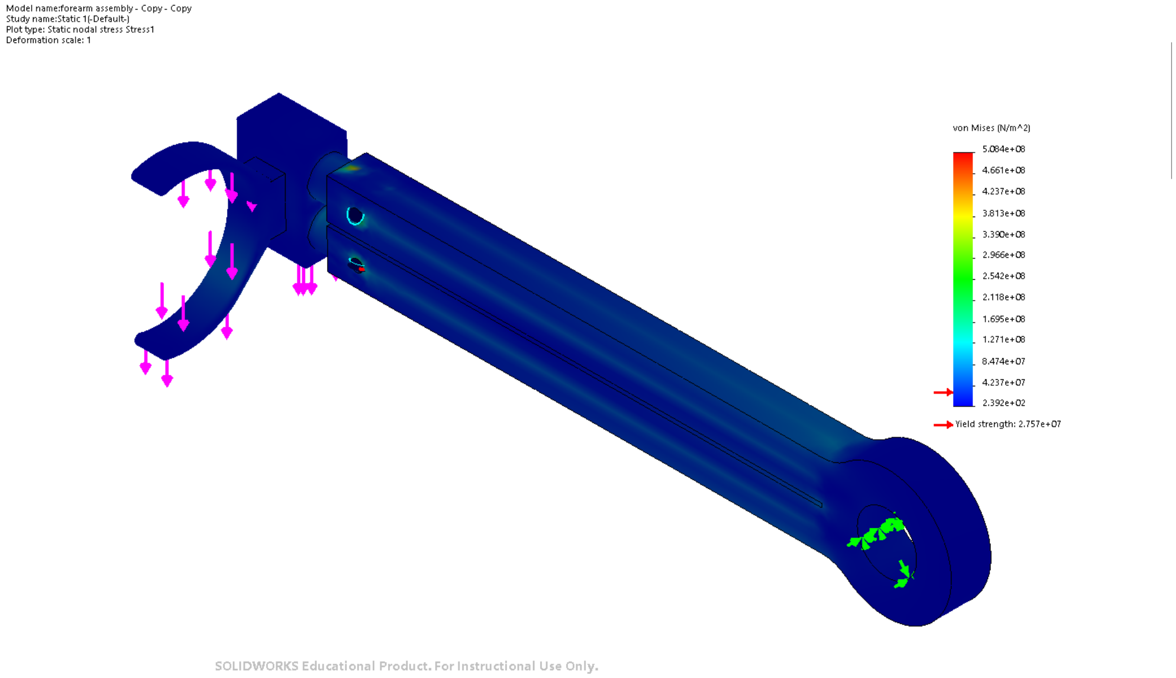


Figure 6.18 von Mises stress results on arm link for first location (15 mm)

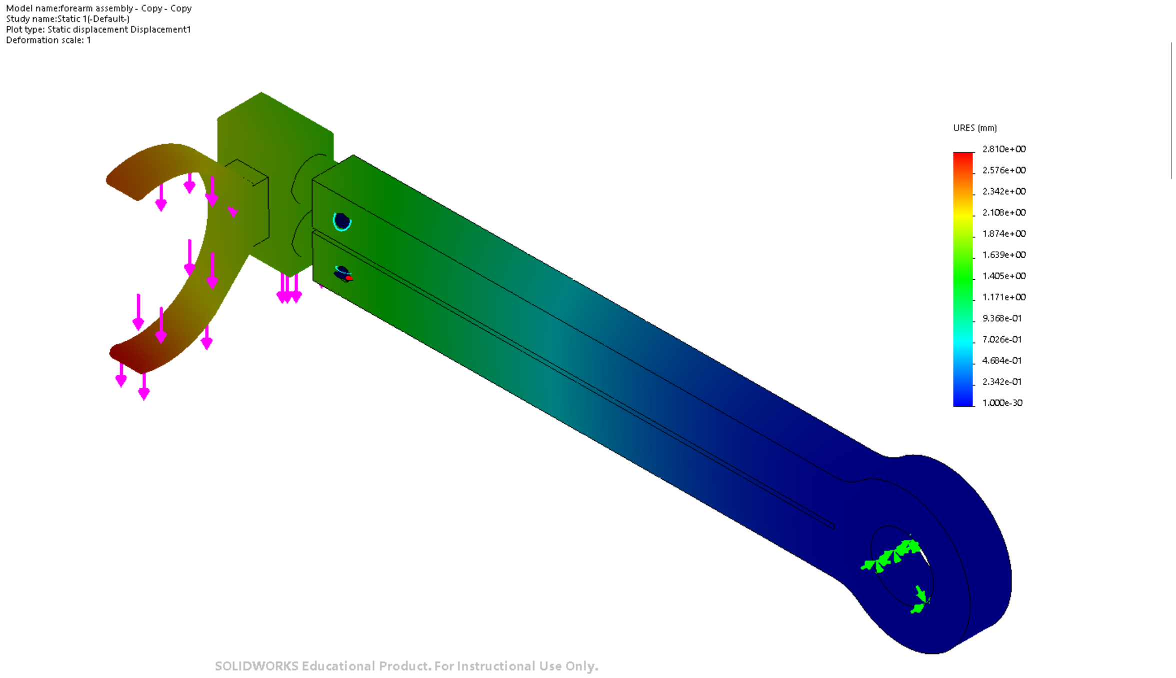


Figure 6.19 Deformation results on arm link for first location (15 mm)

The second location, 30 mm from the edge, had relatively lower von Mises stress values at to 1.53×10^8 N/m^2, Shown in figure 6.20. The high values are around the same aforementioned bolting locations. Deformation values were equal to the first case, shown in figure 6.21.

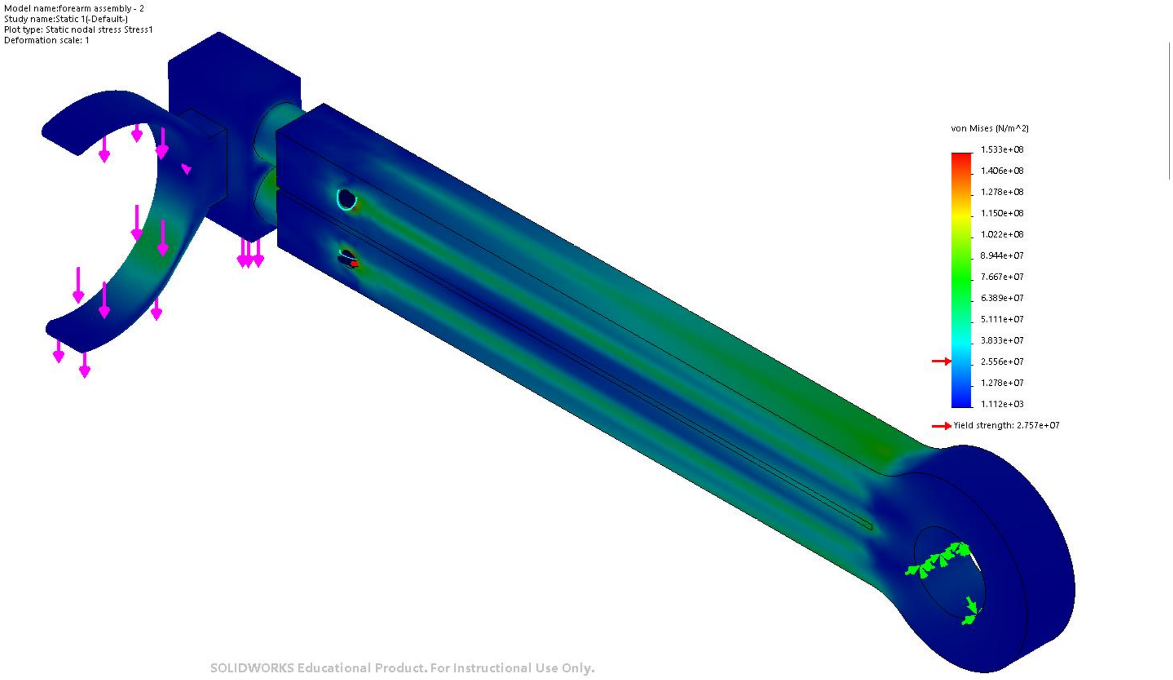


Figure 6.20 von Mises stress results on arm link for second location (30 mm)

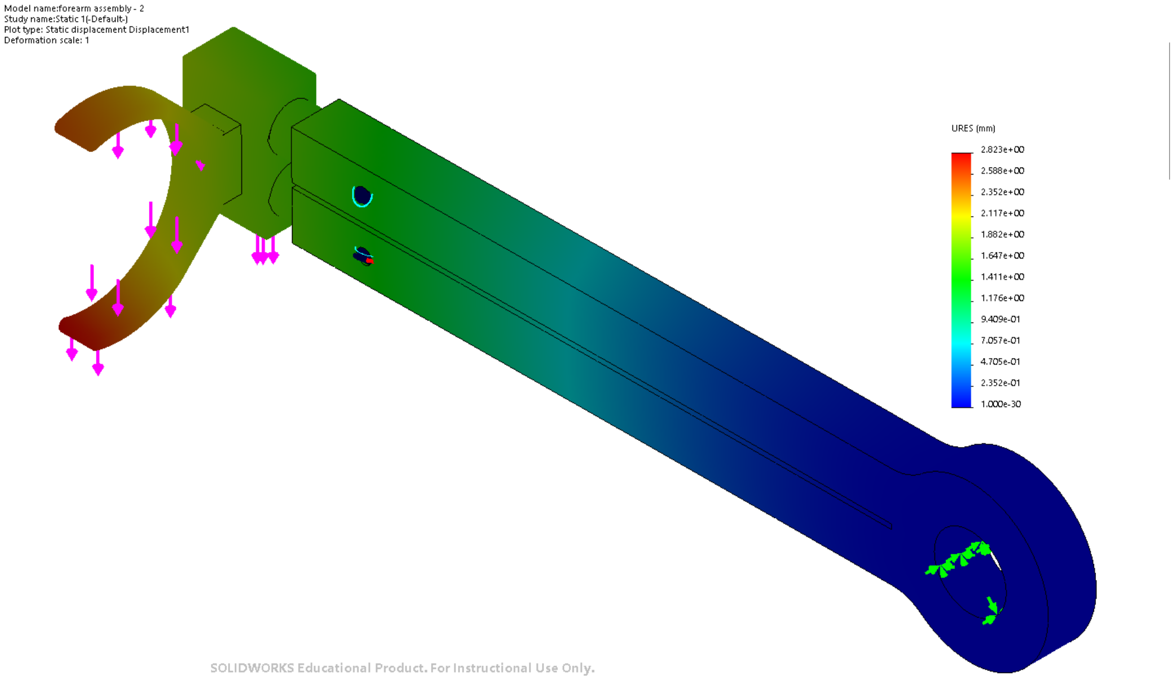


Figure 6.21 Deformation results on arm link for second location (30 mm)

The third location, at 45 mm from the edge, had maximum stress value of to 2.3×10^9 N/m^2. Same deformation values were recorded as the two aforementioned cases, with the highest values for stress being recorded at the same locations.

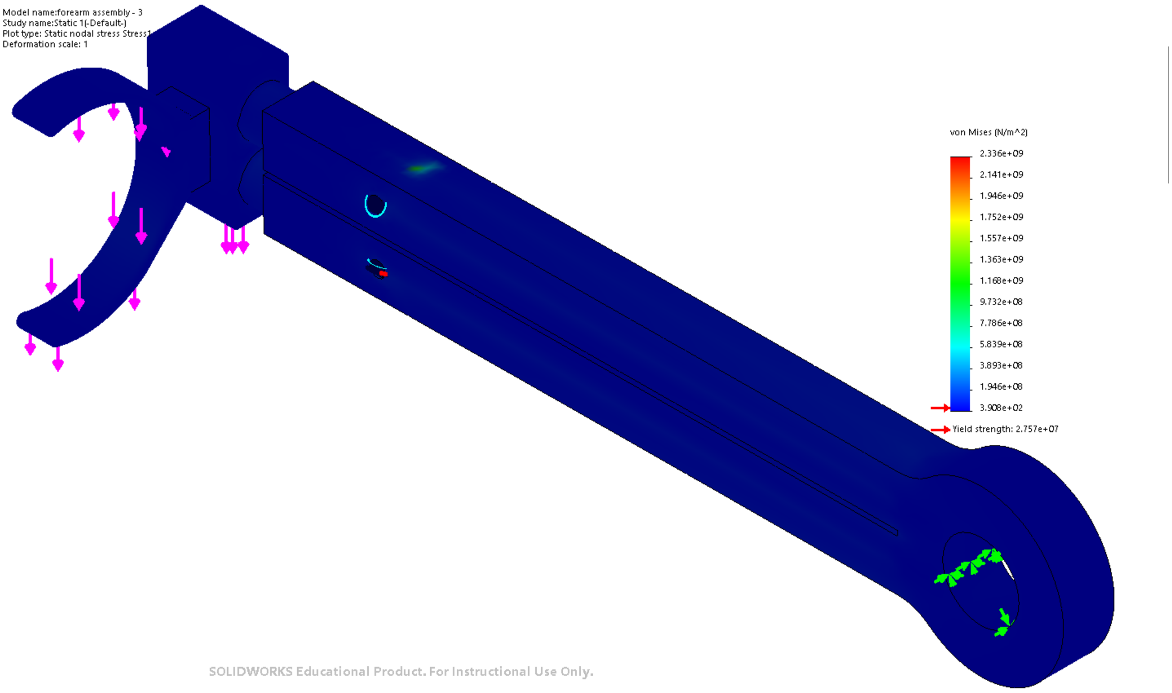


Figure 6.22 von Mises stress results on arm link for third location (45 mm)

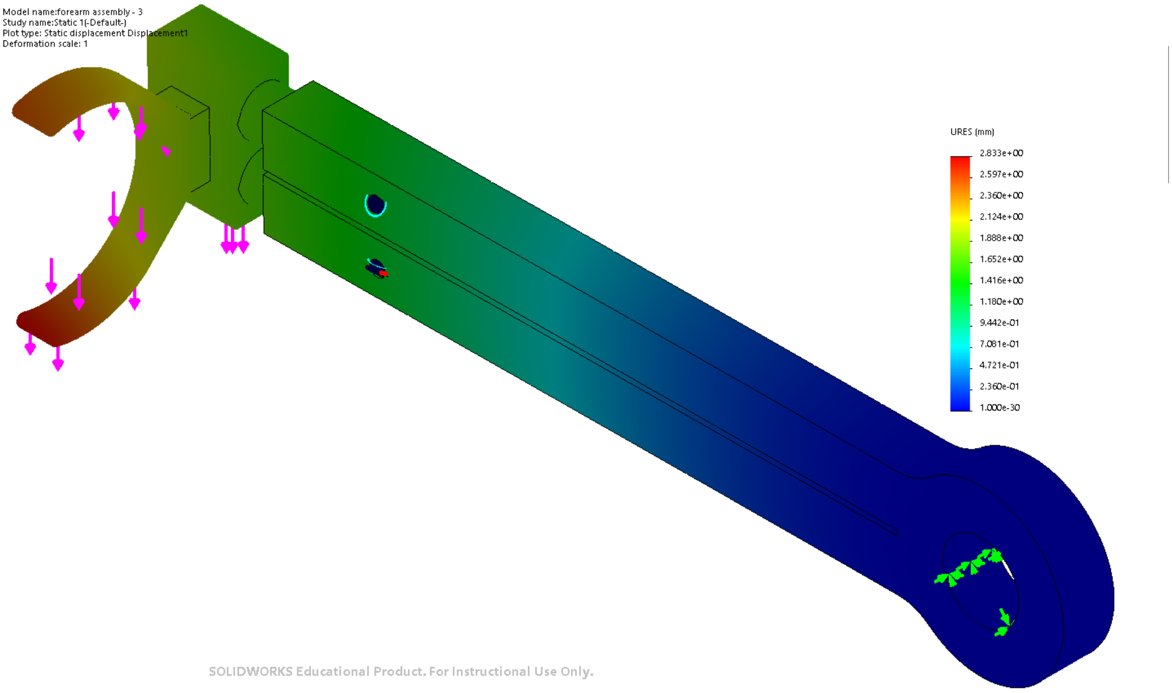


Figure 6.23 Deformation results on arm link for third location (45 mm)

The fifth location, at 55 mm away from the edge, shown in figure 6.24, the highest recorded von Mises stress value was 5.97x10^8 N/m^2, the highest recorded value yet, with deformation at 2.8 mm, shown in figure 6.25.

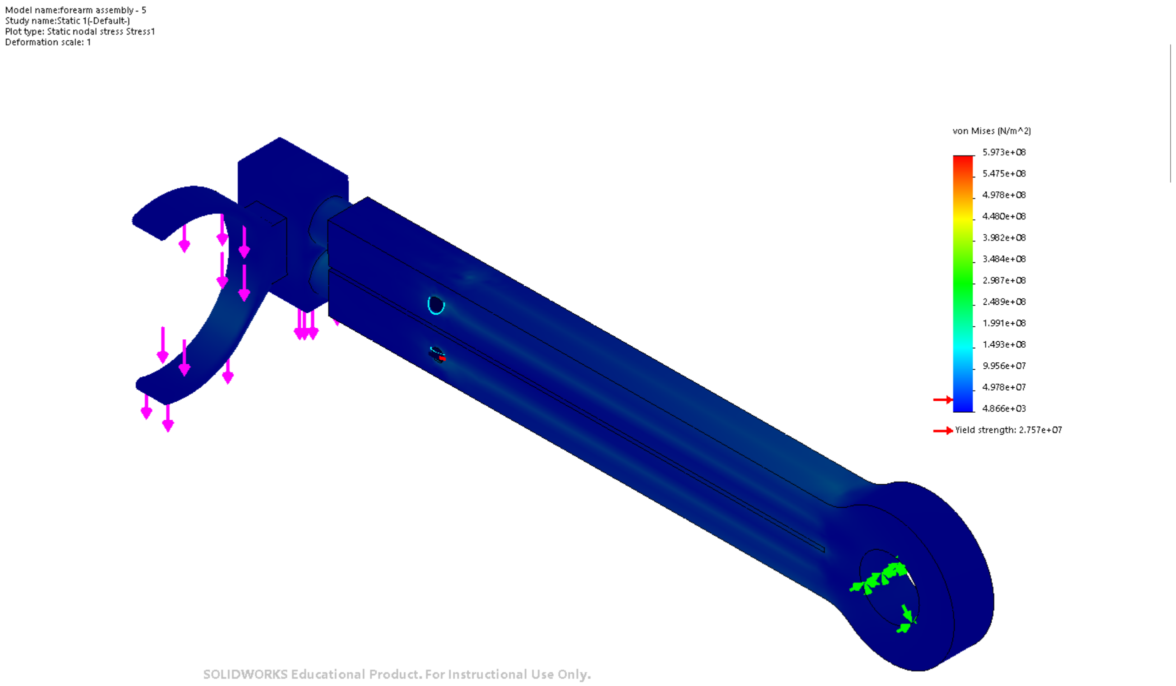


Figure 6.24 von Mises stress results on arm link for fifth location (55 mm)

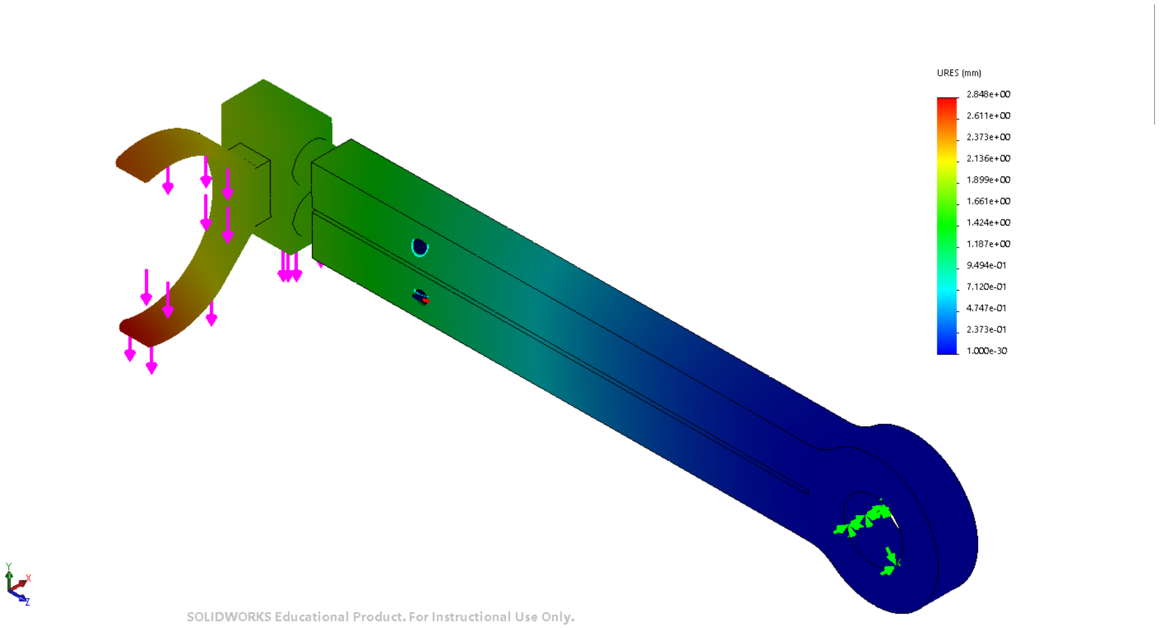


Figure 6.25 Deformation results on arm link for fifth location (55 mm)

6.4.4 Discussion of the results

The design exhibits relatively stable performance under static loading conditions. High stress values exist around curved and sharp edges, which is expected and can be tested under different meshing conditions that usually distribute these stress locations. The structure is relatively thin, therefore the enforced nature of two interconnected tubes provides promising results as the significantly reduce the overall weight, while exhibiting stable loading performance. The complete design parameters can be found in table 6.4.

The analysis provided unstable results for the load attachment ring at the wrist, with the highest stress and deformation values ($1.6\text{x}10^7$ N/m^2 and 0.09 mm respectively). This is expected due to the small thickness of the ring and the direct attachment of load at it. This jeopardizes the user's hand, since the ring is mounted on it, and the relatively high deformation values are dangerous as well. This can be eliminated first hand by increasing the thickness of the ring to sustain the load. However, it is better to design an alternative load attachment mechanism that does not exert direct stress on the user's hand. This required direct knowledge of the shapes of loads to be handled, creating a classification of different grips for the loads and designing a universal hooking mechanism that the user can attach the load to and move side to side. This will eliminate the direct danger to the user's wrist and provide more versatility for different load shapes.

The analysis for fixture locations provided different and unstable results, which can be mainly attributed to switching from setting the pipe as fixed geometry to having the pin connectors instead, hence the maximum stress values recorded exclusively at these points. The results show failure at the pin connectors at different locations, with different maximum stress values at each distance from the load, however, values for deformation remain constant, and the stress distribution across the links lies within similar values. This provides insight on one essential design aspect; fixtures and how early they should be considered in the design process.

The results can be interpreted given the distance between the bolting location and the attached load. However, an additional aspect that this analysis sheds the light on is the inner tube. One solution that can improve these results is increasing the number of bolts used in each analysis to three, and studying how the link interact with the load. Another solution is increasing the length of the inner tube to match that of the outer tube, which will provide more stability for this bolting condition. Moreover, it is essential to increase the aforementioned length given the fact that fixture for adjustable length conditions will require having additional holes in the tube itself for fixture, which will increase its vulnerability to stresses.

Table 6.4 Final design Specifications

Link	**Length**	**Mass**
Forearm assembly	280:330 mm	0.5 kg
Arm assembly	315:406 mm	0.55 kg
Back support	370 mm x 300 mm	1.3 kg
Shoulder to back mechanism (fully extended)	150 mm per side	0.2 kg
Complete design		4.3 kg

6.5 Kinematic conformity

As a subsequent part to the biomechanical analysis of the human body, and given the results obtained from the proposed design's range of motion, this section discusses and combines the results of both fields to provide a theoretical result, based on the final results from the aforementioned analyses.

The nature of the human musculoskeletal system is redundant (in terms of actuation), meaning there exists multiple was to perform one motion, which poses an issue of added complexity for the exoskeleton designer, to have a versatile design that can cope but not fully offer this extended ROM. The developed design has five DOF per arm, explained in figure 6.26; however, it can be represented using four joints given the ball-and-socket joint that performs shoulder extension flexion as the dedicated joint itself. One of the degrees of freedom; horizontal flexion, has a restricted range, compared to four DOF for the upper arm for shoulder and elbow actuation only shown in figure 6.27.

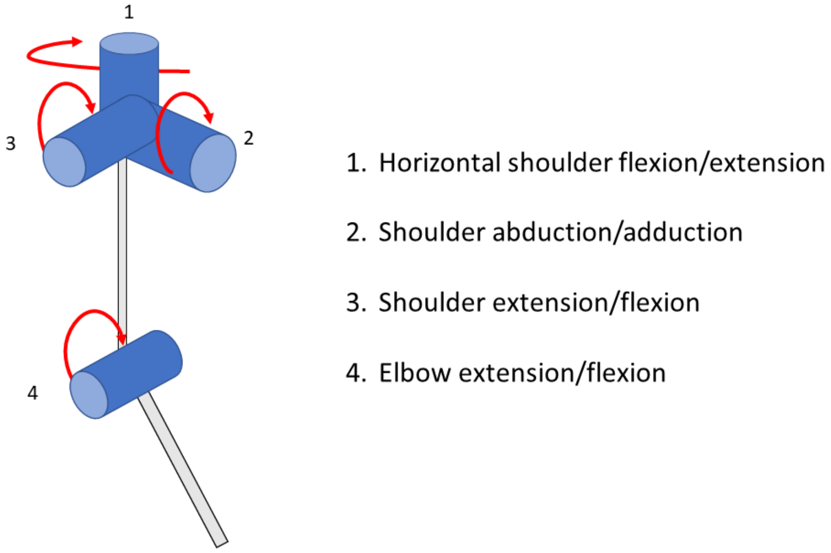


Figure 6.26 Joint representation of the developed design

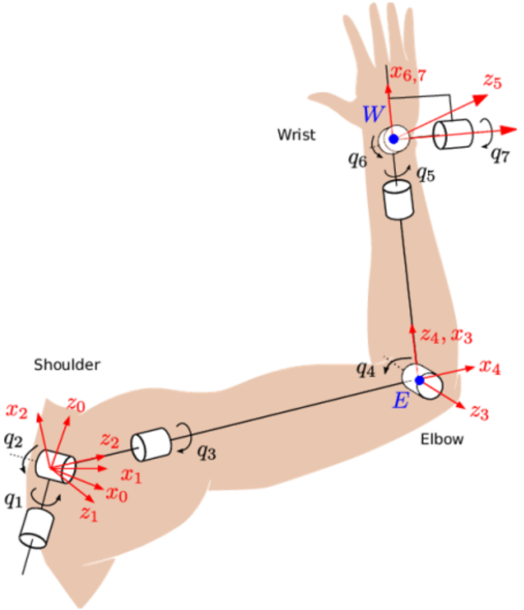


Figure 6.27 Joint representation of the human arm [83]

Given that exoskeleton is attached to human upper body, the first method to validate the design is to have matching kinematics for both exoskeleton and human body. Kinematics are described by the standard Denavit–Hartenberg parameters, which allows for links' motion description about a common joint axis. The DH parameters for the developed design are shown in table 6.5, while DH parameters for the human shoulder and elbow actuation are shown in table 6.6. Both parameter combinations are derived from the same figure 6.22, except for one difference in the human arm model. The parameters are matching for all values except the existing displacement in the developed design between the shoulder extension/flexion joint and abduction adduction joint. In the design, these are separated by the shoulder-to-back joint, while in human anatomy, both motions are performed by simply one joint (glenohumeral joint). Moreover, the design also supports circumduction motion, which is conical rotation of the glenohumeral joint.

Table 6.5 DH parameters obtained for the developed exoskeleton design, derived from joint representation in figure 6.28.

Joint	**θ**	**α**	**r**	**d**
1	θ_0	$-\pi/2$	0	0
2	$\pi/2$	$\pi/2$	0	0
3	θ_2	0	L2	0
4	θ_3	0	L3	0

Table 6.6 DH parameters obtained for the human arm

Motion	**θ**	**α**	**r**	**d**
Horizontal flexion/extension	θ_0	$-\pi/2$	0	0
Abduction/adduction	$\pi/2$	$\pi/2$	0	0
Shoulder flexion/extension	θ_2	0	L2	0
Elbow extension/flexion	θ_3	0	L3	0

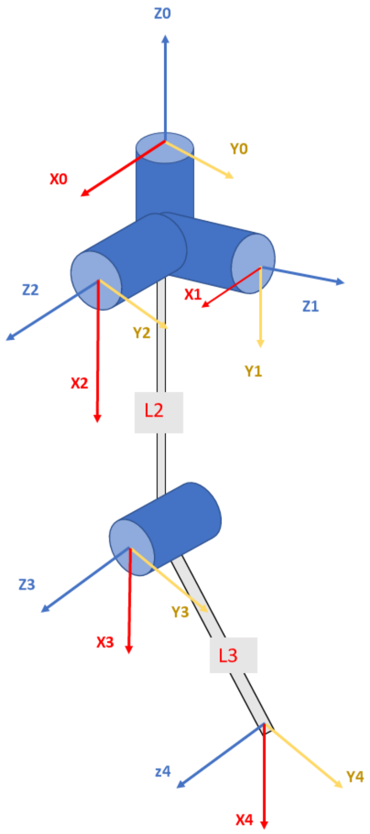


Figure 6.28 Joints' axes of motion for DH parameters

The DH parameters of the human arm can be used to create the complete workspace of the arm motion, which can be used to validate the design. This is done by creating a workspace from the exoskeleton's DH parameters [84], and comparing both workspaces together to validate the range of motion that the exoskeleton can cover, and eliminate singularities. Moreover, it can be used to obtain moments/forces for the exoskeleton design, to help choose motors for the structure in the future.

According to [85] misalignment between exoskeleton and user is a combination of four separate effects; kinematic mismatch, migration of the instantaneous COR, initial offset or movement mismatch. Kinematic mismatch is related to the exoskeleton not having all DOF of the respective human motion, which is achieved in this design, albeit for the displaced extension/flexion, whose effect is yet to be studied. Movement mismatch results from migration of exoskeleton parts from their initial location, due to problems with fixtures that attaches them to the human body.

As for Kinematics of the lifting motion, it include a combination of motions at different body parts, and based on the recommendation from chapter four, it was decided that semi-squat technique would be used preliminarily for loads at heights bigger than 300 mm. The required ROM for this technique, is spine flexion (45°:70°), knee flexion (30°:50°), for shoulder flexion (10°:30°) and for elbow flexion (10°:80°). For squat lifting technique, the spine flexion decreases to (15°:40°), knee flexion increases (45°:80°), shoulder flexion is at (10°:45°) and elbow flexion is roughly equal (10°:60°). These values are summarized in table 6.7.

The current design can perform these motions seamlessly, although it must be taken into consideration to avoid extending the elbow joint, or what is known as "locking", to avoid reducing muscular effort to zero and increasing it again, as it will require more effort afterwards. This case will affect the exoskeleton by creating a "motion singularity". Moreover, based on biomechanical considerations for load handling that requires carrying the load as close to the body as possible, the ROM for the elbow flexion is restricted to 50 degrees, however, this can be modified if needed. This is done to create the shortest distance between the CG of both the load and the user's body to ensure better stability during load handling

Table 6.7 ROM for different body joints for squat and semi-squat techniques

Joint motion	**Semi-squat**	**Squat**
Spine flexion	45°:70°	15°:40°
knee flexion	30°:50°	45°:80°
shoulder flexion	10°:30°	10°:45°
elbow flexion	10°:80°	10°:60°

6.6 Limitations

Even though the current design is confirming with the task it was designed for; load handling, it has limitations as far as generic motion conformity. The first limitation is that the shoulder joint for extension/flexion is shifted compared to the actual human anatomy, to the side of the shoulder. However, this was compensated by the ball-and-socket joint used, which enabled motion more similar to human shoulder, however, having the movable/adjustable shoulder-to-back link poses limitations to the stability of the motions performed by the ball-and-socket joint.

The feature for horizontal shoulder extension/flexion is limited to 30°, from an estimated range of 80°. This is a passive link added to increase ROM and enable users to extend their movement for comfort.

Singularities are points at which a mechanism loses one degree of freedom. The current design has a singularity related to the elbow joint, where the forearm link cannot be flexed for an angle smaller than 125° towards the arm joint. This is a result of having a fixed motor housing unit linked to the arm joint at a 90° angle. This is a simple design error that can be easily overcome by enabling the rotation of the housing itself, and fixture using bolts, without compromising its attachment to the arm joint.

Additional design limitations in the forearm, with respect to future development, include vulnerability to stress loads, after identifying different bolting locations. The load analysis for bolting exposed one main problem with the inner tube of the forearm; its length is not sufficient for load tolerance. This is given the "promise" of versatility that requires having different bolting holes in the structure, which will decrease the link's tolerance. Moreover, the ring where the exoskeleton attaches to the user's wrist have exhibited unstable loading performance and deformation that need to be addressed by changing its dimensions or changing the load attachment mechanism altogether.

The current representation of the ball-and-socket joint is demonstrative and will be unlikely to act in a harmonious motion with the movement due to its disproportionate size to the attached parts and the overall design. Future plans include modifying the entire joint to be bigger and flatter, with more resemblance to the human shoulder joint, and tested to observe how it reacts within the intended range of motion.

7 CONCLUSION

This Thesis intended to take a human-centred approach in the process of developing an upper-body exoskeleton for industrial applications, and based on the obtained results, this goal was achieved. The topics of the thesis complement this goal, and add on different design parameters that were taken into consideration during the design process. The engineering standards research introduced different design considerations, general requirements for the work environment, requirements for the developers of exoskeleton of the information to be provided to users to help ensure optimal device usage. Moreover, it helped list all potential dangers arising from exoskeleton usage from posture problems to insufficient durability.

One main concern of exoskeletons is work-related MSDs, which was defined, discussed and put into design context in this thesis. The causes of MSDs are known and based on the defined motion and purpose of this exoskeleton; load handling, they were discussed and recommendations were made to avoid them. This acts as user information, required by the aforementioned ASTM standards, to be presented in context of device usage by the designer. The research was followed by an analysis of three lifting techniques for load handling, with their adverse musculoskeletal advantages, disadvantages and variations for different load weights. Two types of techniques were selected for different load lifting heights, based on joints' flexion/extension angles for the actuated body parts.

A design was created to address the guidelines set forth by the engineering standards, MSDs and biomechanical analyses. The design contains a novelty shoulder-to-back connection that enables horizontal shoulder flexion/extension, with a ball-and-socket link to the back support that enable shoulder flexion/extension and abduction/adduction. This, in addition to enabling elbow extension/flexion, totals the exoskeleton's DOF at five DOF; two of which are active and the remaining two are passive. The design underwent a load analysis with the intended load to be handled (25 kg total, 12.5 kg per arm). The loading was carried out under the highest loaded orientation of the arm and forearm (30° from vertical axis for arm link, and horizontal forearm link). The exoskeleton exhibited stable performance under static loading conditions, taking into consideration the attached load and joint reaction forces. The exoskeleton kinematics were validated against the human shoulder and elbow kinematics and were matching, even with the displaced joint, the user is able to perform shoulder circumduction, given the ball-and-socket shoulder mechanism.

The results of this thesis are considered within the scope of a bigger approach that lacked the sufficient time, expertise and resources to be complete. Therefore, as future work the main goal would be to carry out a thorough biomechanical analysis using Opensim software. The software requires experimental motion capture data to enable a model human skeleton to perform the motion generated from motion capture data, and study the effects of motion on muscles and bone structure. This can be used to validate the usage of exoskeleton by detecting any negative effects arising from its attachment to the user. Moreover, it can provide design insights by highlighting where in the body it is more essential to have load assistance, to help derive design decisions.

As for the design, it included some versatility points that surpassed the task boundaries, however, it is still limited to tasks similar to lifting, where no extended ROM for the arms is required, especially in the frontal body plane. Moreover, design singularities have to be further inspected and either highlighted to users or eliminated in further design steps. Problems with the load attachment ring at the user’s wrist and the disproportionate ball-and-socket joint are of higher priority before proceeding with further steps towards biomechanical analysis.

8 SUMMARY

Exoskeletons have made a shift from medical rehabilitation applications to industrial performance augmentation, with one major difference. This difference is that for medical rehabilitation the exoskeleton structure is fixed to the ground, therefore, its weight does not act directly on the user; however, it is the opposite for industrial performance augmentation applications. The focus of this thesis was to develop a novel exoskeleton design for industrial load handling (25 kg) purposes, in a human-centred approach. This was achieved through evaluating the relevant engineering standards to be followed during the design process and assessing the dangers and costs of work-related musculoskeletal disorders that result from repetitive motions and constant load handling. This is followed by a biomechanical analysis of the human lifting motion, an analysis of the required ROM for load handling, and using all these results to develop a CAD design that takes all these human-centred factors into consideration.

The design was validated by matching the obtained ROM with the human's ROM required to perform the lifting task, followed by mechanical load analysis to study how the designed parts act with the studied load attached. The parts were studied in the most loaded orientations for the lifting motion (horizontal forearm, inclined arm) and were found to behave in a stable manner. Additional load analysis considered different locations for bolting the adjustable slots in the forearm, which found significantly different results with changing the locations within 10 mm from each other.

The current design contains some limitations to its range of motion; however, they do not obstruct its main task; lifting motion. These limitations can be addressed in the future to expand the range of tasks the exoskeleton can perform, towards the final goal of versatile and simple exoskeleton mechanisms.

Biomechanical analysis is proven to be an essential tool in the design process, however, due to specific limitations, it was not ideally implemented in this thesis. Future plans will include motion analysis of the lifting mechanism, using motion capture software, to be used in different simulations to focus on the internal effects of motion and load handling on various body parts. This is considered as a comparative study between lifting with and without exoskeleton assistance, to validate or disprove its merits.

9 KOKKUVÕTE

Eksoskelettide kasutamise rakendus on liikunud taastusravist meditsiinis tööstuslikku valdkonda. Seda ühe suure erinevusega, milleks on eksoskeleti struktuuri mõju kasutajale. Meditsiinilise taastusravi protsessis on eskoskelett maapinna külge kinnitatud ja struktuuri kaal ei avalda kasutajale otsest mõju, kuid tööstuslikult kasutades tuleb kasutajal taluda struktuuri raskust. Magistritöö eesmärk oli välja töötada uuenduslik eksoskeleti disain tööstuslikuks kasutamiseks koormuse (25 kg) liigutamisel, mille keskmes on inimene. Disainimisel kasutati tehnilisi standardeid, mis on seotud luu-lihaskonna probleemidega, ülekoormusega ja kaasnevate ohtudega, mis tulenevad korduvatest liigutustest ning pidevast koormuse käsitlemisest. CAD-disaini väljatöötamisel võeti arvesse nii tehnilisi standardeid kui ka korduvatest liigutustest ja pidevast koormusest tingitud inimkeskseid tegureid, nagu luu-lihaskonna probleemid. Lisaks analüüsiti inimese tõstmisliigutuse biomehaanikat ja koormuse käsitlemiseks vajalike liigeste liikuvusulatust (ROM).

Disaini valideerimiseks sobitati algselt tõstmiseks vajaliku inimese liigesliikuvusulatus eksoskeleti liikuvusulatusega. Seejärel teostati mehaanilise koormuse analüüs uurimaks, mis muutused toimuvad kavandatud detailides liikumisel koos koormusega. Antud detaile uuriti enim tõstmisel koormust taluvatel suundadel (käsivars horisontaalselt, käsi kallutatud asendis), mis leiti olevat liigutustel stabiilsed . Täiendavas koormusanalüüsis võrreldi erinevaid reguleeritavaid poltide kinnituste asukohti käsivarrel, ning leiti märkimisväärselt erinevad tulemused, kui poldi asukohta 30 mm raadiuses liigutada.

Praegune kujundus sisaldab mõningaid liikumisulatuse piiranguid, kuid need ei takista täitmast põhiülesannet, milleks on tõstmisliigutus. Sellistele piirangutele saab tulevikus tähelepanu pöörata, et suurendada eksoskeleti poolt tehtavaid ülesandeid ning liikuda lõppeesmärgi poole, milleks on mitmekülgse ja lihtsa eksosleketi mehhanismi arendamine.

Antud protsessis on biomehaaniline analüüs väga oluline, kuid ei olnud käesolevas magistritöös spetsiifiliste piirangute tõttu ideaalselt rakendatud. Edasised plaanid hõlmavad liikumist salvestava tarkvara kasutamist tõstemehhanismide liikumisanalüüsil. Selleks kasutatakse erinevaid liikumise ja koormuse käsitluse simulatsioone erinevatel kehaosadel, keskendudes sisemistele mõjudele. Antud uuring on võrdlev uuring, mille eesmärgiks on kinnitada või ümber lükata eksoskeleti abil raskuste tõstmise eelised võrreldes abita tõstmisega.

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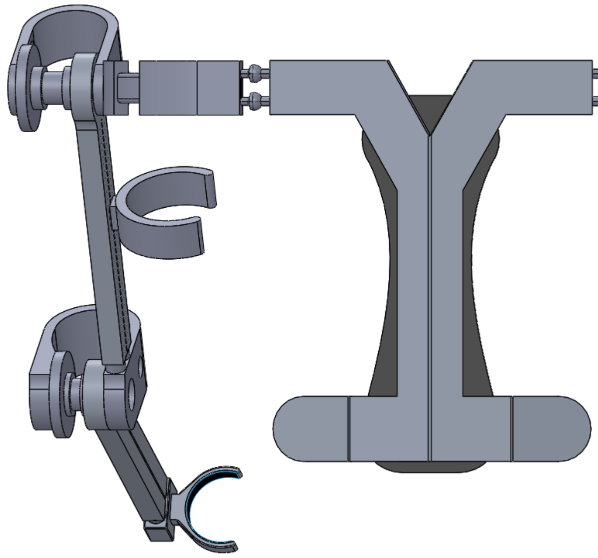
APPENDIX A

Complete design



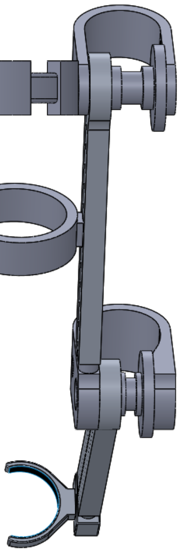


Figure A.13 Back projection of the design

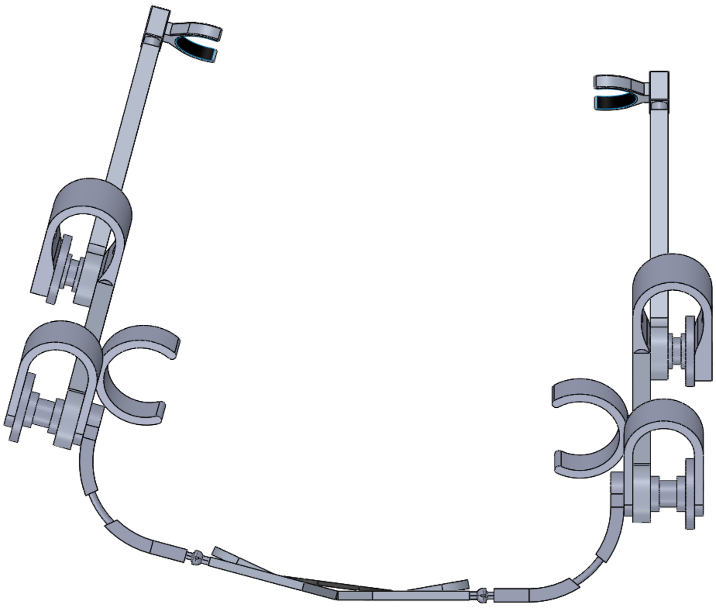


Figure A.14 Top projection of the design

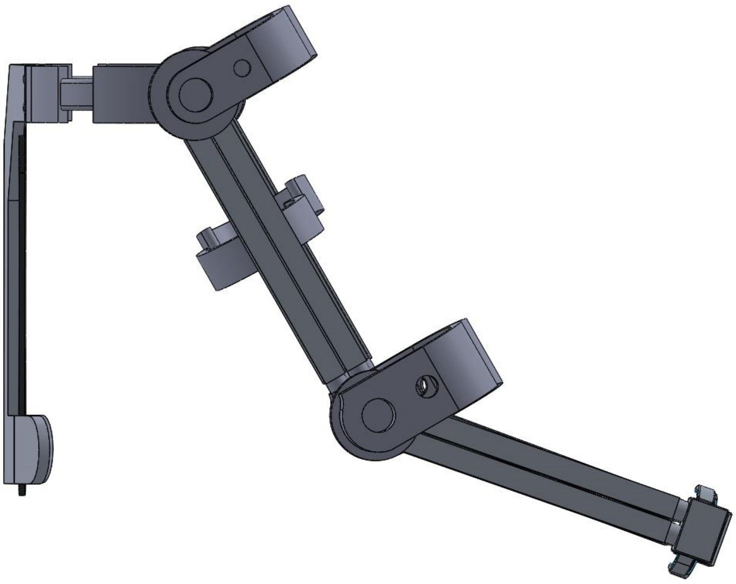


Figure A.15 Side projection of the design

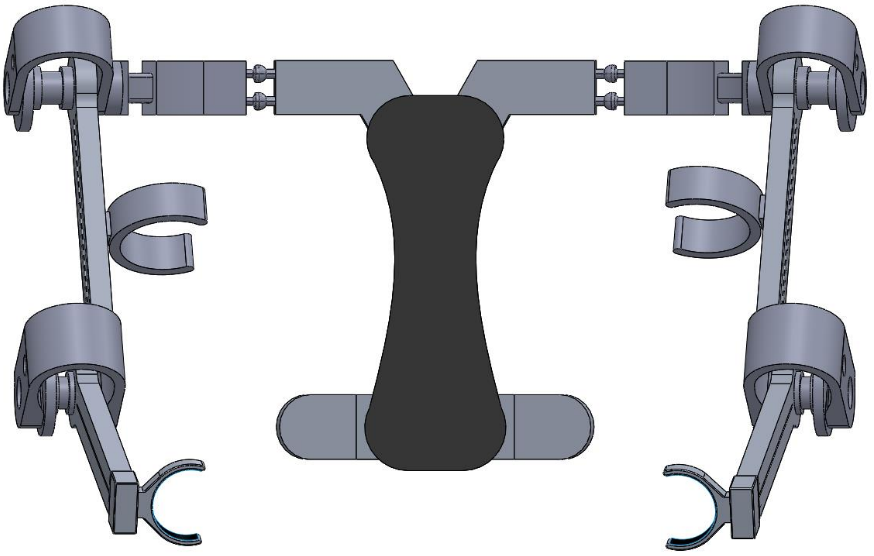


Figure A.16 Front projection of the design

APPENDIX B

ASME Standards

i. Temperature

Temperature values and variations can affect the exoskeleton parts (retract, melt) and electronic components, causing serious damages that may affect the user. For proper documentation, the following temperature levels should be followed:

- Level 1—Below 0°C;
- Level 2—0°C to 15°C;
- Level 3—16°C to 26°C;
- Level 4—27°C to 49°C;
- Level 5—Above 49°C.

ii. Humidity

Variations in humidity levels, both high and low, can affect exoskeleton parts in various ways. High humidity levels (above 60%) can cause an increase in erosion of metal parts, while low humidity levels can cause a rise in static electricity that needs to be discharged. Humidity levels are defined in this standard as relative humidity level and dew point temperature. Relative humidity is further classified into low (less than 30%), moderately low (31%:55%) and moderately high (higher than 75%). Dew point temperature is the highest temperature at which airborne water vapor condenses to liquid dew.

iii. Lighting

Depending on exoskeleton’s material, lighting conditions can affect its operation in terms of material absorption/reflection of light. Light sources are classified into Ambient lighting (exposed bulb, spotlight, sunlight, reflected or filtered) and Directed lighting (exposed bulb with no cover, spotlight, sunlight, reflected, filtered, laser or light from another vehicle. Location of the light source needs to be specified with respect to exoskeleton. Moreover, light levels are set based on light intensity that cover levels from dark to full sunlight.

iv. External Sensor Emission

External emitters can interfere with exoskeleton's sensors or control system. These must be described in documentation based on their configuration (type and quantity), location (elevation and location, relative to exoskeleton and its path) and spectrum (primary color and wavelength).

v. Electrical Interference

Proper grounding of exoskeleton is not guaranteed based on its material. There exists a risk of static build-up that might negatively affect electronics components. In this regard, with respect to electro-magnetic compatibility issues, the following standards apply and can be referred to: BS EN 12895, Mil-Stnd-462, IEC 61000-4-1, and IEC 61000-6.

vi. Environment Consistency

Another important standard concerns Documenting Environmental Conditions for Utilization with Exoskeleton Test methods. It starts by classifying environments into static, dynamic or translational.

Static describes similar conditions throughout the test setup, where the latter is demonstrating a transition between two static environments, which is different from a translational environment.

Dynamic describes an environment with significant temperature changes throughout the test setup, for example, temperature change within repetitions.

Translational describe a significant change in environment in different areas of test setup, regardless of repetitions, whether it's changes from warm to cold, cold to colder.

vii. Ground Surface

Different ground surfaces affect exoskeletons' mobility. This standard aims to defining different types and conditions of surfaces and different classifications. It starts by defining types (concrete, linoleum tile, carpet, dirt, grass, etc.). A description of surface inconsistencies must be provided (manhole covers, transparent floor, etc.).

Other factors include the surface's coefficient of friction, gaps or steps that might affect smooth movement, surface's deformability (rigid, semi-rigid, soft-malleable) and surface ramp with classification for different angles ranges.

ISO Standards

i. Terminology

In order to better define the scope of any set of standards, terminology is initially defined in order to fully describe the devices and specify the ones covered by the standard. ISO 13482 has three main categories, under which further specification is defined. It defines Personal care robot as a service robot that carries out actions contributing directly towards improvement in the quality of life of humans, excluding medical applications. This definition is classified into two sub-definitions; mobile servant robot, Physical assistant robot or Person carrier robot.

Physical assistant robots are personal care robots that physically assist a user to perform required tasks, by providing supplementation or augmentation of personal capabilities. They are classified into restraint type and restraint-free type physical assistant robots. Exoskeletons lie in the first category, defined as physical assistant robot that is fastened to a human during usage.

ii. Important definitions:

A weight is considered "lightweight" if it is sufficiently low so that injuries other than minor injuries caused by impact are unlikely, and that a single user can lift the weight to free oneself if being trapped. Maximum weight to be considered as lightweight is to be determined by manufacturer, considering intended task and target group.

Statically stable assumes that robot stability is maintained during stand-still, without drive power. Depending on the intended use of the robot, this can include maintaining stability of robot and user when the user is in contact with the robot.

iii. Power Storage: uncontrolled release of energy

Due to the usage of batteries, the device is governed by clauses concerning uncontrolled release of stored energy, which applies in both operation and shutting down states, where the controlled release of stored energy cannot cause additional hazards. This includes adding guards/covers to minimize risks during release of energy, and providing the robot with means to regulate its energy supply, to prevent overheating or over-currents cause by overloads or short circuits. Moreover, labels should be added to identify stored energy hazards and their locations. Information shall be added to describe the means, procedure of removal or controlled release of stored energy.

iv. Contact with hazardous energy parts

Electrical equipment of a personal care robot is designed according to the relevant requirements of IEC 60204-1. All hazardous energy sources (electrical, mechanical, etc.) shall be isolated, and clearly identified. Any type of stored energy shall be kept as low as reasonably practicable.

For electrical equipment, it is recommended to use extra-low voltage sources according to IEC 61140 (below 25V AC and 60V DC). Moreover, in cases of excessive heat, attention should be paid to applying heat dissipation measures.

viii. Hazards due to emissions

Hazardous noise

Personal care robot shall be constructed with components with inherently silent operation. Moreover, robot actions/motions shall be designed to be as quiet as practicable, given the performed task. Personal care robot shall be constructed with materials that limit acoustic noise and reduce its emission. One of the following measures shall be applied; adding sound absorbing materials, as foams, to the personal care robot body, or using active noise cancellation mechanisms.

Hazardous vibrations

A personal care robot user shall be protected from harmful vibrations that could cause vibration-related injuries; tendon inflammations, backache, neurosis, or similar injuries resulting from continuous use of the robot. Moreover, a personal care robot user shall be protected from vibrations between 0.5 Hz and 80 Hz that can cause problems for health, comfort and perception, and vibrations between 0.1 Hz and 0.5 Hz that can cause motion sickness.

Extreme temperatures

A personal care robot user shall be protected from extreme temperatures (either too high or too low); defined by temperatures below 10°C and above 43°C, from the robot or its components, which might cause burns, stress or any discomfort. This is performed by eliminating or avoiding extreme heat sources, and choosing material with appropriate texture and thermal conductivity. Other protective measures include reducing surface temperature with an appropriate heating/cooling system, and isolation or applying guards.

ix. Hazards due to stress, posture and usage

Mental stress and usage hazards

A personal care robot shall be designed to minimize and reduce mental stress to its user. User interface such as controls, signaling and data display elements shall be designed to be easily understood to ensure clear interaction between human and personal care robot. Safe design measures include the provision of adequate lighting, and designing personal care robot to avoid the need for sustained attention as far as reasonably practicable.

x. Hazards due to stress, posture and usage

Physical stress and posture hazards

Design of personal care robot should consider minimizing physical stress or strain to its user, resulting from continuous usage. Moreover, design shall take into consideration the typical body size of intended population, to avoid physically demanding body postures.

Safe design measures include designing and locating manual control devices, that are detachable and/or hand-held, instead of being permanently attached to the personal care robot. Protective measures include using shock absorbing mechanisms and posture supports.

Hazards due to robot motion

Risks of hazards resulting from intended or unintended motion of personal care robot shall be reduced to an acceptable level. Exposed persons shall be protected from hazardous movements; rollovers and runaways, under normal operation. This section covers various cases of instabilities; mechanical instability, instability while carrying loads, instability in cases of collision and instability while attaching or removing a restraint-type physical assistant robot.

Instability in case of collision

Design considerations regarding mass distribution and shape of personal care robot must be considered that unintended collisions lie within maximum expected limits do no result in overturning. In addition, thereto, using materials to absorb forces that lead to hazardous instability should be considered.

Other protective measures include design of motion behaviour of personal care robot to minimize impact forces, and using speed control to minimize instability and high impact forces during collisions.

Instability while attaching or removing a physical assistant robot

Stability shall be maintained while attaching/removing the robot to/from the user. Design considerations include designing the means to attach/remove the robot in a way that keeps the human in a stable position (sitting, lying) during the attaching/removal procedure. Moreover, actuators with sufficiently low power shall be used, not to harm the user while attaching or removing the robot.

Safety measures include designing the robot to detect when it is not properly attached to user, and issuing a warning. Forces should be restricted during mounting process to safety-related force control.

xi. Hazards due to insufficient durability

Durability of a personal care robot must be ensured throughout its design life, without creating a hazard. Minimum durability requirements shall consider; mechanical stresses, material properties, vibrations and other emissions, environmental conditions and maximum operation conditions.

Design considerations include; preventing mechanical failure through adherence to appropriate standards (ISO 13823), incorporating overload prevention measures, applying appropriate fatigue limits, applying appropriate static and dynamic balancing and the inclusion of passive heat dissipation. Information for use shall specify maintenance procedures necessary for ensuring the personal care robot’s durability.

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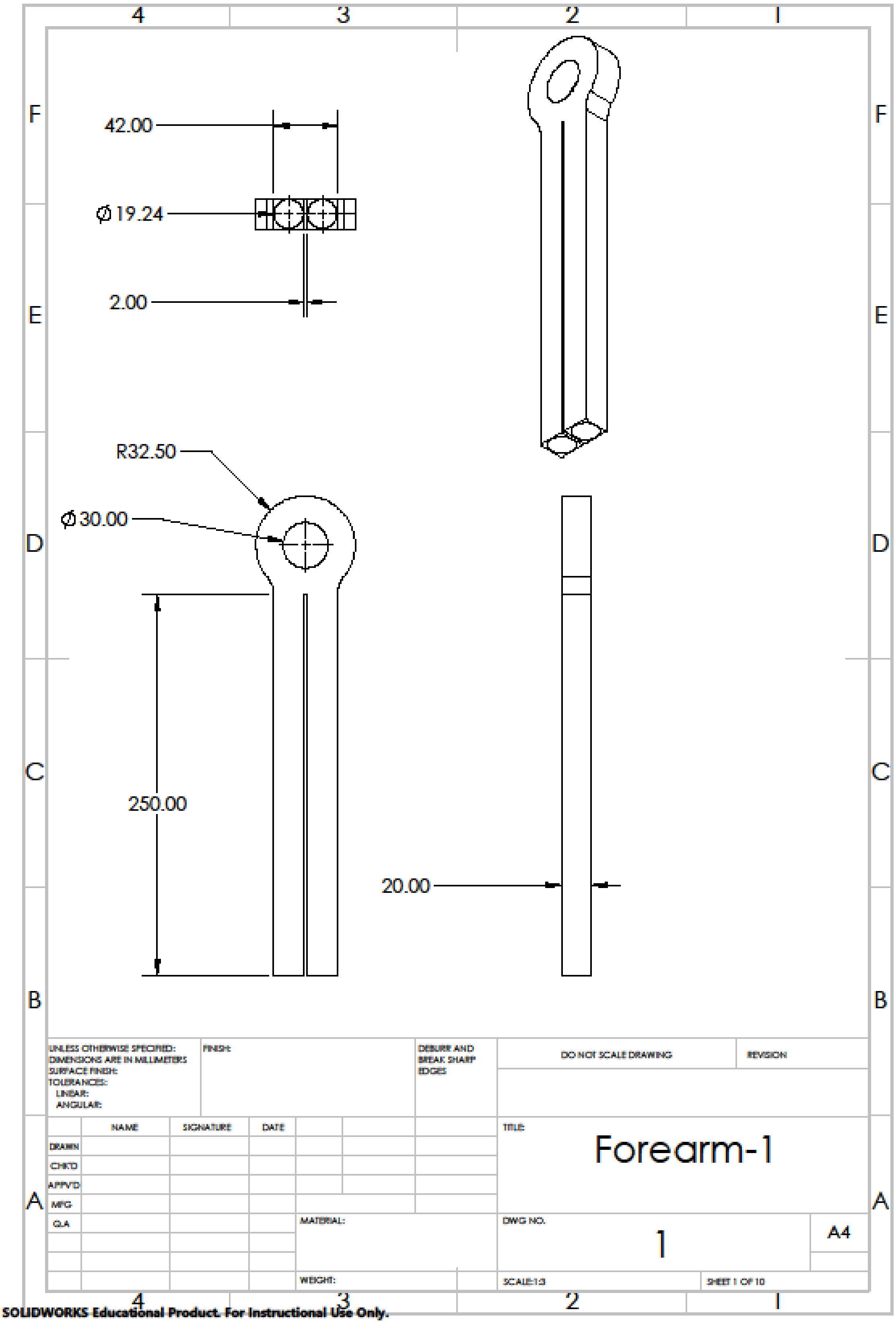

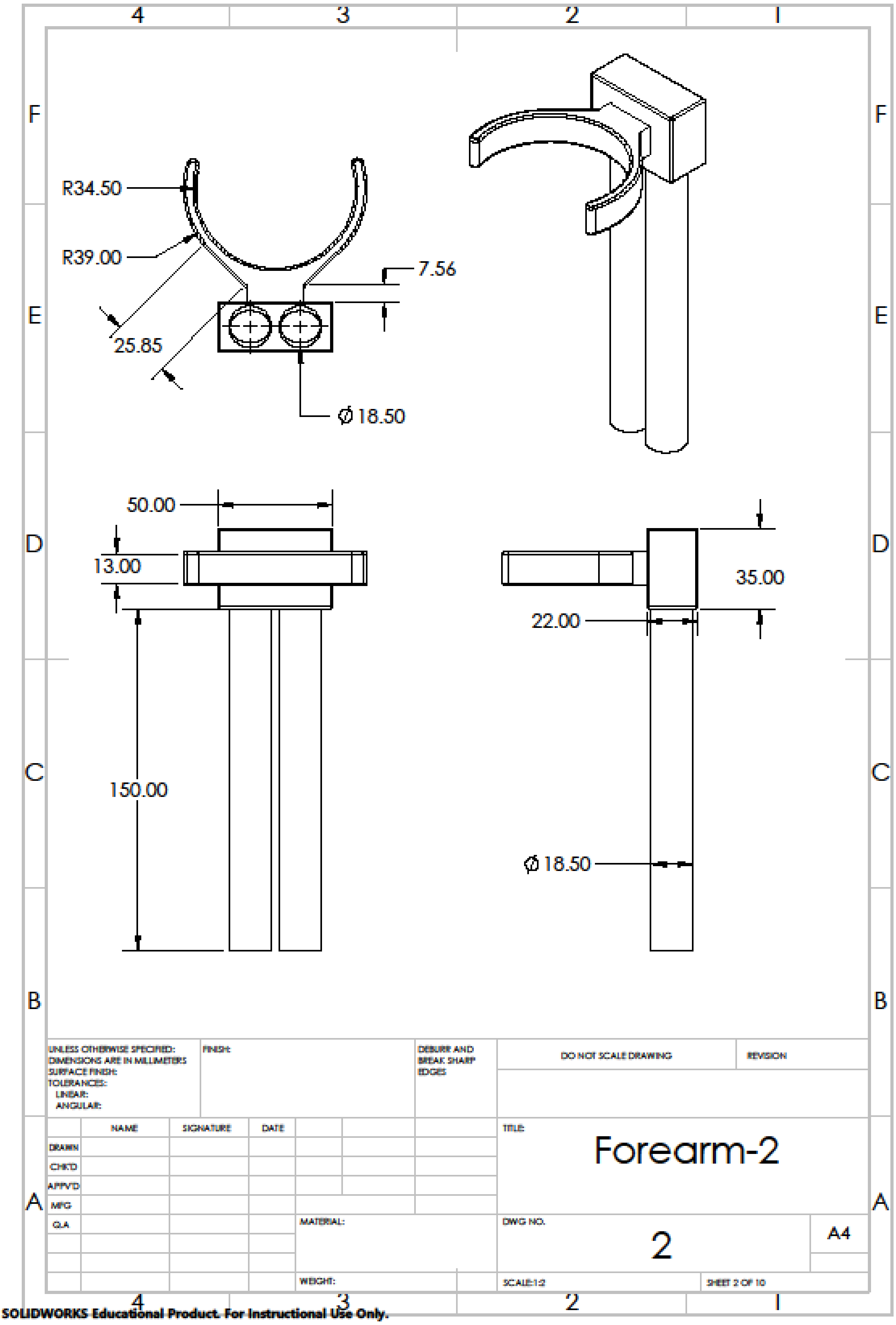
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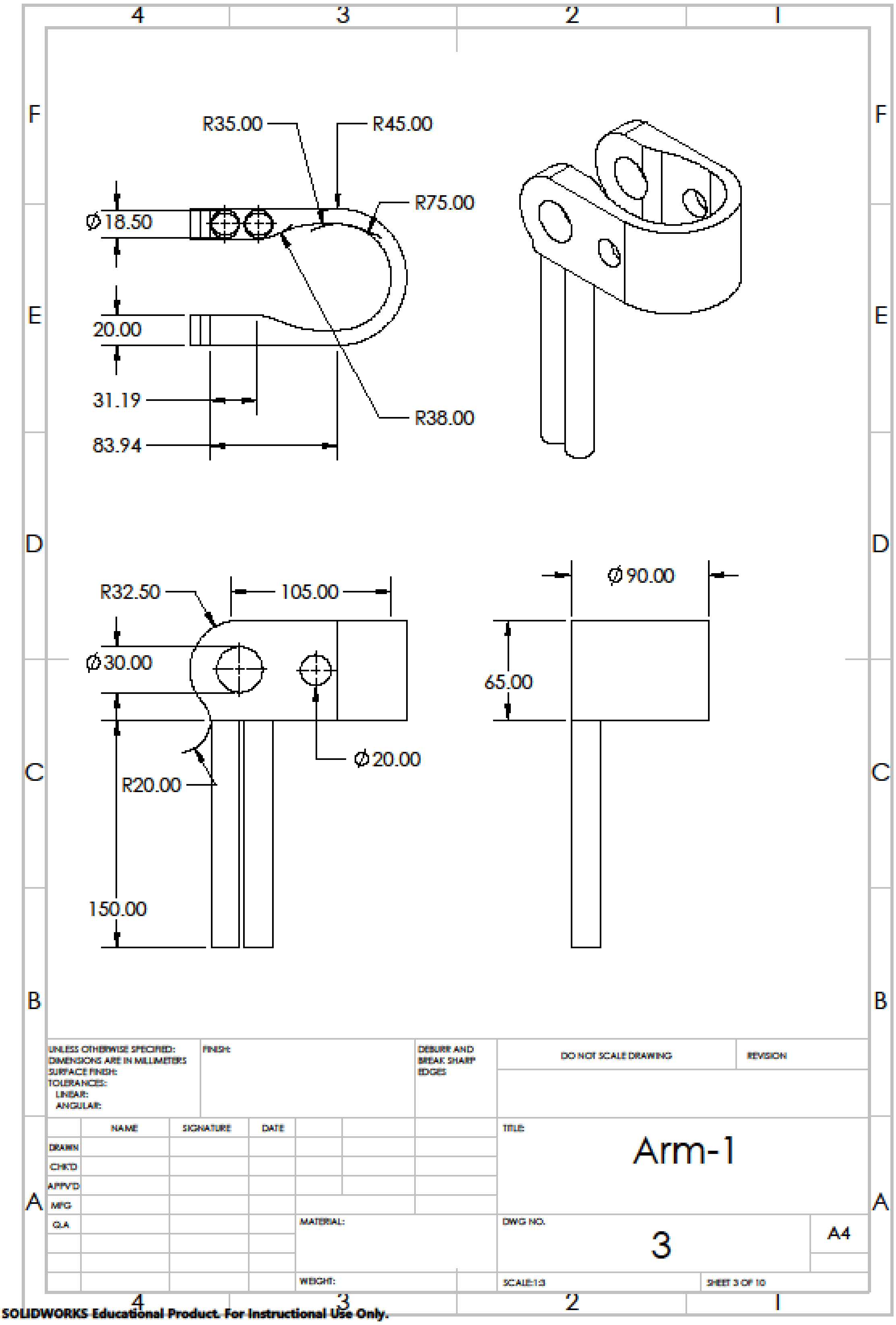

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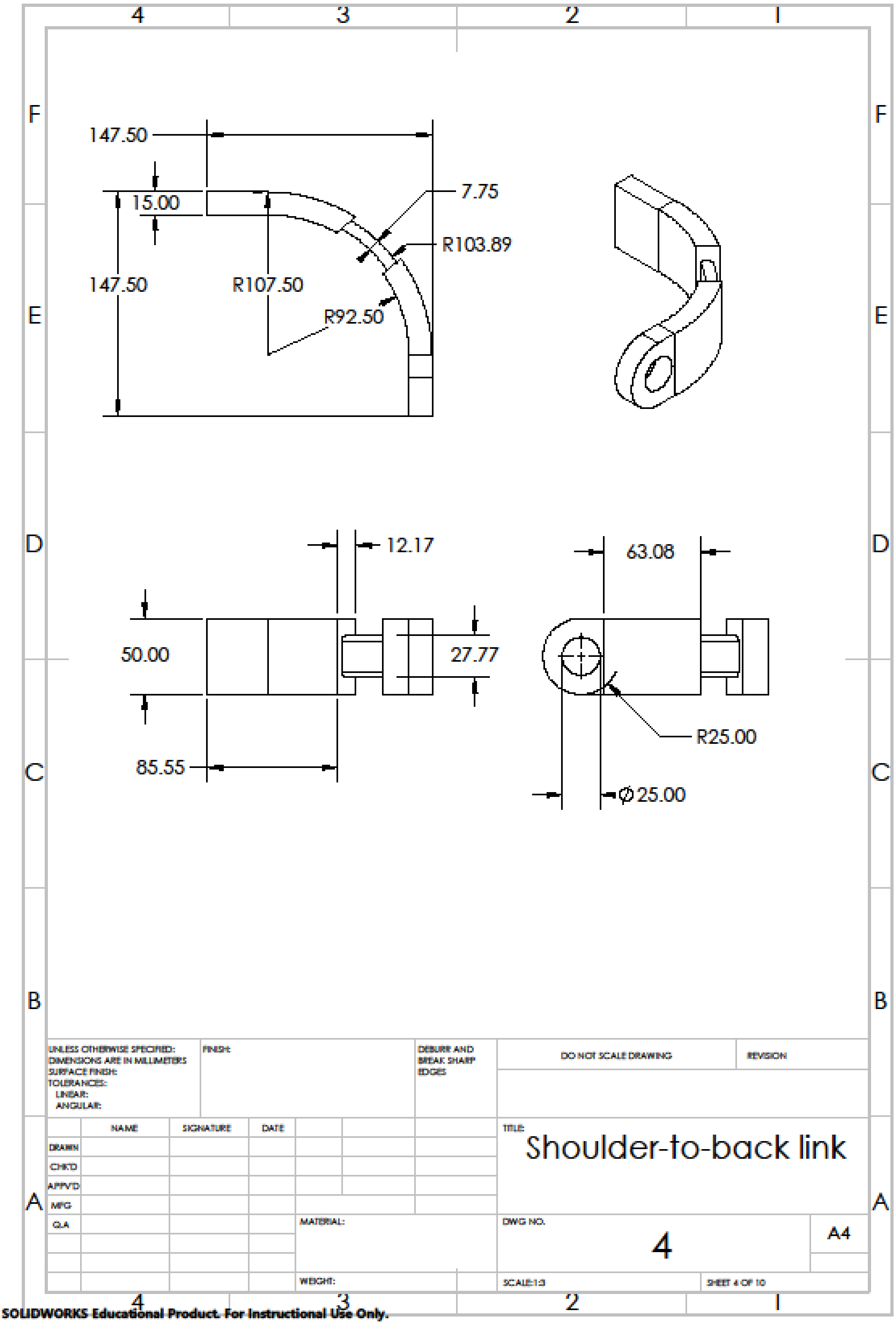
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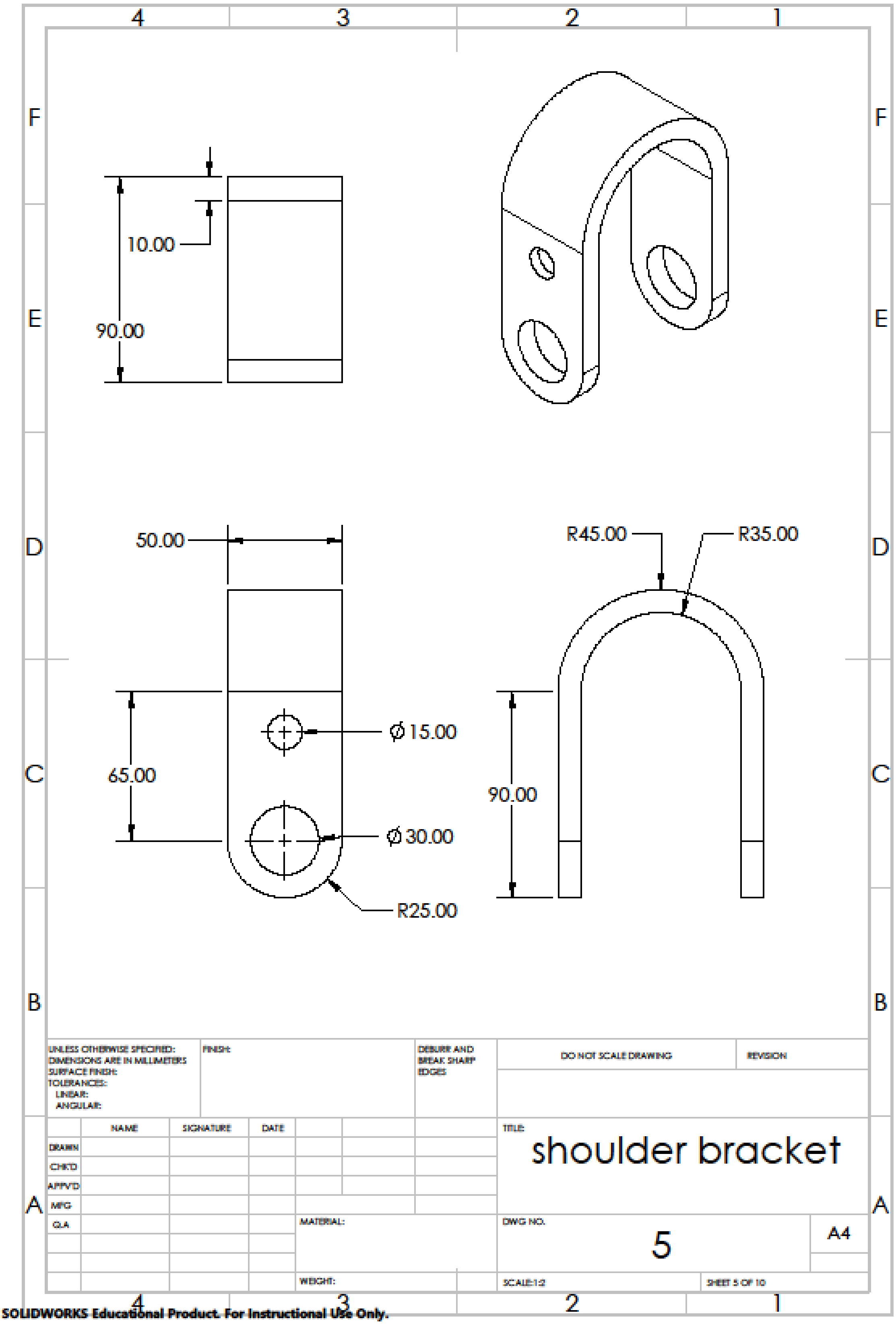
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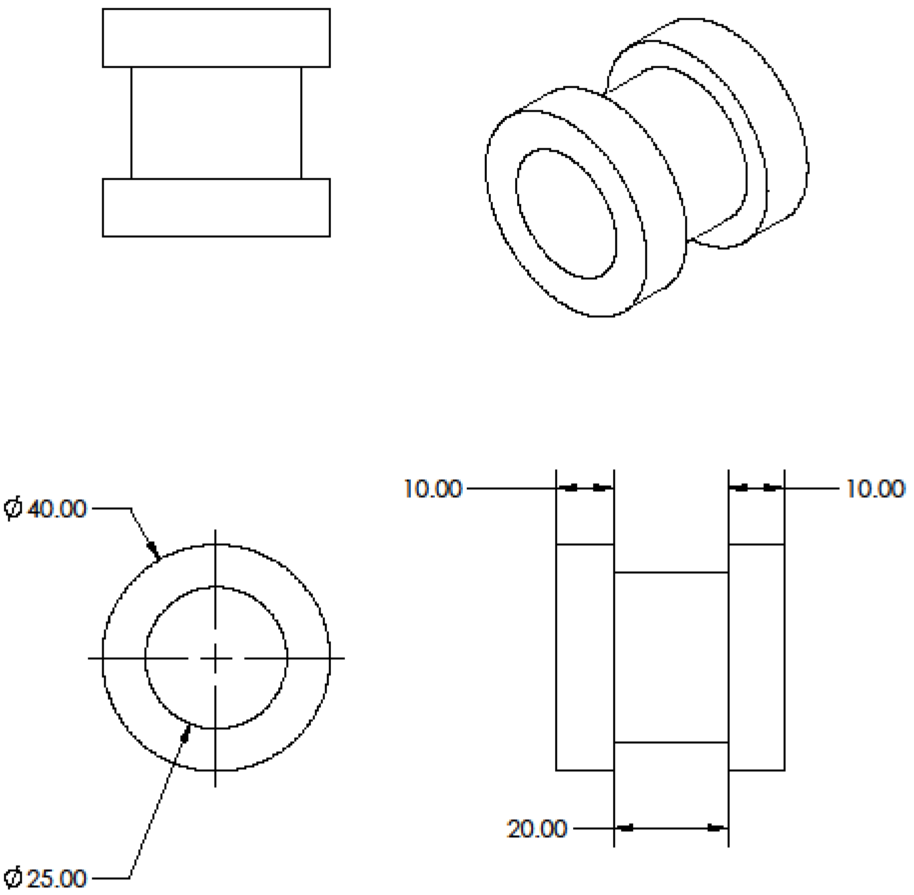

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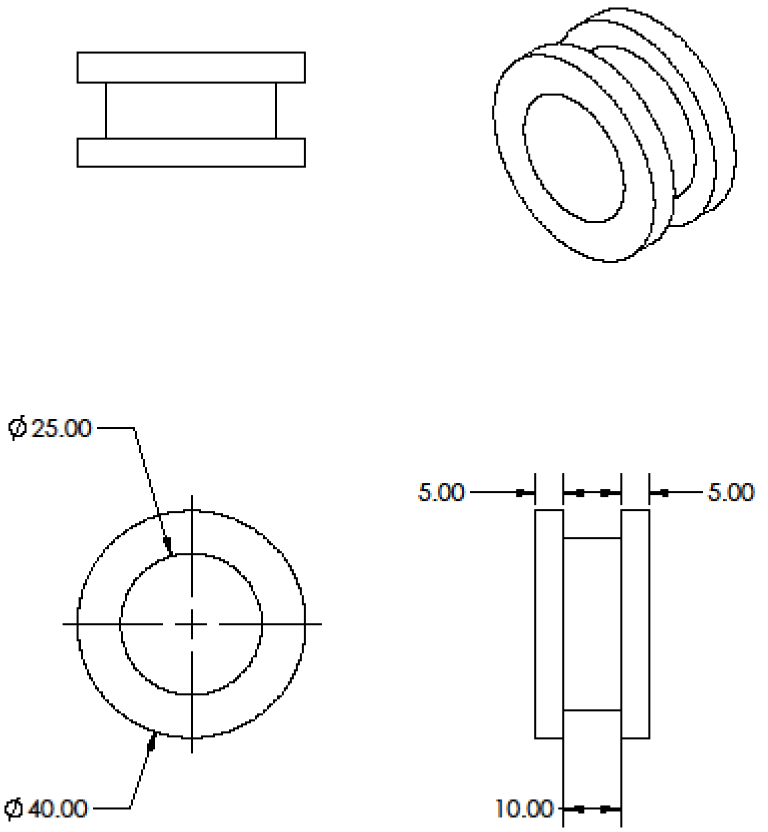

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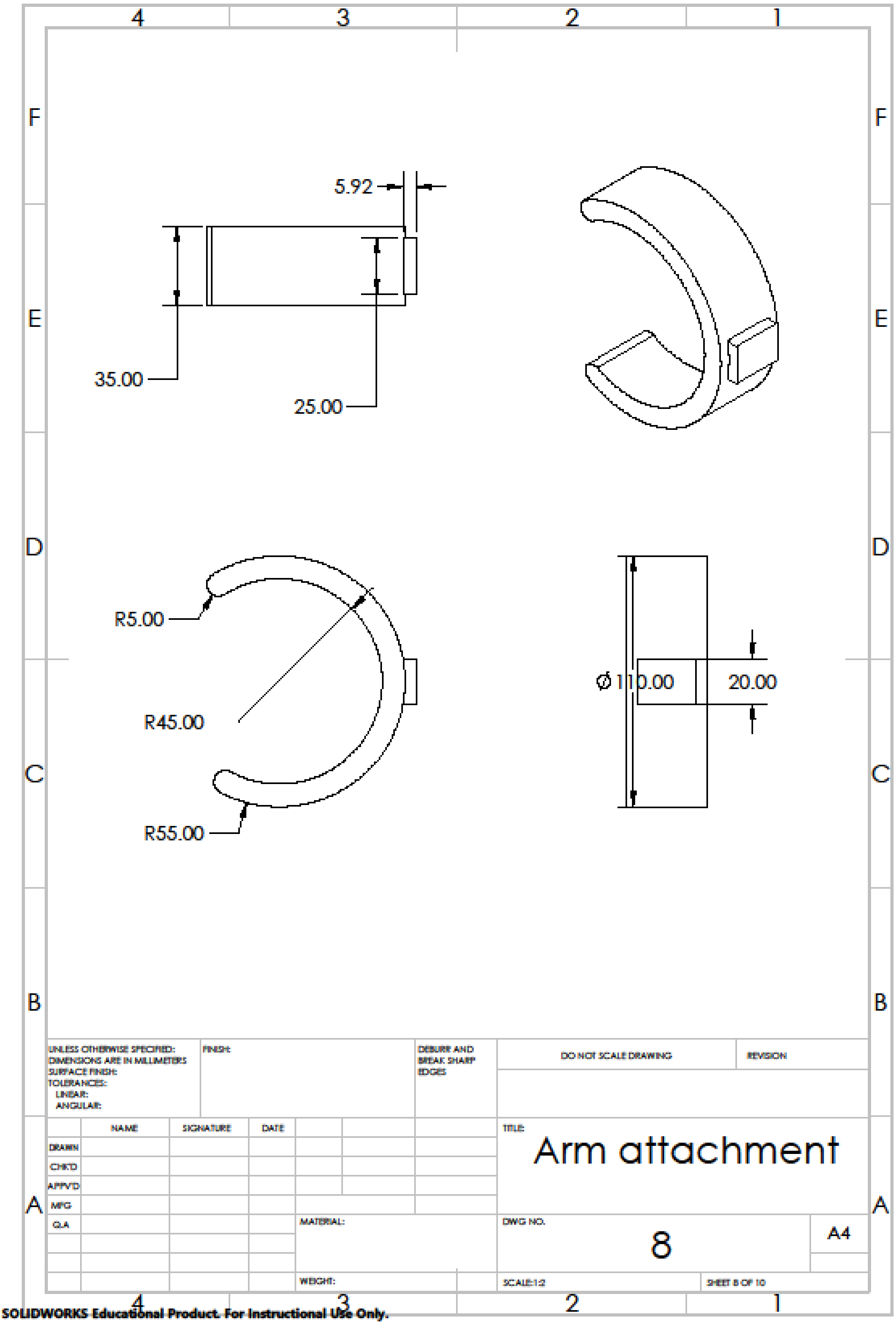
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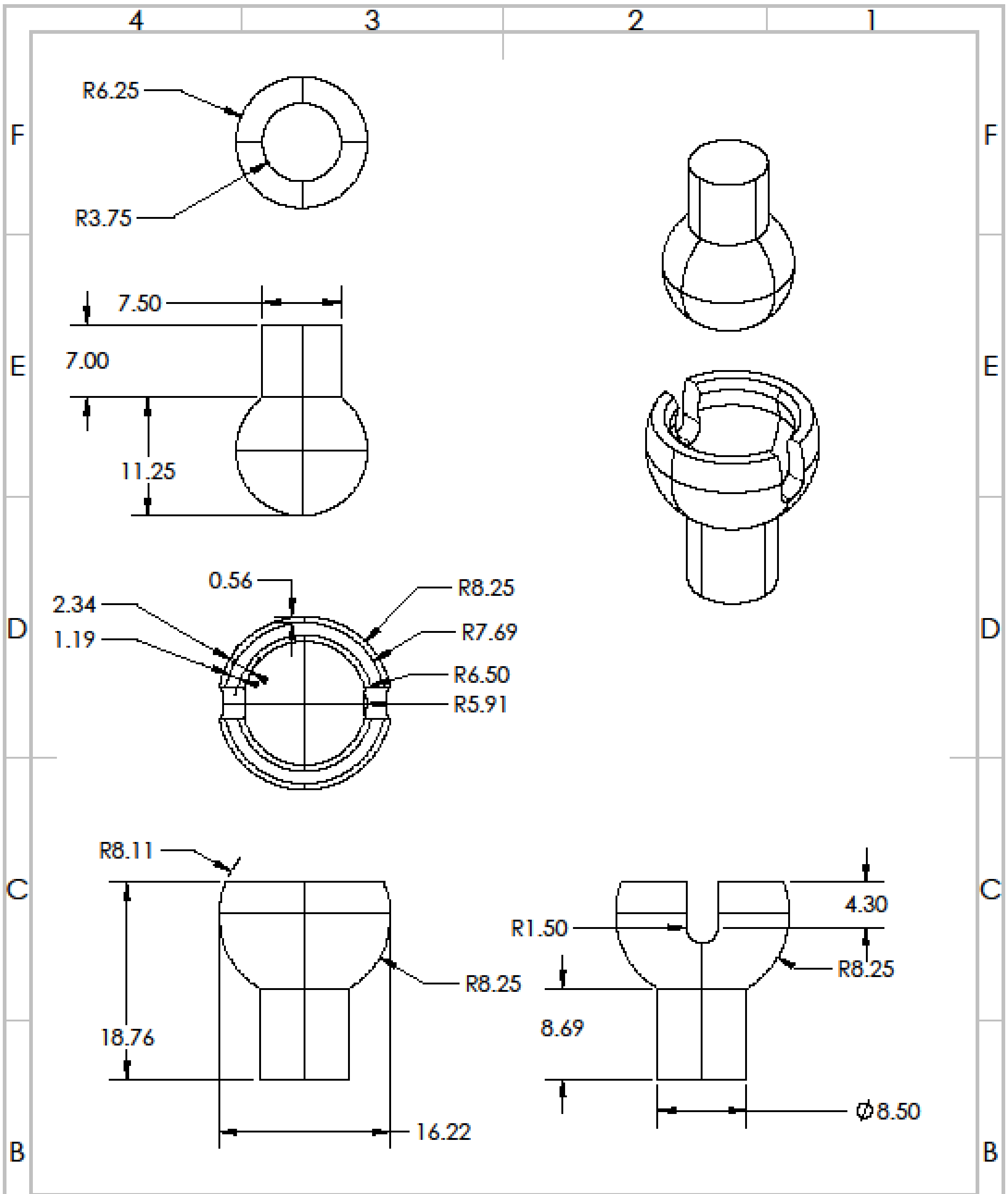

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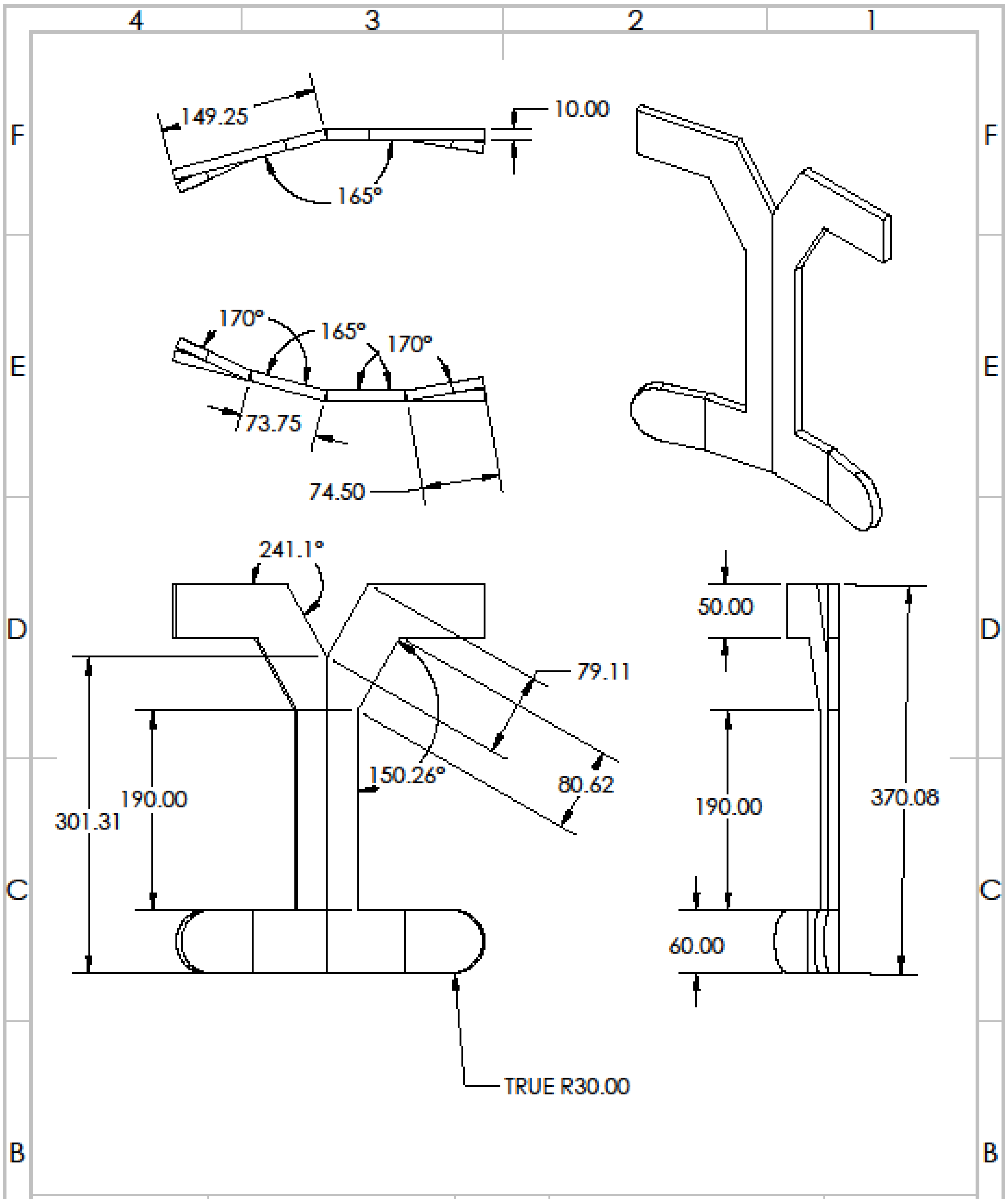

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