UNIVERSITÀ
POLITECNICA
DELLE MARCHE

Facoltà di Ingegneria
Corso di Laurea in Biomedical Engineering

Experimental evaluation of passive exoskeletons for manufacturing applications through motion analysis, electromyography and physiological measurements

Candidate:
Samuele Tonelli

Advisor:
Prof. Giacomo Palmieri

Coadvisor:
Dott.essa Cecilia Scoccia

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Via Brecce Bianche – 60131 Ancona (AN), Italy

To my parents
for their love, endless support
and encouragement

Abstract

This thesis presents an in-depth investigation into the efficacy of two passive exoskeletons, PAEXO back and PAEXO shoulder, designed to assist individuals in executing manual tasks with reduced muscular load and fatigue. The study engaged ten non-expert participants in a series of lifting, assembly, and simulated work tasks, comparing their performance with and without the assistance of the exoskeletons. The evaluation encompassed analyses of muscular activity, joint angles, metabolic cost, and subjective experiences. The PAEXO back showcased a significant reduction in muscle activity for the back and legs during lifting activities, demonstrating its potential to mitigate muscle fatigue. Despite variations in metabolic cost analysis, the exoskeletons displayed a promising trend of reducing metabolic consumption, suggesting the need for extended familiarization to optimize this aspect. Conversely, the PAEXO shoulder significantly alleviated muscle activation and perceived fatigue during overhead tasks, indicating its potential for ergonomic support. Subjective assessments highlighted users' satisfaction and perceived usability of the exoskeletons, emphasizing the importance of user experience in their effective implementation. The findings underscore the potential of these passive exoskeletons in enhancing workplace ergonomics, recommending further research to fine-tune their design and facilitate integration into occupational settings.

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Chapter 1

INTRODUCTION

1.1 Work related muskoloskeletal disorders

As indicated by the National Institute for Occupational Safety and Health (NIOSH), numerous epidemiological investigations have highlighted a clear cause-and-effect relationship between physical exertion during work and the development of work-related musculoskeletal disorders (WMSD). A multitude of factors have been linked to the occurrence of WMSD, including repetitive movements, excessive force application, awkward or prolonged postures, and extended periods of both sitting and standing [1].

Musculoskeletal conditions involve injuries or dysfunctions that impact various aspects of the musculoskeletal system, including muscles, bones, nerves, tendons, ligaments, joints, cartilage, and spinal discs. Such conditions encompass a range of issues like sprains, strains, tears, discomfort, pain, carpal tunnel syndrome, hernias, and injuries to the connective tissues within the aforementioned structures.

Musculoskeletal disorder (MSD) complaints are affecting workers, businesses, society, and personal lives, regardless of their connection to work-related factors. These disorders can profoundly impact an individual's physical, mental, and economic well-being, as well as aspects like their career, family, and social interactions. For workers, MSDs primarily affect their health status, sustainable employability in their current role, and position in the labor market. These complaints can lead to substantial health issues, potentially forcing individuals to exit the labor market due to their inability to continue working [2].

In 2015, the sixth wave of the European Working Conditions Survey revealed that around 3 out of every 5 workers in the EU-28 reported experiencing MSD complaints, specifically in their back, upper limbs, and/or lower limbs. Among workers in the EU-28, the most prevalent types of MSDs were backache and muscular pains in the upper limbs, accounting for 43% and 41% of reported cases respectively in 2015. Muscular pains in the lower limbs were less frequently reported, with a prevalence of 29% in the same year [2], see Figure 1.1.

Workers frequently report experiencing multiple types of MSDs, as noted in the earlier report on work-related MSDs from the European Agency for Safety and Health at Work (EU-OSHA) in 2010. The same report highlighted that work-related

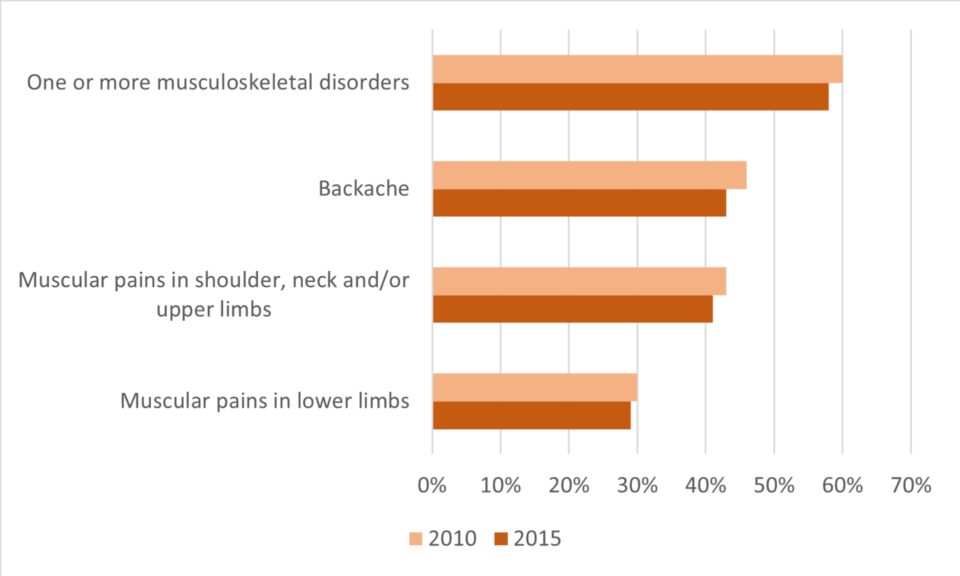


Figure 1.1: Percentage of workers reporting different musculoskeletal disorders, EU-28, 2010 and 2015

muscular pains in the lower limbs could be equally as prevalent as those in the upper limbs.

Innovative wearable technologies, like exoskeletons, have emerged as a promising avenue to offer physical assistance during demanding tasks. These technologies hold the potential to alleviate the occurrence of pain issues and subsequently lower of injuries or chronic musculoskeletal disorders.

During recent years, there has been a rise in the development and assessment of both active and passive exoskeletons. Active exoskeletons commonly utilize mechanisms like electromagnetic motors, series elastic actuators, or artificial muscles to offer assistance. While these systems can generate substantial forces, their weight, size, and the necessity for a power source render them less practical for prolonged physical tasks. On the other hand, passive exoskeletons can achieve much lighter designs by employing passive components such as flexible beams or rubber bands. These elements can be seamlessly integrated into textiles, resulting in compact, comfortable, and relatively cost-effective solutions.

1.2 Anatomy

In this section, it was examined the parts of the human body in which the work-related musculoskeletal disorder is prevalent, and they will benefit from the use of the exoskeletons. Thus, we will focus on the upper limb back ,on the back and on the lower limb, analysing in detail the bone segments, the joints and the muscles.

1.2.1 Upper limb

The upper limb is characterized by its mobility and ability to grasp, strike, and conduct fine motor skills. Its joints work in harmony to synchronize the movements of different segments, ensuring seamless and effective motion executed at the optimal distance or posture required for a given task. It is composed by four parts: the shoulder, the arm, the forearm, and the hand [3].

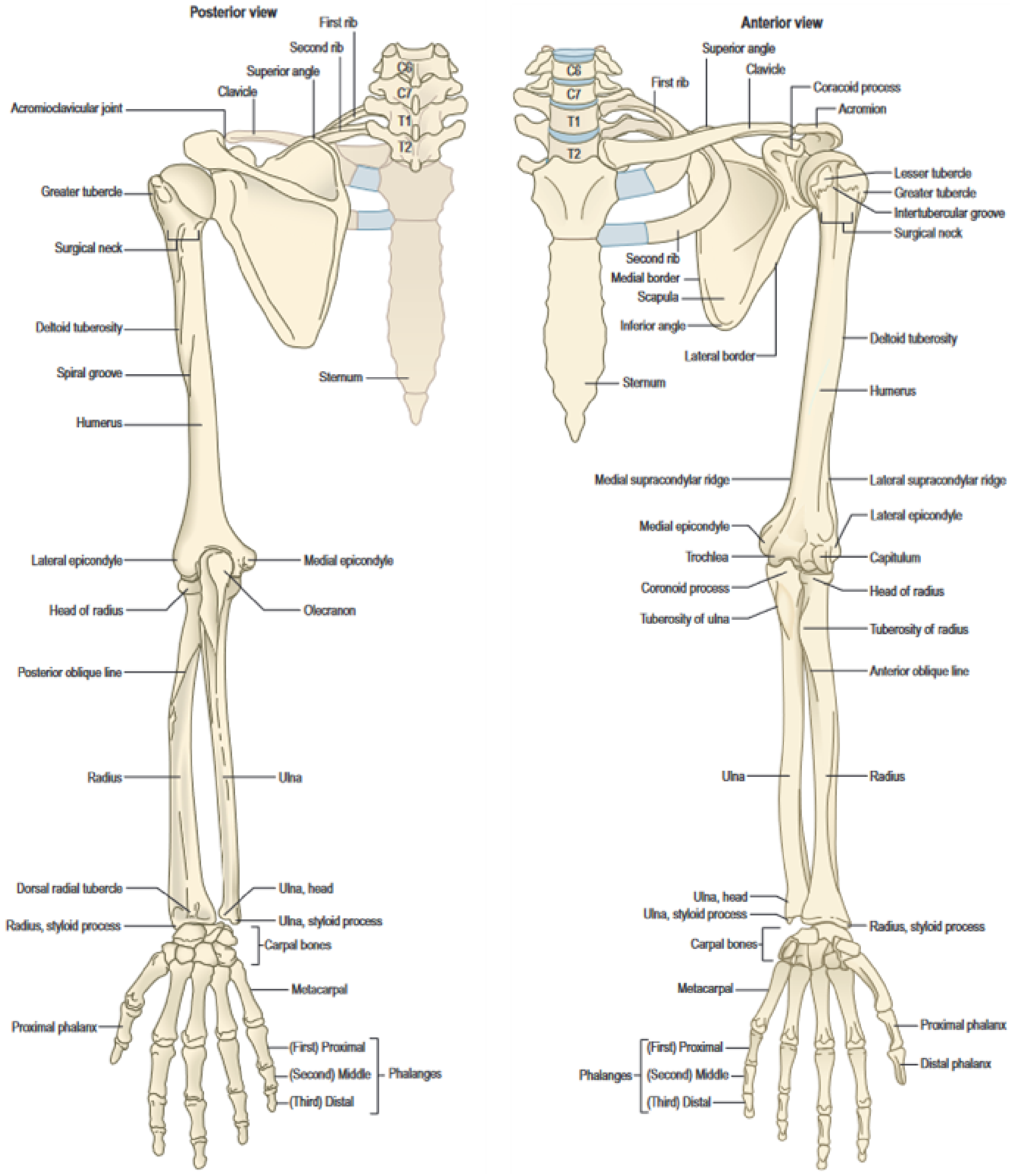
The shoulder is considered the region in which are included different part: the shoulder joint, the axilla, the scapular region around the shoulder blade, and the pectoral on the front of the chest. The arm is the part between the shoulder and the elbow, it is longest segment of the limb. The forearm extends from the elbow to the wrist, it contains the ulna and radius. The hand is the part of the upper limb distal to the forearm and consists of the wrist, the hand proper or metacarpus, and the digits; it is richly supplied with sensory endings for touch, pain, and temperature.

The upper limb's skeletal structure includes various bones (Figure 1.2a and Figure 1.2b), namely the scapula, clavicle, humerus, radius, ulna (interconnected by the interosseous membrane), the eight carpals, five metacarpals, and fourteen phalanges (with two phalanges in the thumb and three in each finger). The thoracic scapular joint plays a crucial role in upper limb function, with the trapezius and serratus anterior muscles being essential for movement; paralysis of either can be debilitating. The connection between the limb and the axial skeleton is facilitated by the sternoclavicular joint. The glenohumeral joint, having a narrow structure, offers extensive movement due to the muscles and joints involved.

The elbow includes a hinge joint between the humerus and ulna, along with two pivot joints: one between the humerus and radius, and another between the proximal radius and ulna. This arrangement allows for a substantial range of extension, flexion, and pronosupination. The wrist complex permits flexion, extension, adduction, and abduction, while the condylar metacarpophalangeal joint allows for flexion, extension, abduction, adduction, and rotation. The human upper limb uniquely incorporates pronation and supination movements [4].

The muscles of the upper limb can be categorized based on their origins and the joints they influence:

- Muscles originating from the axial skeleton and acting on the scapula include trapezius, levator scapulae, rhomboids, and serratus anterior.
- Muscles originating from the axial skeleton and affecting the glenohumeral joint consist of the sternal head of pectoralis major, pectoralis minor, and latissimus dorsi (Figure 1.3).
- Muscles spanning between the scapula and proximal humerus control the glenohumeral joint, including supra- and infraspinatus, subscapularis, teres major and minor, and coracobrachialis. Deltoid and the clavicular head of pectoralis major also play a role in this group.



(a) (b)

Figure 1.2: The bones of the pectoral girdle and upper limb: anterior (a) and posterior (b) view

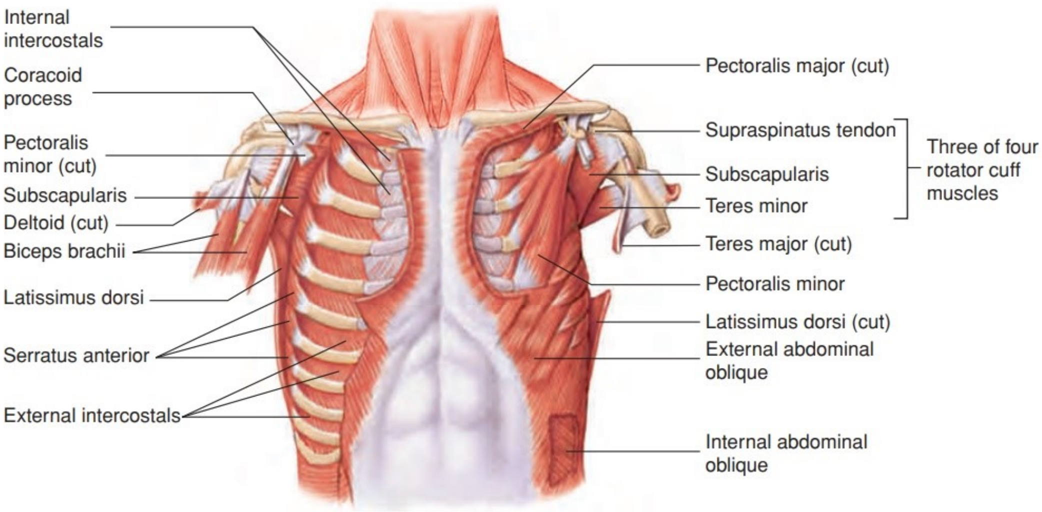


Figure 1.3: Muscles of the upper limb: anterior view

- The primary muscles controlling the elbow are biceps and triceps; both muscles have long heads that traverse the glenohumeral joint to attach to the scapula (Figure 1.4).
- Supination and pronation are controlled by biceps brachii and supinator, as well as pronator teres and pronator quadratus.
- Muscles affecting the radiocarpal joint include extensors carpi radialis longus and brevis, extensor carpi ulnaris, flexors carpi ulnaris and radialis, and palmaris longus.
- Muscles influencing the thumb ray include powerful flexor pollicis longus, weaker abductor pollicis longus, and extensors pollicis longus and brevis.
- Extension and flexion of the metacarpophalangeal and interphalangeal joints of the fingers involve coordinated action between extensor digitorum, flexors digitorum superficialis and profundus, interosseous muscles, and lumbricals.
- Small hand muscles include those controlling the thumb ray and web space. They involve adductor pollicis, abductor pollicis brevis, flexor pollicis brevis, and opponens pollicis, as well as interosseous muscles, abductor and opponens digiti minimi, and flexor digiti minimi brevis (Figure 1.5).

Many muscles have influence over multiple joints. For instance, biceps and triceps' long heads flex and extend both the glenohumeral joint and the elbow. Certain muscles are functionally specialized; the anterior part of deltoid flexes the glenohumeral joint, while the posterior part is a potent extensor [4].

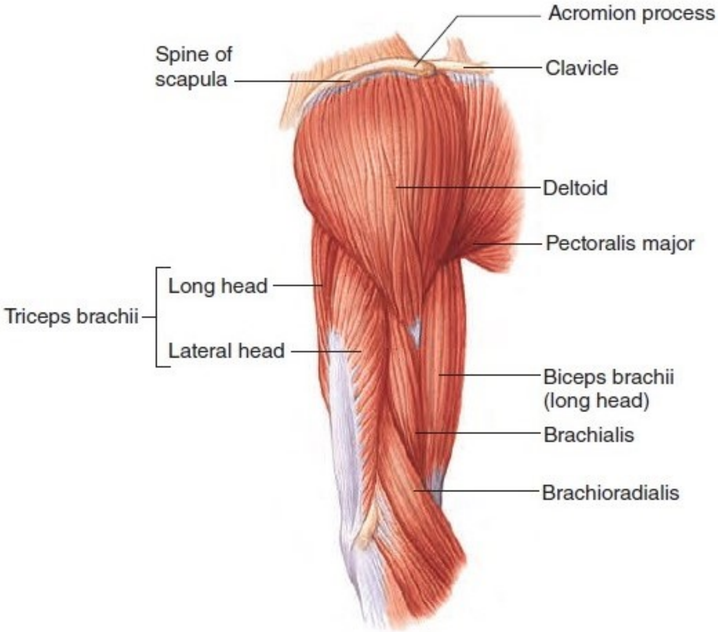


Figure 1.4: Muscles of the arm

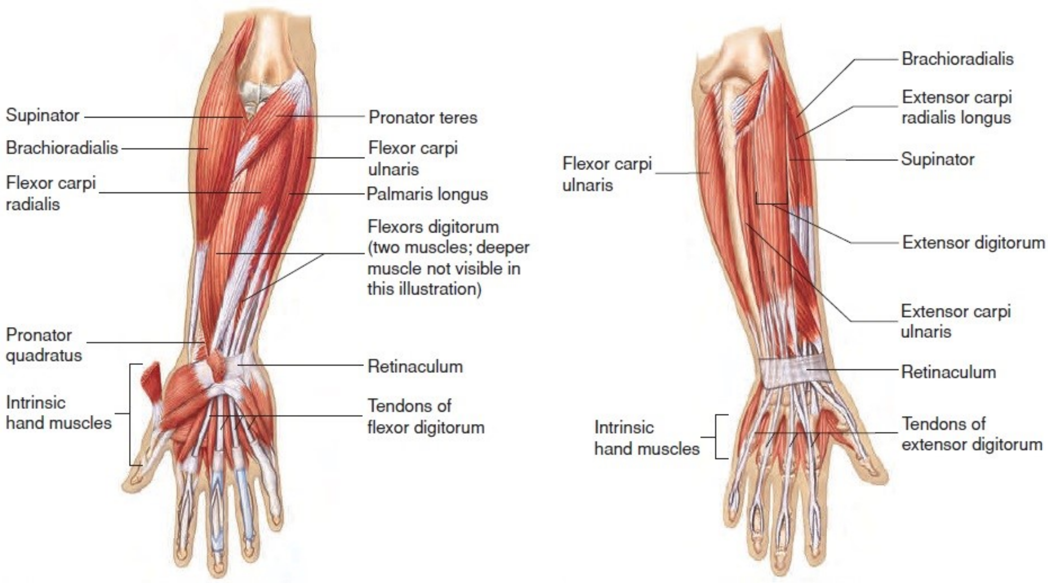


Figure 1.5: Muscles of the forearm and hand

1.2.2 Back

The back encompasses the posterior portion of the trunk, situated below the neck and above the buttocks. This region serves as the point of attachment for the head, neck, and limbs. The skeletal structure of the back includes the vertebral column and the ribs in the thoracic region while the muscles consist in a superficial layer, primarily concerned with positioning and moving the limbs, and a deeper layer (true back muscles), specifically concerned with moving or maintaining the position of the axial skeleton (posture).

The vertebral column is a complex arrangement of individual bones, known as vertebrae, forming a curved structure, see Figure1.6. These vertebrae are linked in a continuous series, with vertebral foramina passing through them posterior to their bodies. This series together forms the vertebral canal, which serves as a conduit to transmit and protection the spinal cord, nerve roots, their coverings, and associated blood vessels. Adjacent vertebrae also have paired lateral intervertebral foramina, creating pathways for spinal nerves and their corresponding vessels.

The connections between vertebrae include cartilaginous interbody joints and paired synovial facet joints. These connections are supported by a complex system of ligaments, muscles, and fasciae. Muscles mainly involved in vertebral movements are situated posteriorly. Larger muscles that drive significant spinal movements, such as those of the anterolateral abdominal wall, are located further away from the column and aren't directly attached to it.

In adults, the vertebral column typically comprises 33 vertebral segments. Except for the first two cervical segments, each presacral segment is separated by a fibrocartilaginous intervertebral disc. The column has multiple functions, including supporting the trunk, safeguarding the spinal cord and nerves, and providing attachment sites for muscles. Additionally, it serves as a site for lifelong haemopoiesis (formation of blood cells). Its length is approximately 70 cm in males and 60 cm in females. Intervertebral discs contribute about one-quarter of this length in young adults, with some variation throughout the day.

The vertebral column's segments are distributed as follows: approximately 8% of overall body length is attributed to the cervical spine, 20% to the thoracic region, 12% to the lumbar region, and 8% to the sacrococcygeal region. While the typical configuration consists of 7 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 4 coccygeal vertebrae, variations are common, and reports exist of totals ranging between 32 and 35 bones [4].

Most of the body weight is situated anterior to the vertebral column. This emphasizes the importance of the robust muscles attached to the spinous and transverse processes, as they play a vital role in supporting and manoeuvring the vertebral column. The muscles of the back are shown in Figure1.7. Within the back, two main categories of muscles can be identified:

- The superficial extrinsic back muscles establish connections between the upper

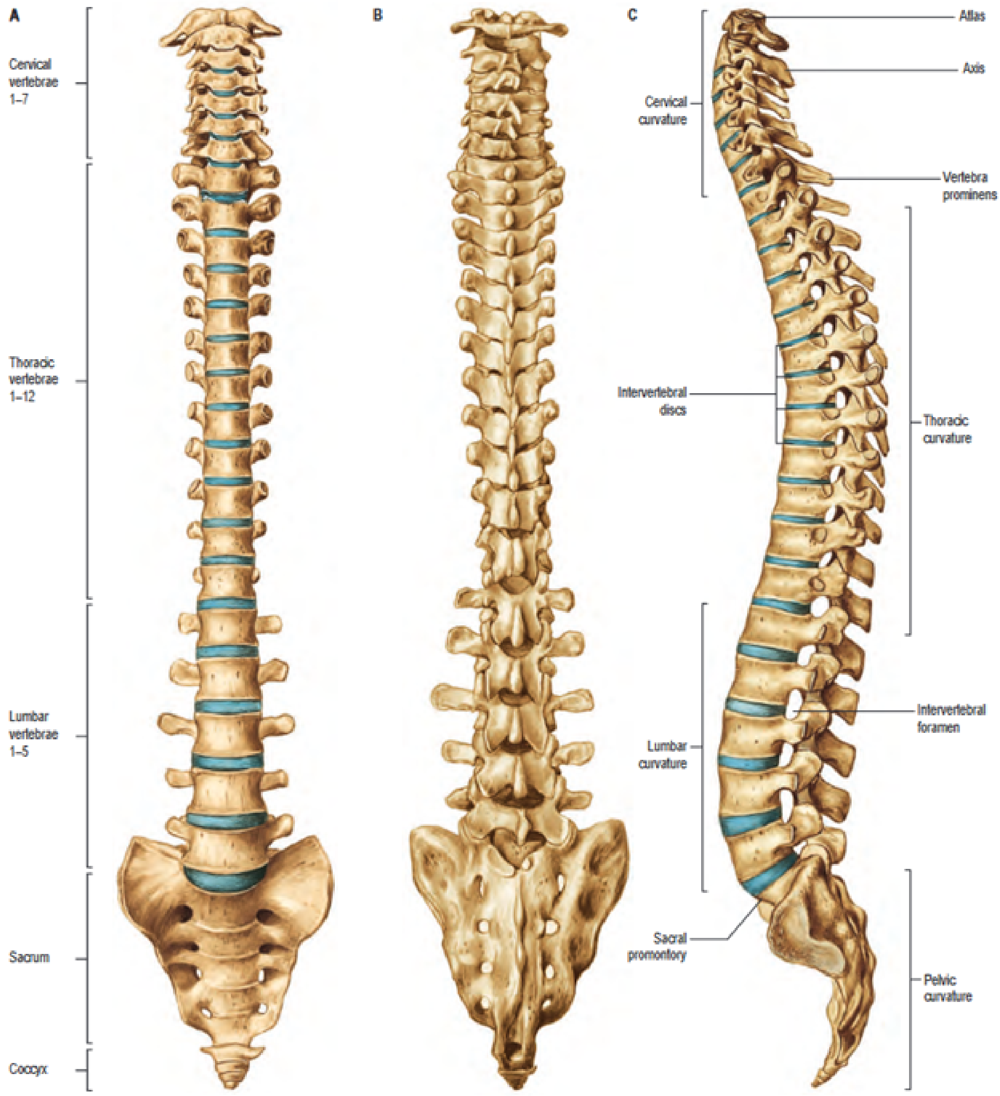


Figure 1.6: Skeletal structure of the vertebral column

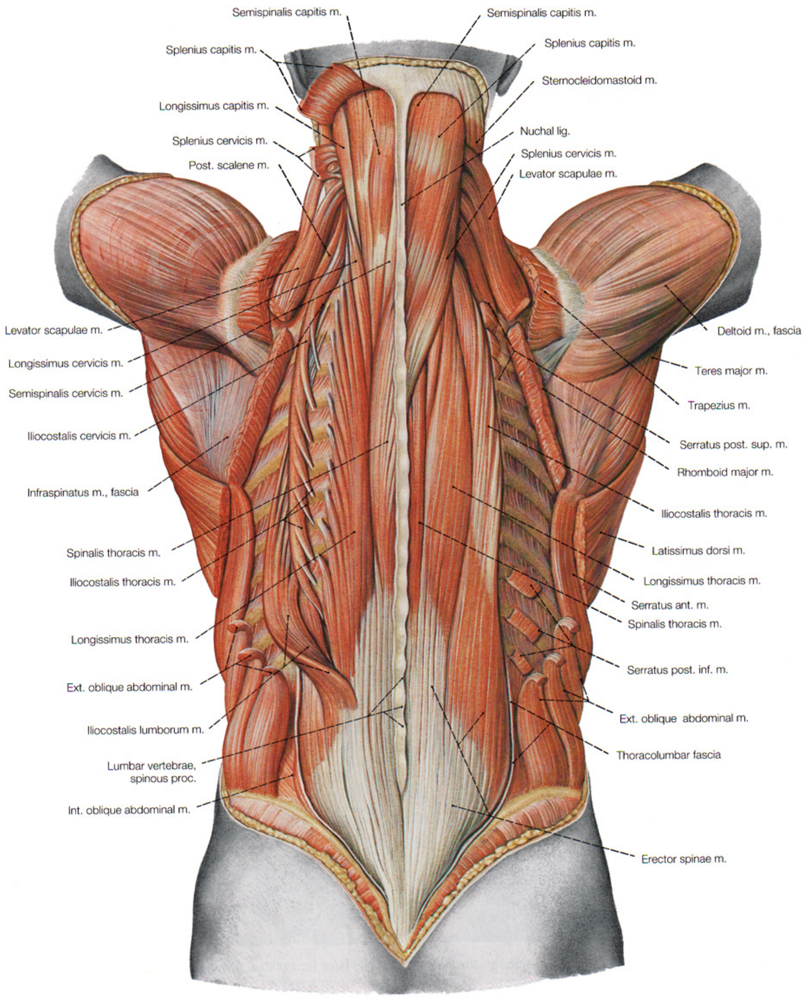


Figure 1.7: Back muscles

limbs and the trunk, thereby enabling and managing limb movements. They include trapezius, latissimus dorsi, levator scapulae, and rhomboids

- Intrinsic back muscles (also known as muscles of the back proper or deep back muscles) are responsible for maintaining posture and controlling the movements of the vertebral column. The deep back muscles are categorized into superficial, intermediate, and deep layers based on their relationship to the body's surface. The intrinsic muscles are also arranged in layers. The more superficial layers contain the splenius muscles in the neck and upper thorax, and the erector spinae group in the trunk. The deeper layers include the spinotransverse group, which is itself layered into semispinalis, multifidus and the rotatores, and the suboccipital muscles. Deepest of all lie the interspinal and intertransverse muscles.

Most of the muscular activity is involved in providing stability to maintain posture and provide a stable platform for limb function. Recognizing the intricate interplay between the muscles of the back and those of the abdominal wall, particularly the oblique and transversus muscles, along with their coordination with the muscles of the lower limbs, is essential. One significant connection exists between the erector spinae group, the internal oblique, and transversus abdominis muscles. This connection is both anatomical and functional, facilitated by the presence of the thoracolumbar fascia, which envelops the erector spinae muscles and provides a site for insertion of the abdominal muscles. Especially, this fascia, along with the collagenous tissue within the back muscles, performs a pivotal role in countering forward bending of the trunk and in activities such as manual handling.

The thoracolumbar fascia, serving as a bridge between these muscle groups, experiences tensioning primarily when the trunk is flexed. While this tension is primarily generated through trunk flexion, there is a possibility that the lateral pull exerted by the abdominal muscles slightly augments this tension. This coordination and interaction between the muscles of the back and the abdominal wall are crucial for maintaining stability, posture, and proper mechanics during various activities, including those involving the lower limbs [4].

1.2.3 Lower limb

The anatomical design of the lower limb is highly specialized to achieve several crucial functions, including providing support for the body's weight, facilitating movement (locomotion), and ensuring the maintenance of overall body stability and balance. Notably, these adaptations for weight-bearing and stability are the primary factors responsible for the significant structural and functional distinctions between the upper and lower limbs. The lower limb can be divided into 4 different parts or regions: the hip and the buttock, the thigh, the leg and, the foot [3], see Figure1.8.

The combined hip and buttock regions form what is known as the gluteal region. This area covers the lateral and posterior aspects of the pelvis, extending from the waist down to the groove called the gluteal fold. It includes the space from the waist to the lower part of the buttock and extends to the depression located on the lateral side of the hip. The groove that runs between the buttocks is termed the natal cleft, and it contains the lower portions of the sacrum and coccyx, the terminal segments of the spine. The skeletal structure of this region is composed of the hip bone, which is made up of three parts: the ilium, ischium, and pubis. These three bones fuse together at a point known as the acetabulum, where the head of the femur connects with the hip bone. The right and left hip bones, together with the sacrum and coccyx, make up the skeleton of the pelvis. Here The hip joint exhibits a very effective compromise between mobility and stability that allows movement in all three orthogonal planes.

The thigh, also known as the femur, extends from the hip to the knee. The femur, the bone of the thigh, forms connections at its upper end with the hip bone to constitute the hip joint. This bone also articulates with the tibia and the patella at the knee joint. This joint allows flexion, extension and some medial and lateral rotation of the leg. It is not a true hinge joint because its axes of flexion and extension are variable and there is coupled rotation. The knee joint also includes the articulation between the patella and femur.

The leg extends from the knee joint down to the ankle joint. This part is composed of two bones: the tibia, commonly known as the shin bone, and the fibula. These bones are positioned adjacent to each other, with the slender fibula situated laterally. The tibia and fibula are connected through the interosseous membrane along their length. They also articulate with each other at the upper and lower ends, forming the superior and inferior tibiofibular joints. The lateral and medial malleoli are protrusions at the sides of the ankle that result from the lower ends of the tibia and fibula. These malleoli hold the talus, the first bone of the foot, in place between them, creating the ankle joint, that allows dorsiflexion and plantar flexion.

The foot, extending from the heel to the tips of the toes, is composed of distinct regions: the superior surface is referred to as the dorsum, while the inferior surface is referred to as the sole or planta. The structural components of the foot, arranged from proximal to distal, include the tarsal bones, metatarsals, and phalanges.

The tarsal bones are organized into two rows. The first row comprises two significant bones, the talus and the calcaneus, where the talus rests on the calcaneus. The calcaneus, the largest bone of the tarsus, constitutes the framework of the heel. The talus, on the other hand, articulates with two primary structures: the upper surface of the calcaneus and the tibia and fibula, collectively forming the ankle joint.

The ability of the lower limb to maintain equilibrium during locomotion and in stance is also employed by muscles. Muscles of the lower limb may be subdivided into those of the iliac and gluteal regions, and those of the thigh, leg, and foot [4].

In the posterior abdominopelvic region, the primary muscles are the psoas major and iliacus, which collectively form the iliopsoas. These muscles are essential hip flexors, Figure1.9b. The muscles located in the gluteal region consist of the three gluteal muscles along with the deeper short lateral rotators of the hip joint. The gluteal muscles include the gluteus maximus, gluteus medius, and gluteus minimus. The gluteus maximus acts as a powerful extensor of the hip joint. However, its function often involves extending the trunk on the femur more than extending the limb on the trunk, Figure1.9a.

On the other hand, the gluteus medius and gluteus minimus function as abductors of the hip joint. Their primary role lies in stabilizing the pelvis on the femur during movements like walking. To assist in this function, the tensor fasciae latae, a muscle situated more anteriorly, aids in stabilizing the pelvis. The muscles of the thigh are organized into three functional compartments, each serving specific roles. The anterior compartment, known as the extensor compartment, is composed of the sartorius and the quadriceps femoris muscles. Both the sartorius and rectus femoris muscles have proximal attachments to the pelvis, allowing them to act on both the

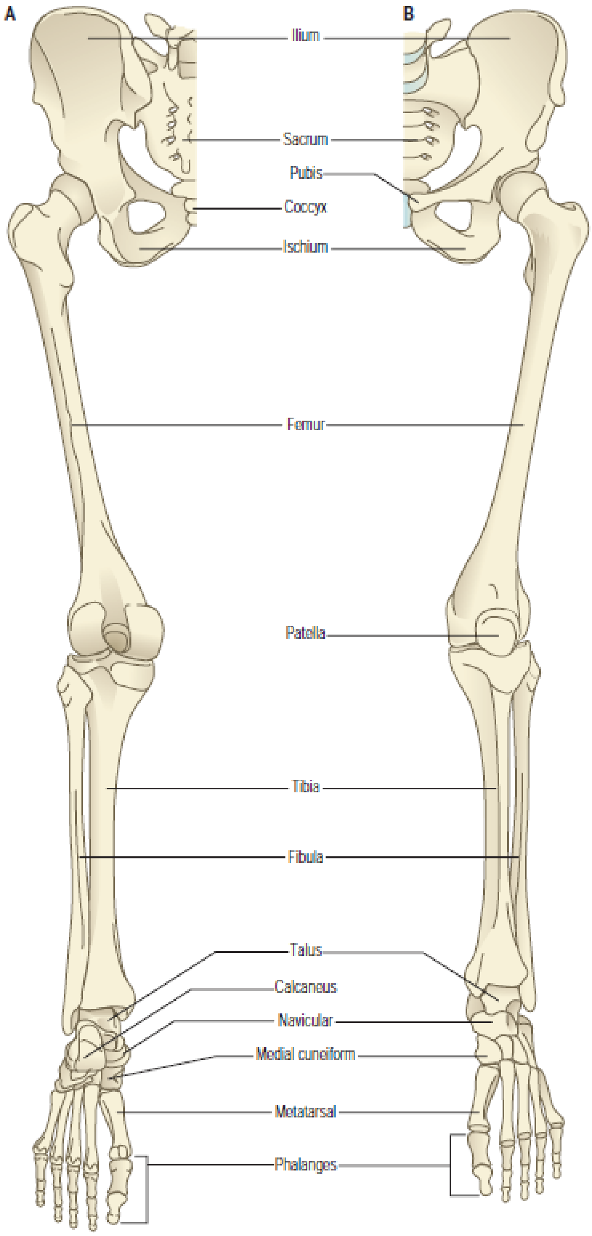
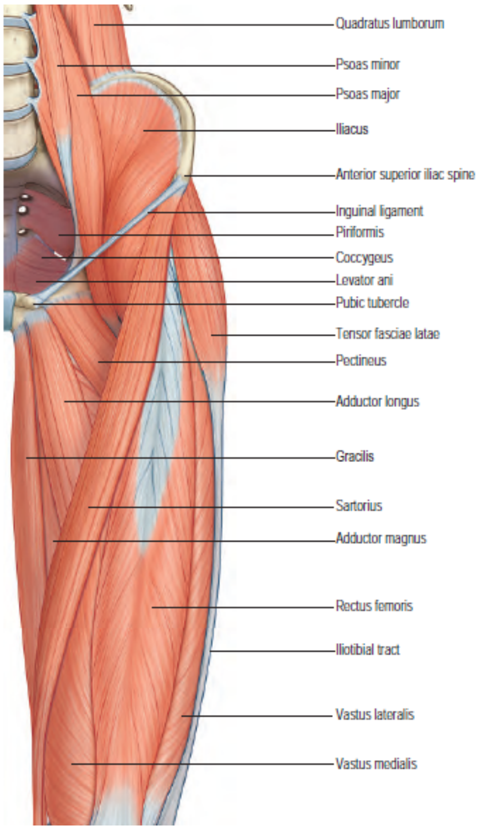
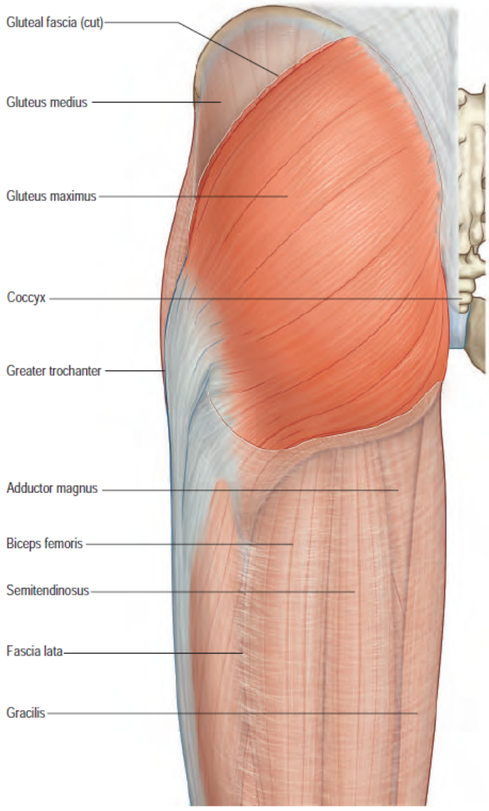


Figure 1.8: Lower limb: A) posterior view, B) anterior view



(a)



(b)

Figure 1.9: Muscles of the lower limb: anterior (a) and posterior (b) view

hip joint and the knee. The vasti muscles, part of the quadriceps femoris function as powerful knee extensors.

The medial compartment, instead, contains the adductor muscles along with the gracilis muscle, and sometimes includes the pectineus muscle. The posterior compartment of the thigh consists of the semitendinosus, semimembranosus, and biceps femoris muscles. Functionally, they serve to extend the trunk on the femur and to flex and rotate the knee joint. In the leg, the anterior compartment is responsible for dorsiflexion (lifting the foot upwards) and includes both the dorsiflexors of the foot and the extrinsic extensors of the toes. The primary muscle involved in foot dorsiflexion is the tibialis anterior, which also has the additional function of inverting the foot at the subtalar joint.

Moving to the posterior compartment, it has both superficial and deep components. The superficial part comprises the gastrocnemius and soleus muscles, which are powerful plantar flexors responsible for pointing the foot downward. In the deep component of the flexor compartment, you find the popliteus muscle, which plays a role in rotating the knee. The extrinsic flexors of the toes and the tibialis posterior muscle, the main inverter of the foot, are also found in this compartment, see Figure1.10. The lateral compartment contains the primary evertors of the foot, the

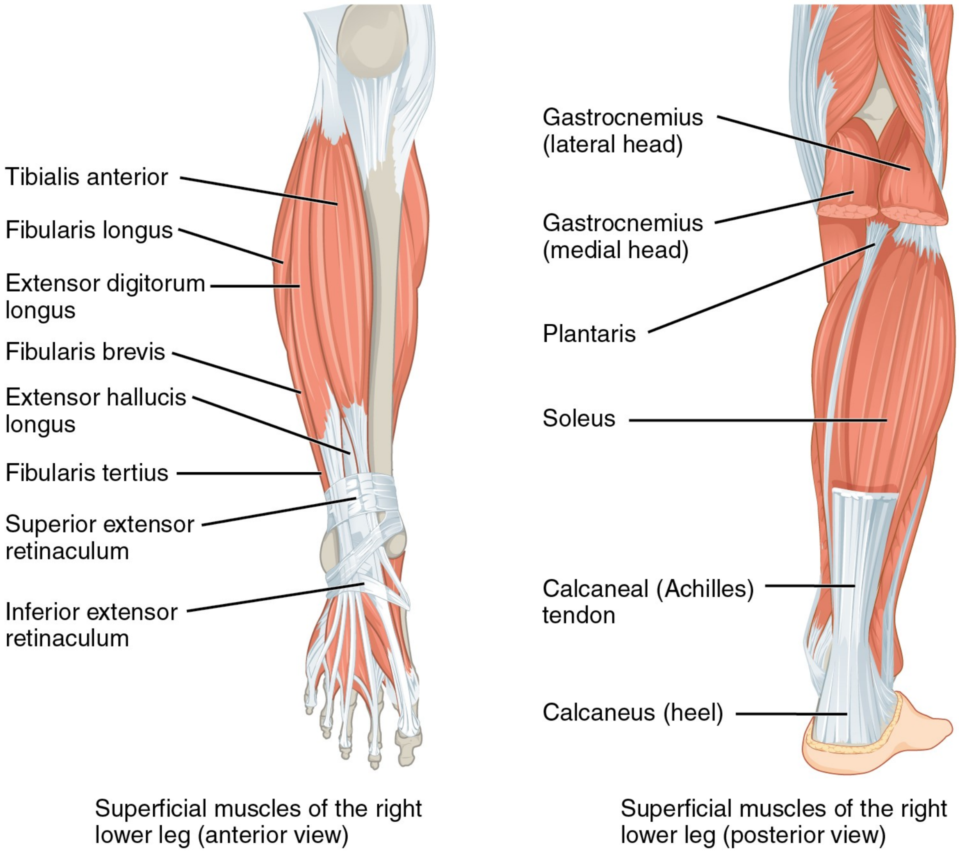


Figure 1.10: Muscles of the leg and foot

fibularis (peroneus) longus and brevis muscles. Additionally, both muscles serve as plantar flexors of the foot.

It's important to note that muscles like the gastrocnemius and plantaris are connected proximally to the femur and distally to the calcaneus. This allows these muscles to have an effect not only on the ankle joint but also on the knee joint.

1.3 exoskeleton

In animals, as for examples grasshoppers, crabs and tortoise, the exoskeleton is the external skeleton structure, which provides support and protection against predators.

However, in human use the exoskeleton can be defined as a type of powered robotic electro-mechanical support that is created to be worn by a person. It applies a suitable level of torque or force at the joints of the human limbs to facilitate natural or improved (augmented) limb motion. This technology is designed to mimic the human form and walking pattern (the way humans move using their limbs). The exoskeleton operates in synchronization with the wearer and can be driven actively or passively, contributing its power to enhance the wearer's strength [5].

The history of exoskeleton research dates to 1890 when N. Yagn conceptualized a robotic exoskeleton [6], earning him a US Patent for his lower extremity enhancer model. This concept involved a bow operating in parallel to the user's legs, aiding in walking, running, and jumping, see Figure1.11.

In 1965, the General Electric Company initiated the development of the Hardiman I Exoskeleton in collaboration with the Army and Navy. This full body powered exoskeleton had 30 degrees of freedom and weighed 680 kg.

In 2004, the Human Engineering and Robotics Laboratory at the University of California, Berkeley introduced the energetically autonomous load carrying BLEEX exoskeleton. This design augmented the wearer's strength and endurance during locomotion, achieving walking speeds of 0.9 m/s with payloads up to 75 kg. Subsequent exoskeletons included the MIT Exoskeleton, HULC, HUMA, Hybrid Assist Limb (HAL), Nurse Assisting Robot, eLEGS, RoboKnee, and ReWalk.

MIT's exoskeleton incorporated passive elements like springs and dampers at limb joints, leveraging human walking dynamics for efficiency. HULC, developed by Lockheed Martin, employed hydraulic actuators to allow soldiers to carry heavy loads with minimal fatigue. HUMA by Hyundai ROTEM aided in carrying heavy backpack loads, using BLDC motors and harmonic drives.

For rehabilitation, HAL by the University of Tsukuba and Cyberdyne Systems Company provided both performance augmentation and physical assistance for patients. Ekso Bionics' eLEGS enabled paraplegics to stand and walk again, based on weight and sensor inputs. RoboKnee featured a 1-DOF exoskeleton for climbing stairs and deep knee bends, while ReWalk utilized motor-driven joints and centre of gravity control for rehabilitation clinics.

Exoskeletons have captivated the interest of researchers due to their immense potential across two major areas: the military and rehabilitation sectors. In the military field, exoskeletons are rapidly gaining ground as fundamental tools for amplifying the physical skill and endurance of soldiers. This translates to their ability to carry heavy loads over prolonged periods while traversing diverse terrains, all achieved with a significant reduction in metabolic expenditure. This reduction in metabolic costs directly translates to reduced fatigue levels and enhanced agility, resulting in soldiers with a distinct edge. Categorized as augmentative exoskeletons, these designs not only enhance locomotion dynamics but also empower wearers with augmented load-bearing capacities, redefining the possibilities of modern warfare.

Conversely, within the rehabilitation field, exoskeletons are emerging as transformative solutions for reinstating mobility and physical capabilities among those afflicted with impairments. These impairments could be caused by athletic injuries, spinal cord traumas, or the result of cerebral vascular incidents like strokes. By providing targeted support and guidance, rehabilitative exoskeletons facilitate faster recovery for patients, facilitating a journey back to functional mobility.

These devices also have the potential to serve as assistive tools for restoring function to limbs, or as therapeutic aids to help individuals overcome disabilities by training muscles and nervous systems. It's important to differentiate these rehabilitative

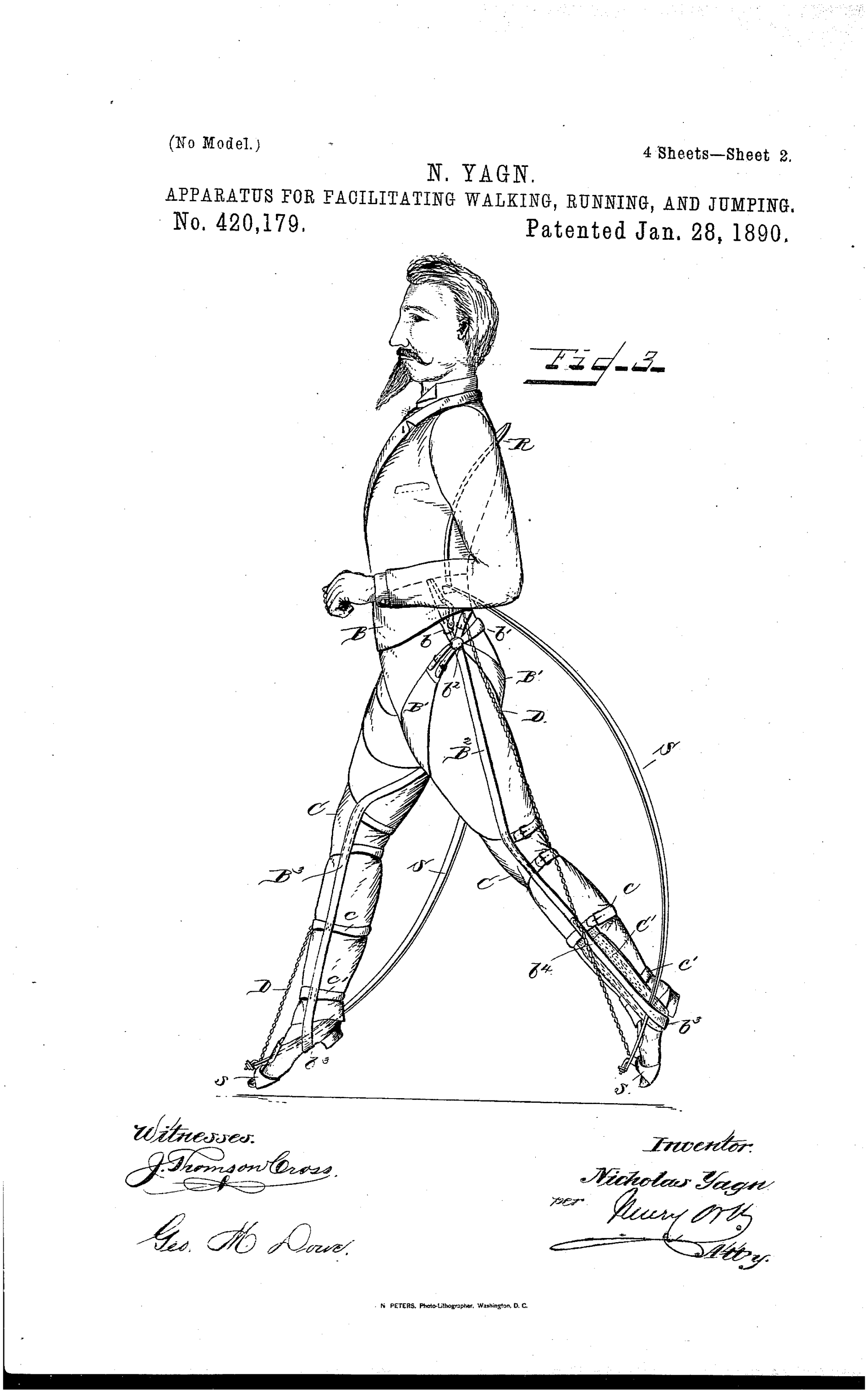


Figure 1.11: Concept model of N. Yagn Exoskeleton

devices from industrial exoskeletons. Industrial exoskeletons are designed to enhance the performance of a worker's existing body components, mainly focusing on the lower back and upper extremities. There are two primary types of industrial exoskeletons: "active" exoskeletons powered by actuators like electric motors, pneumatics, and hydraulics, often called "robotic exoskeletons," and "passive" exoskeletons utilizing springs and counterbalance forces driven by natural human movement [7].

Industrial exoskeletons are commonly categorized as back assist, shoulder and arm assist, tool holding/support, and leg assist. Back assist exoskeletons provide lumbar spine support and aid in maintaining proper posture during lifting or static tasks. Shoulder assist and non-anthropomorphic arm tool holding support exoskeletons are used for overhead work and holding heavy tools. Leg assist devices augment hip, knee, or ankle joints during locomotion or load carrying, and some even offer relief from prolonged standing.

The perceived benefits of industrial exoskeletons include increased productivity, improved work quality, and a reduction in the risk of work-related musculoskeletal disorders (WMSDs). Despite this, industrial exoskeletons are already being adopted in various sectors like construction, mining, manufacturing, and warehousing, where manual material handling tasks are prevalent [7].

Many studies on passive exoskeletons have demonstrated promising results in various aspects. [8],[9],[10],[11], [12] and [13] observed a decline in muscles engagement during a range of tasks when utilizing exoskeletons with respect to non utilizing it. Exoskeletons have been noted to potentially limit or alter movement kinematics [14]. These alterations in movement patterns, load distribution, or the added weight of the exoskeleton could heighten biomechanical stress in other areas of the body[14], consequently impacting postural strain [8]. Additionally, not only positive findings in objective assessments are important but also the user perceptions on the workload and satisfaction or dissatisfaction with specific aspects of the exoskeleton [11].

The primary objective of this thesis is to assess the effectiveness of two distinct exoskeletons: one offering upper limb support and the other designed for the back. This evaluation will encompass a comprehensive set of measurements, aiming to estimate the advantages that these exoskeletons may offer to workers. The assessment will be conducted both within our laboratory, replicating an industrial setting, and in an small on-field test, providing a more comprehensive view of the evaluation.

Chapter 2

MATERIALS AND METHODS

2.1 Ottobock PAEXO

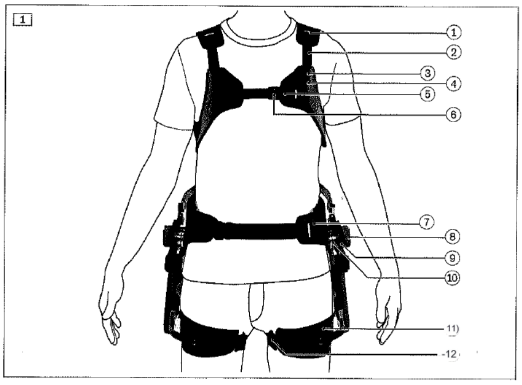
This study was conducted with two passive exoskeleton produces by Ottobock, that provide support one for back and the other for the shoulders.

Ottobock is a company based in Duderstadt Germany, that operates in the field of orthopaedic technology. It is considered the world market leader in the field of prosthetics and one of the leading suppliers in orthotics, wheelchairs, and exoskeletons.

The two exoskeletons that were analysed are the *PAEXO back* and the *PAEXO shoulder*.

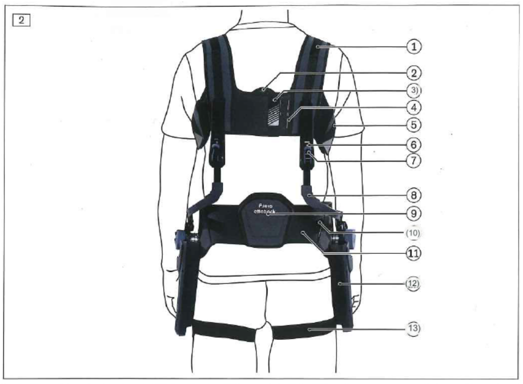
2.1.1 PAEXO Back

The Paexo Back is an exoskeleton design to reduce the load on the lower back when lifting heavy objects. It is a passive, spring based, exoskeleton that does not need any powered actuators. The exoskeleton assists in relieving tension in the lumbar region of the back during lifting and carrying operations, including actions like supporting and depositing a load. As a result, it plays a preventive role in the spinal region. The Paexo Back is worn like a backpack and secured at the shoulder, waist, and thighs. Its dimensions are 850 mm in length, 500 mm in width, 350 mm in height, and it weighs 4.5 kg. The design is conceived to be adjustable to fit different body sizes. Modifications can be made to the width and depth of the shoulder straps, the length of the back, the waist circumference, and the thigh belts. Its components include a waist belt, shoulder straps with rigid rods, and thigh cuffs with a spring system. These parts are connected through joints that allow independent movement when the support mechanism is inactive. Activation of the support causes forces from forward bending to transfer to the legs via the rods, with the spring system converting kinetic energy from trunk movement into stored elastic potential energy. The hip joint supporting moment is concentrated at the trochanter major's height, increasing with bending. The support's onset is adjustable based on trunk-to-waist belt angle and user preference. This results in perceived support during forward bending. Upon extending the trunk upright, the stored energy aids the user by lifting both the upper body and external load. A mechanical clutch discerns between walking and lifting, toggling the spring-based support on or off. Designed as one-size-fits-all, adjustments



Front view			
Pos.	Name	**Pos.**	Name
1	Shoulder strap clip	7	Magnetic pelvic belt closure
2	Shoulder brace	8	Support capacity adjustment wheel
3	Vest with chest pads	9	Hip joint unit ON/OFF mode
4	Pocket for the end of the shoulder strap, with Velcro		Hip joint unit
5	Chest belt snap closure	11	Leg shell
6	Chest belt clip	12	Leg belt

(a)



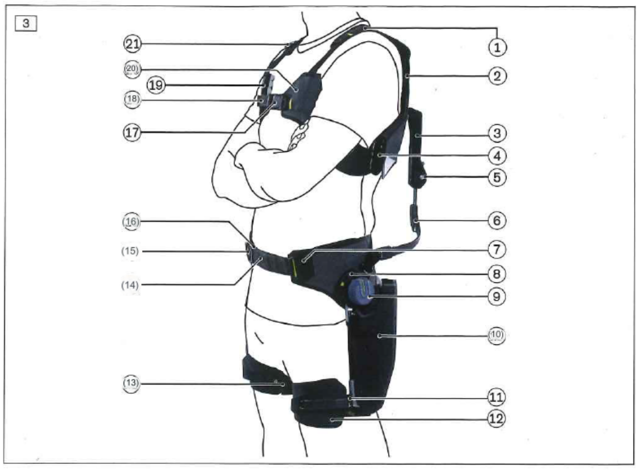
Rear view			
Pos.	Name	**Pos.**	Name
1	Shoulder brace	8	Trunk-pelvis joint
2	Wearing strap	9	Back fabric part with padding
3	Vest velcro closure (back)	10	S-M size adjustment (pelvic belt)
4	Size indication S-XL (back)	11	Pelvic girdle
5	S-XL size adjustment (trunk side)	12	Internal extender cover
6	Size indication S-XXL (arm)	13	Leg belt
7	Fastening closure (rod)		

(b)

Figure 2.1: PAEXO Shoulder components: a) front view, b) back view

can be made to shoulder strap widths and depths, back rod lengths, and waist and thigh belt circumferences [15].

Figure2.1a, Figure2.1b and Figure2.2 show all the components of this exoskelton.



Side view			
Pos.:	Name	**Pos.:**	Name
1	Shoulder brace	12	Leg shell
2	Vest	13	Leg belt
3	Rod system, adjustable	14	Pelvic girdle
4	S-XL size adjustment (torso side) 15		Pelvic belt tightening eyelet
5	Fastening closure	16	Belt fastener for pelvic girdle
6	Trunk-pelvis joint	17	Chest belt snap closure
7	Magnetic pelvic belt closure 18		Chest belt
8	Articulation unit ON/OFF mode of the hip	19	Chest padding
9	Support capacity adjustment wheel	20	Vest with internal chest pads
10	Internal extender cover	21	Shoulder strap clip
11	Extensor joint with leg shell		

Figure 2.2: PAEXO Back components: lateral view

2.1.2 PAEXO Shoulder

The Paexo shoulder is an upper-limb assistive device designed to optimize user mobility, comfort, and assistance. Its primary goal is to provide users with enhanced support while ensuring a high level of freedom of movement. One of the key features of the Paexo shoulder is its passive nature, meaning that it does not rely on powered actuators but rather utilizes its mechanical design to provide assistance.

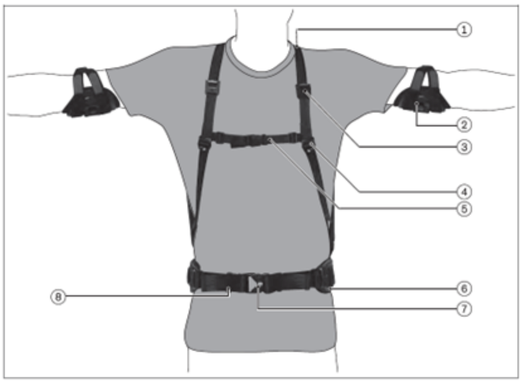
The exoskeleton's main function revolves around reducing the strain on the user's arms by redistributing a portion of their arm weight to the pelvis. This is achieved through the utilization of a hip belt, which acts as a connection point for transferring the weight. The underlying structure of the Paexo exoskeleton involves two crucial components: a support bar and an arm bar. These two bars are linked together by means of a hinge joint, allowing for the necessary range of motion and flexibility.

The design and construction of the Paexo exoskeleton allow users to experience a more comfortable and ergonomic interaction with the device. By providing a mechanism to offload part of the arm weight to the pelvis, users can carry out their activities with reduced fatigue and strain. This can be particularly advantageous in scenarios where repetitive or prolonged arm movements are involved, such as tasks that require lifting or holding objects for extended periods.

This exoskeleton has dimensions of 850 mm in length, 400 mm in width, 200 mm in height, with a weight of 1.99 kg, and it is adjustable to fit different body sizes.

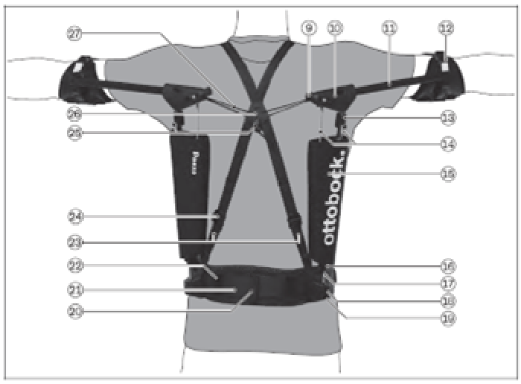
The exoskeleton is fitted snugly against the body, like a backpack, by sliding the arms through the shoulder straps. Then, the pelvic belt should be fastened so that it is positioned above the gluteal muscle at the pelvic level and to prevent it from sliding downward. Following this, the chest belt with a snap closure can be secured. It should be positioned in a way that allows the shoulder straps to rest above the shoulders without being tight, thus avoiding obstacle to arm movement. At this point, by pulling forward the initially resting hooks (attached to magnetic closures), it's possible to position the arm shell under the arm. The arm should be rested on the support and fastened using the arm shell strap that can be variably adjusted.

The assistive structure of the exoskeleton consists of a support bar and an arm bar that are connected through a hinge joint. Its functionality is determined by the passive actuator, which generates an adjustable supporting torque at this joint. Inside this joint, protected by a plastic casing, two elements can be found: a rigid shaft directly connected to the joint unit through a hinge joint, and two springs. The first spring is connected to an adjustment screw positioned on the arm shaft. This screw allows for modifying the stiffness, thereby increasing, or decreasing the supporting force. The second spring rests on the rigid shaft by default. To increase resistance, it's possible to engage the second spring from the rigid shaft to the screw, enabling it to contribute to generating the torque. Further adjustment of the support capacity can be achieved by turning the screw, clockwise to increase the level of support or counterclockwise to decrease the level of support, placed on the joint. All



Front view			
Item:	**Description**	**Item:**	**Description**
1	Shoulder belt	5	Chest strap
2	Arm shell with pad	6	Waist strap pad
3	Magnetic closure parking position	7	Clip fastener
4	Shoulder strap clip	8	Waist strap holder

(a)



Back view			
Item:	**Description**	**Item:**	**Description**
9	Adjustment wheel for level of support	19	Locking clip
10	Joint unit	20	Hanging loop
11	Arm bar	21	Waist strap reinforcement
12	Magnetic closure	22	Waist strap pad hook-and-loop closure
13	Rotation stop	23	Back strap
14	Expander	24	Back strap clip
15	Expander cover	25	Pull clamp
16	Fixing nut	26	Back plate
17	Threaded bar	27	Lace
18	Adjustment unit with ball holder		

(b)

Figure 2.3: PAEXO Shoulder components: a) front view, b) back view

the components of the exoskelton are shown in Figure2.3a and Figure2.3b.

The PAEXO shoulder is designed to provide support torque that adjusts based on the angle of arm elevation. This support torque is highest when the arm is at a 90-degree angle (upper arm horizontal) and decreases as the arm is lowered along the body, eventually reaching zero. This design ensures effective and transparent assistance, maximizing comfort and natural movement for the user [11].

2.2 Test platform

In order to drive forward standards development and promote the adoption of technology, a dedicated test platform has been meticulously designed and developed. This platform serves to replicate a diverse range of industrial tasks, facilitating the evaluation of exoskeletons specifically adapted for occupational purposes. Within this framework, novel experimental methods for testing industrial exoskeletons were conceptualized and put into practice. These methods encompass crucial aspects such as load handling [16], load alignment, force, screwing, and drilling. The creation of these testing methods was underscored by the high priority given to the development of a suitable test protocol. This is especially pertinent considering that the utilization of hand tools has been significantly associated with a notable incidence of Work-Related Musculoskeletal Disorders (WMSDs), particularly affecting the lower back and shoulders.

The platform consists of two shelves that have been adapted and modified to function as a base for simulating tasks. It was designed to facilitate testing on both the shoulders and lower back.

Figure 2.4: Test platform: a) back configuration, b) shoulder configuration

In the first configuration for the shoulders tasks, Figure2.4b, there are three distinct stations. The first station includes a horizontally positioned perforated metal panel above the user, Figure2.5, fitted with threaded inserts to simulate screwing actions. The second station features a front-facing perforated plywood panel, Figure2.6, allowing for a simulated drilling path using a drill. This panel is hinged, providing versatility for various configurations. The third station involves another plywood panel with incorporated blocks where wires can be inserted to simulate cable assembly, Figure2.7.

On the other hand, the second configuration for the lower back is simpler, Figure2.4a. It primarily utilizes the left section of the platform, keeping the drilling panel, previously mentioned, open. This setup enables the simulation of lifting a load, specifically a box from the ground to a surface positioned at a height of 70 cm (the standard height of a workbench).

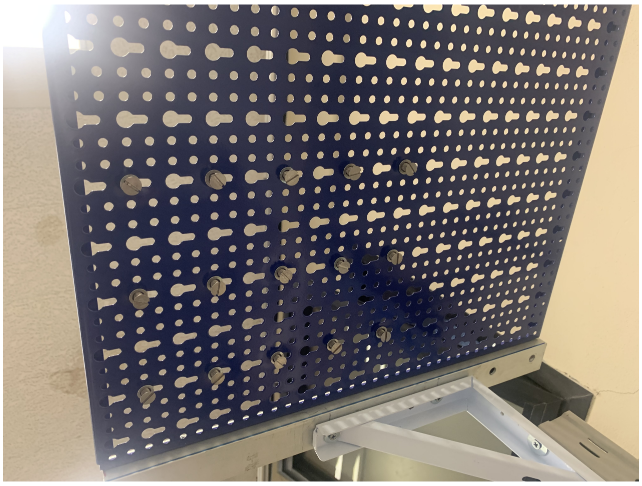


Figure 2.5: Focus on the screwing simulation of the platform

Figure 2.6: Focus on the drilling simulation of the platform

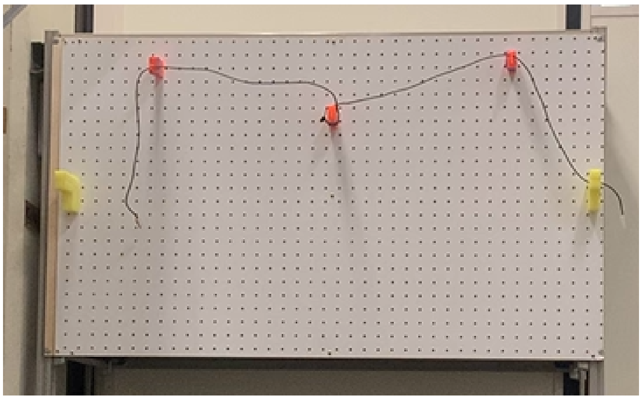


Figure 2.7: Focus on the assembling simulation of the platform

2.3 Evaluation criteria

The main objective of assistive exoskeletons, in our case PAEXO, is to reduce the effort required in the targeted limb. However, it's essential that this reduction in effort does not compromise the overall physical, physiological, or psychological well-being of the users. To ensure a comprehensive evaluation and address all aspects, we recommend including the following criteria into the assessment process [17] [18]:

- Analysis of muscular activity: measurement of the reduction in muscle effort and workload in the targeted limb during the test.
- Metabolic cost analysis: quantification of the reduction in energy expenditure and metabolic load on the targeted limb during the test in order to assess energy consumption.
- Motion analysis: measurement of body kinematics and joint angles for posture analysis.
- Subjective assessment: user opinions on the perceived workload during the test. Feedback on comfort, fit, and overall experience while wearing the exoskeleton together with the psychological well-being of the user.

2.3.1 Analysis of muscular activity

The evaluation of exoskeleton assistance often utilizes electromyography (EMG) as the primary technique to measure muscle activity [19]. Essentially, the greater the assistance provided by the exoskeleton, the more reduction in muscle activity is expected. This reduction can be quantified, for instance, by calculating the relative (percentage) variation of EMG-based metrics during the performance of a task with and without the exoskeleton.

Surface electromyography (sEMG) is a technique that involves placing electrodes on the skin to measure the electrical activity produced by muscles. This method is non-invasive, making it relatively comfortable for individuals undergoing the assessment. It captures and records signals generated by muscle contractions during both periods of rest and movement, allowing for a comprehensive understanding of muscle behavior and activation patterns. Moreover, sEMG plays a significant role in ergonomic evaluations. It helps in understanding muscle strain and fatigue during specific tasks, guiding the design of ergonomic workspaces to prevent musculoskeletal disorders and enhance overall workplace productivity and comfort.

For the analysis of muscular activity we used the BTS FREEEMG 1000. This system is characterized by wireless technology, designed for the acquisition and evaluation of EMG signals and related parameters such as angles, velocities, accelerations, and pressures. It achieves this through the utilization of 8 miniaturized probes, each equipped with extremely lightweight active electrodes. The miniaturized probes,

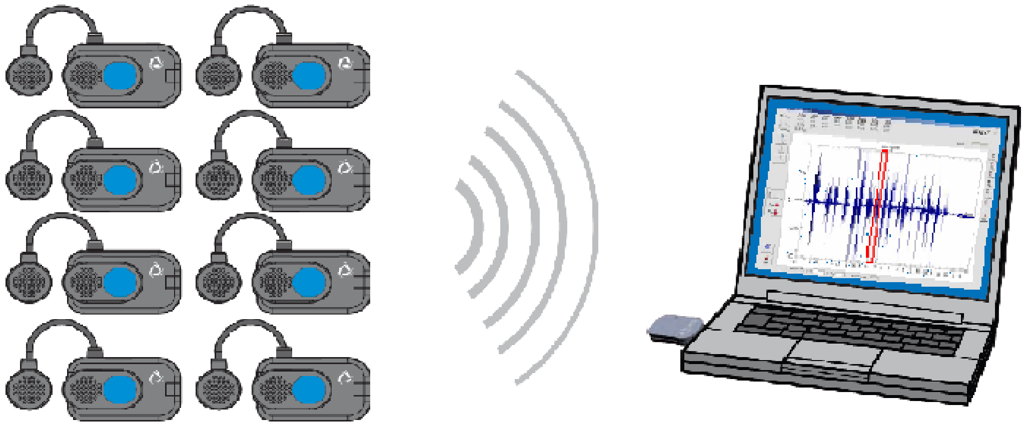


Figure 2.8: FREEEMG system. The EMG sensors transmit real-time signals to the EMG-Analyzer software.

due to their lightweight and active electrodes, expedite patient preparation and provide a higher level of comfort, permitting unhindered movement during data acquisition. The BTS FREEEMG 1000 works together with the BTS EMG-Analyzer, an advanced software application for analyzing electromyographic signals. It encompasses predefined templates for assessments in clinical, sports, and research fields. Additionally, it incorporates an editor for creating processing protocols, Figure2.8.

The collected raw data were saved in CSV format and then downloaded for in depth analysis.

In this study, we create a customized processing protocol inside EMG-Analyzer in which we select specific muscles that better evaluate the efficacy of both the exoskeleton.

Specifically, for what concern the PAEXO shoulder the muscle activity on the following neck, arm, shoulder and back muscles was recorded. Upper Trapezius (UT), Biceps Brachii (BB) and Deltoid medial (MD) were chosen because are the main responsible for supporting the arm weight and for overhead working. Furthermore, for the upper limb exoskeleton that transfers force to the pelvis, we also monitored the activity of the Erector Spinae (ES) muscles [11].

While, for PAEXO back muscle activity of muscle groups crucial to lifting tasks was measured. These included the Erector Spinae Longissimus (ESL) Erector Spinae Ileocostalis (ESI), Semitendinosus (ST), and Rectus Abdominis (RA), in both side of the body. The selection of these muscles was based on their role in generating torque around the hip and spine (ESL, ESI, ST), as well as their relevance in monitoring potential compensatory muscle activity (RA) [13].

2.3.2 Energy consumption analysis

Localized measures, as discussed in prior sections, provide valuable insights into the precise biomechanical impacts of an exoskeleton. However, it's important to acknowledge that these measures have limitations. Firstly, they may not consider potential cognitive fatigue induced by exoskeleton use. Secondly, unforeseen side effects, unmonitored due to the inability to track all muscles, could occur. To comprehensively assess the exoskeleton's effects, it's essential to evaluate global physiological strain as a complementary and validating approach. The gold standard metric for this evaluation is energy expenditure.

For the analysis, we utilized the Empatica E4 wristband, Figure2.9a Figure2.9b, a wearable wireless device specifically designed for continuous and real-time data acquisition to monitor a range of physiological signals. This wristband is equipped with four sensors, including:

- an electrode for measuring Electrodermal Activity (EDA);
- a 3-axis accelerometer;
- a temperature sensor;
- a photoplethysmography (PPG) sensor;

The PPG sensor captures data related to blood volume pulse (BVP), which is then utilized to calculate heart rate (HR) and inter-beat interval (IBI) measurements.

To facilitate data collection, participants wore the E4 wristband on their non-dominant hand, in adherence to the manufacturer's guidelines. This placement was chosen to minimize the likelihood of motion artifacts that could potentially affect the data quality [20].

The collected data was uploaded using the Empatica Manager software and subsequently transferred to Empatica Connect for further in-depth analysis. The raw data, available in CSV format, could then be downloaded and analyzed for various research purposes. In particular in in this study we focus on the heart rate and electrodermal activity.

Electrodermal activity (EDA) is the measurement of electrical changes occurring at the skin's surface, which result from signals sent by the brain to the skin. When an individual experiences emotional arousal, heightened cognitive workload, or physical exertion, the brain signals the skin to increase sweating levels. Although the sweat may not be noticeable on the skin's surface, the electrical conductance significantly increases as the sweat glands start to fill below the surface. In terms of measurement, EDA can be assessed electrically through various parameters such as skin potential, resistance, conductance, admittance, and impedance [21]. The Empatica E4 device captures electrical conductance, which is the inverse of resistance, across the skin. This is achieved by applying a tiny electric current between two electrodes that are in contact with the skin.

(a) (b)

Figure 2.9: Empatica E4 wristband: a) front view, b) back view

2.3.3 Motion analysis

It's crucial to investigate potential modifications in users' movements resulting from exoskeleton use to assess their implications. For example, alterations in natural movement patterns may lead to awkward postures or necessitate a learning period for adapting to a new motor strategy. Understanding these changes is essential for optimizing exoskeleton design and ensuring user safety and effectiveness. The evaluation of an exoskeleton's effect on movement strategy often centers around joint kinematics, primarily assessed through metrics like range of motion or maximal value. These parameters provide essential information regarding alterations in movement patterns and mechanics influenced by the exoskeleton.

To study these parameters an optical motion capture system with twelve cameras was used. The system used is the Optitrack, a a leading motion capture technology company that provides high-precision 3D motion tracking systems. The system involves specialized cameras, Figure2.10, markers, and software, allowing for the precise tracking and recording of movements in 3D space. The cameras work together with the reflective markers placed on subject to be tracked. The markers reflect light emitted by the cameras, enabling them to precisely determine the position and orientation of the markers in real-time. The Optical Data Processor (ODP) is the nerve center of the system. It processes the data captured by the cameras, instantly identifying markers and their exact positions in the 3D space. However, to transform this raw data into meaningful insights, the motion capture system uses a sophisticated tool, the Motive software. Motive acts as the bridge between the captured data and the user, providing a comprehensive platform for setup, calibration, real-time data visualization, recording, and in-depth analysis.

Moreover, to assessing joint angles from Motive raw data, Optitrack developed in collaboration with STT Systems, InSight, a software that offers a streamlined workflow for effortless marker tracking, data collection, real-time analysis and reporting. STT InSight receives 3D marker position data (not labeled) from Motive.

Figure 2.10: Optitrack cameras

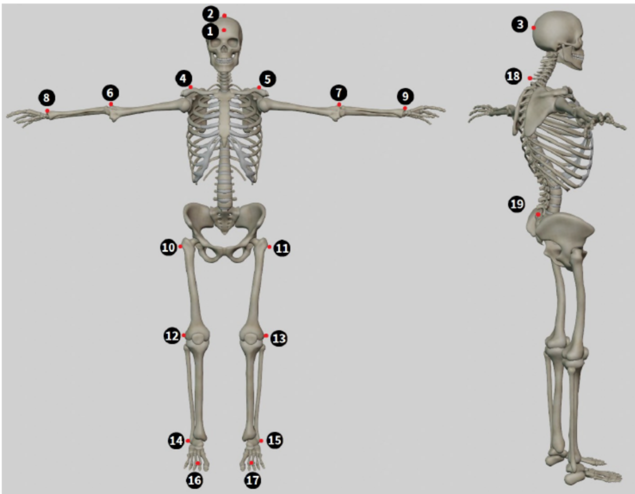
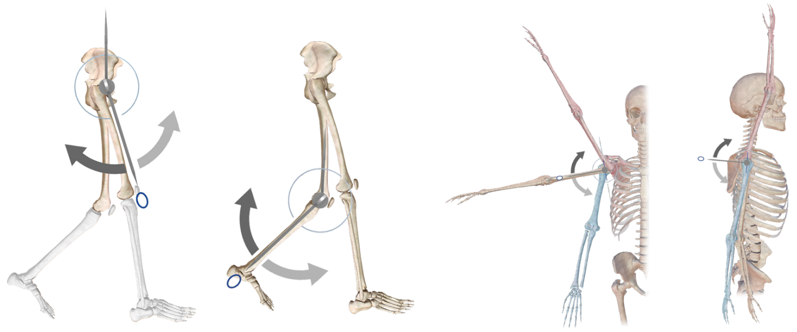


Figure 2.11: Full body markerset

Using preconfigured markersets, it automatically labels the markers based on the selected protocol. Additionally, it calculates joint locations, bone positions, and orientations with high accuracy. For this study, we opted for the full body markerset consisting of nineteen markers, see Figure2.11. This protocol enabled us to conduct a comprehensive full-body analysis, focusing on specific aspects such as shoulder joint angles of flexion/extension(Figure2.12d) and abduction/adduction (Figure2.12c) during the analysis of the upper limb. While, it facilitated the evaluation of knee and hip flexion/extension angles (Figure2.12bFigure2.12a) when analyzing the back.

2.3.4 Subjective assessment

Metrics within the subjective domain are designed to assess the user experience and overall impression of the wearer concerning comfort, discomfort, and the assistance provided by the exoskeleton. Subjective questionnaires play a crucial role in understanding whether the exoskeleton effectively reduces perceived difficulty and effort during the execution of tasks. These assessments are vital in capturing the human-centric aspect of exoskeleton evaluation, shedding light on user perception



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

Figure 2.12: Detailed joint angles: a) hip flexion/extension, b)knee flexion/extension, c) shoulder abduction/adduction and d) shoulder flexion/extension

and satisfaction. Subjective metrics are useful for evaluating wearing comfort, a factor that significantly impacts task execution, as well as the perceived musculoskeletal effort, which in turn affects perceived pain, stress, and fatigue. Subjects are typically presented with a visual analog scale after completing a specific task both with and without the exoskeleton, providing valuable insights into their perceptions and experiences. This approach offers a standardized way to quantify subjective experiences and preferences related to exoskeleton use [19].

In this study, perceived exertion was assessed using the BORG CR-10 scale [22]. Specifically, participants were prompted to indicate their perceived fatigue at two distinct points during the task. They were asked to provide a score ranging from one to ten, aligning with the Borg scale they had been introduced to earlier, Table 2.1. This approach allowed for a quantified measurement of the participants' perceived fatigue levels at those specific moments during the task.

BORG CR-10 SCALE	
0	nothing at all
0.5	Extremely weak (hardly noticible)
1	Very weak
2	Weak (light)
3	Moderate
4	
5	Strong (heavy)
6	
7	Very strong
8	
9	
10	Extremely strong

Table 2.1: Post-experimental questionnaire

Furthermore, as the Borg scale primarily addresses physical effort, to evaluate the overall perceived workload comprehensively, we utilized the NASA Task Load Index (NASA-TLX) [23]. This index encompasses six aspects: mental demand, physical

POST-EXPERIMENTAL QUESTIONNAIRE		
N.	Class	Question
1	CO	Wearing the exoskeleton makes me feel more confident during movements
2	FU	I think constant use of the exoskeleton can improve my dexterity
3	CL	I think I lose my independence by wearing the exoskeleton
4	FU	I think the exoskeleton makes me lose time
5	FU	I think the exoskeleton helps me move in an ergonomic way
6	CL	I think using the exoskeleton requires a certain mental effort
7	FU	I don't feel free in my movements wearing the exoskeleton
8	CL	I think a longer training period is necessary
9	PE	I feel less tired if I use the exoskeleton to perform tasks
10	CL	Wearing the exoskeleton makes me feel more powerful
11	PE	I think the exoskeleton requires more physical effort
12	CL	I think the exoskeleton is easy to use
13	FU	I feel physically restricted by the exoskeleton
14	CO	I feel I can rely on the exoskeleton to assist my movements
15	PE	I feel uncomfortable using the exoskeleton
16	CL	The exoskeleton has been useful to me in performing tasks

Table 2.2: Post-experimental questionnaire - scores

demand, temporal demand, performance, effort, and frustration, each evaluated on a 20-point scale. However, recognizing that acceptance of an exoskeleton is influenced by factors beyond perceived workload, such as usability, comfort, and image, we developed a tailored questionnaire. This questionnaire was designed based on insights from a previous study [11], aiming to collect a holistic understanding of the wearer's perception and experience with the exoskeleton. The questionnaire consist in sixteen different questions each assessed with a 10-point scale and divided in four categories, Table 2.2:

- CO: Confidence
- CL: Cognitive Load
- FU: Functionality
- PE: Physical Effort

Furthermore, to assist users in completing the questionnaire, we provided guidelines for each question, as illustrated in Table 2.3.

2.4 Data Processing

This section describes the methods used for processing the previously mentioned data collected during the experiment.

	Scores			
N.	0	3	7	10
1	not confident at all	slightly confident	somewhat confident	completely confident
2	not improved at all	slightly improved	somewhat improved	greatly improved
3	totally lost independence	lost a lot of independence	lost some independence	didn't lose independence at all
4	only wasted time	wasted a lot of time	wasted some time	didn't waste time at all
5	no help	little help	some help	total help
6	a lot of mental effort	quite a bit of mental effort	some mental effort	no mental effort
7	not free at all	slightly free	somewhat free	completely free
8	Definitely yes	much more time needed	just a little more time needed	no
9	much more tired	a bit more tired	less tired	much less tired
10	not powerful at all	slightly powerful	somewhat powerful	very powerful
11	a lot of physical effort	quite a bit of physical effort	some physical effort	no physical effort
12	not easy at all	slightly easy	somewhat easy	very easy
13	totally restricted	quite restricted	slightly restricted	not restricted at all
14	no trust at all	little trust	some trust	complete trust
15	totally uncomfortable	quite uncomfortable	slightly uncomfortable	not uncomfortable at all
16	not useful at all	slightly useful	somewhat useful	very useful

Table 2.3: Post-experimental questionnaire - scores

2.4.1 EMG signals

EMG data were recorded with EMG-Analyzer at 1000 Hz, saved in CVS format and then downloaded. After recording, raw data were post processed in Python. The EMG signals, initially, were high-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 20 Hz. Following this, a low-pass filter was applied using a 4th order Butterworth filter with a cut-off frequency of 450 Hz. The signals were then rectified and normalized by the maximum value reached during the task (both NE and WE) for each participant. Finally the Root Mean Square (RMS) of each signal was calculated in a moving window of 2 seconds with an overlap of 1.8 seconds. The EMG signals from the back evaluation were also processed to remove the 2-minute pauses between each phase. Subsequently, they were divided for separate analysis, focusing on each phase individually.

2.4.2 Heart rate and Electro dermal activity signals

Heart rate and electrodermal activity data were recorded at sampling frequencies of 1 Hz and 4 Hz, respectively, using the Empatica wristband. The recorded data was then downloaded in CSV format for further processing. The signals were normalized using the baseline signal collected before each test [24].

2.4.3 Motion capture data

Motion capture data were acquired from motive at 360 Hz and then developed in STT InSight to evaluate joint angles. Joint angles were then postprocessed in MATLAB to calculate maximal and minimal angle.

2.5 Statistics

The statistical analysis was conducted using MATLAB. The collected data, including RMS from EMG signals, heart rate, electrodermal activity, and joint angles, was checked for normality using the Lilliefros test. A significance level of 5% is adopted for all statistical tests. Data that followed a normal distribution, a paired sample t-test was utilized to compare the two sessions (with exoskeleton and without exoskeleton). Conversely, for variables that violated the normality assumption, a Wilcoxon signed-rank test was employed.

2.6 Participants

Ten healthy males volunteered for the experiment. On average, their age was 29.6 years (SD = 7.9 years), their height was 180.2 cm (SD = 6.7 cm), and their body mass averaged at 76.8 kg (SD = 11.5 kg). Eight of the participants were right-handed, while two were left-handed. None of the participants had prior experience with exoskeletons. All volunteers provided informed consent and confirmed the absence of any orthopedic issues. The study was approved by the ethics committee.

2.7 Protocol

After the initial general information data acquisition, participants were given comprehensive instructions regarding the adjustment and utilization of the exoskeleton. They were encouraged to take the time to become familiar with operating both the exoskeleton by engaging in activities like walking around and lifting external loads for some minutes. Subsequently, Empatica sensor were applied and normalization values were obtained for a duration of around 60 seconds.

From this point onward, the protocol will be divided into two parts, each corresponding to one of the exoskeletons. Participants will complete both parts separated by a break of approximately 10 minutes. Additionally, participants will be divided into two groups: the first group will begin with the back exoskeleton, while the second group will start with the shoulder exoskeleton. This division is designed to ensure a balance in the effects experienced, with specific consideration given to mitigating potential fatigue throughout the study.

2.7.1 Back protocol

As a first step, electromyography electrodes are placed on the muscles of interest, as outlined in the "Evaluation Criteria" section, following SENIAM recommendations [25]. Simultaneously, participants are introduced to the Borg Scale and briefed on the various steps of the test.

The test for the PAEXO back evaluation consist in the action of lifting and subsequently placing a crate from the floor onto a shelf set at a height of 70 cm, and

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

Figure 2.13: Lifting movement

vice versa.The lifting movement is represented in Figure2.13. The test is structured into three phases: the first phase involves lifting a weight of 6 kg for a duration of five minutes, the second phase includes lifting a weight of 12 kg for four minutes, and finally, the third phase necessitates lifting a weight of 20 kg for three minutes. A two-minute break is provided for participants between each phase. The total duration of the the trail was around 16 minutes. Acoustic signals (beeps) guide the participants throughout the entire test, marking the initiation and conclusion of each phase. Another beeps during each phase was sounding every 7-second. Clear instructions were given to the participants, emphasizing the execution of a single lifting or placing movement of the crate at each beep sound. This standardization aimed to ensure a consistent number of repetitions for each participant and to streamline the processing and analysis of the collected data. All participants performed the task both wearing the exoskeleton (EXO), and without wearing it (NOEXO). Between the two sessions, participants were instructed to rest for a duration of 5/10 minutes, intended to prevent excessive fatigue. Participants were divided into two groups. One group initiated the experiment wearing the exoskeleton and then proceeded to the second session without it. Conversely, the second group began without wearing the exoskeleton and then wore it for the second session. This approach was adopted to balance the resulting data and account for any potential order effects.

After completing both sessions, participants were instructed to fill out the post-experimental questionnaire.

In the final step, motion data was evaluated. Participants were instructed to wear the motion capture suits in which the nineteen markers of the full-body markerset were then carefully placed. They were then asked to replicate every step of the previous session, with each step lasting 100 seconds. Actually, participants were directed to perform the lifting tasks for the three different weights (6 kg, 12 kg, and 20 kg) both with and without the exoskeleton. This was to be done in accordance with the auditory cues provided by the beeps every 7 seconds, replicating the tasks they performed earlier but now under the motion capture setup (Figure2.14).

(a) (b) (c)

Figure 2.14: Lifting movement with motion capture suit

2.7.2 Shoulder protocol

As a first step, electromyography electrodes are placed on the muscles of interest, as outlined in the "Evaluation Criteria" section, following SENIAM recommendations [25]. Simultaneously, participants are introduced to the Borg Scale and briefed on the various steps of the test.

For what concern the PAEXO shoulder evaluation, the test consist in three different simulation task:

- Simulation of a screwing actions
- simulation of a drilling actions
- Simulation of a cable assembly

The screwing simulation is carried out using a specialized screwdriver on the horizontally positioned perforated metal panel above the user ("Test platform" section). in this panel were positioned threaded inserts in which the participants were able to screw and unscrew the screws(Figure2.15a). On the other hand, the drilling simulation required participants to insert the tip of a turned-off drill into designated holes,that follow a specific path, in a front facing perforated plywood panel (Figure2.15b). After the path was complete, were asked to the participants to insert the tip of the drill in ten different holes in the above metal panel, allowing the choice of holes without suggesting a specific path. Once they completed the drilling simulation above, participants resumed by following the initial path in the front-facing panel. Lastly, the final task involved a cable assembly simulation. Participants were tasked with inserting cables into specific blocks to construct an electrical circuit. After all wires were properly inserted, participants were then required to unplug each wire and place them down. Subsequently, they would repeat the process by beginning with the insertion of the cables again.

The test required each task to be performed for a 2-minute duration, constituting a cycle. Participants completed this cycle twice consecutively, resulting in a total test duration of 12 minutes. Also in this case, acoustic signals (beeps) guide the participants throughout the entire test, marking the initiation and conclusion of each task.

In the same way it was done for the back protocol, all participants performed the task both wearing the exoskeleton (EXO), and without wearing it (NOEXO). Between the two sessions, participants were instructed to rest for a duration of 5/10 minutes, intended to prevent excessive fatigue. Participants were divided into two groups. One group initiated the experiment wearing the exoskeleton and then proceeded to the second session without it. Conversely, the second group began without wearing the exoskeleton and then wore it for the second session. This approach was adopted to balance the resulting data and account for any potential order effects.

After completing both sessions, participants were instructed to fill out the post-experimental questionnaire.

In the final step, motion data was evaluated. Participants were instructed to wear the motion capture suits in which the nineteen markers of the full-body markerset were then carefully placed.

In the final step, motion data was evaluated. Participants were instructed to wear motion capture suits with the nineteen markers of the full-body markerset meticulously positioned on their bodies. Participants were instructed to replicate a drilling action for a duration of 100 seconds, commencing with the drill in front of them. They were then directed to extend their arms, move the drill overhead, and subsequently return it to the initial position, simulating a drilling motion (Figure2.16). This was to be done following the auditory cues provided by beeps at 7-second intervals. Each beep marked the execution of both movements - first in front and then moving the drill overhead. Participants synchronized their movements with these auditory cues.

In conclusion, after the preparation phase where participants became familiar with the exoskeletons and completed the consent and initial general information questionnaires, they proceeded to perform both tests, wearing and not wearing the exoskeleton. Following the tests, participants completed the post-experimental questionnaire. The overall duration of the experiment was approximately three hours. In Figure2.17, a schematic representation of the test protocol is displayed.

(a) (b)

Figure 2.15: Screwing and drilling simulations

(a) (b) (c)

Figure 2.16: drilling simulation with motion capture suit

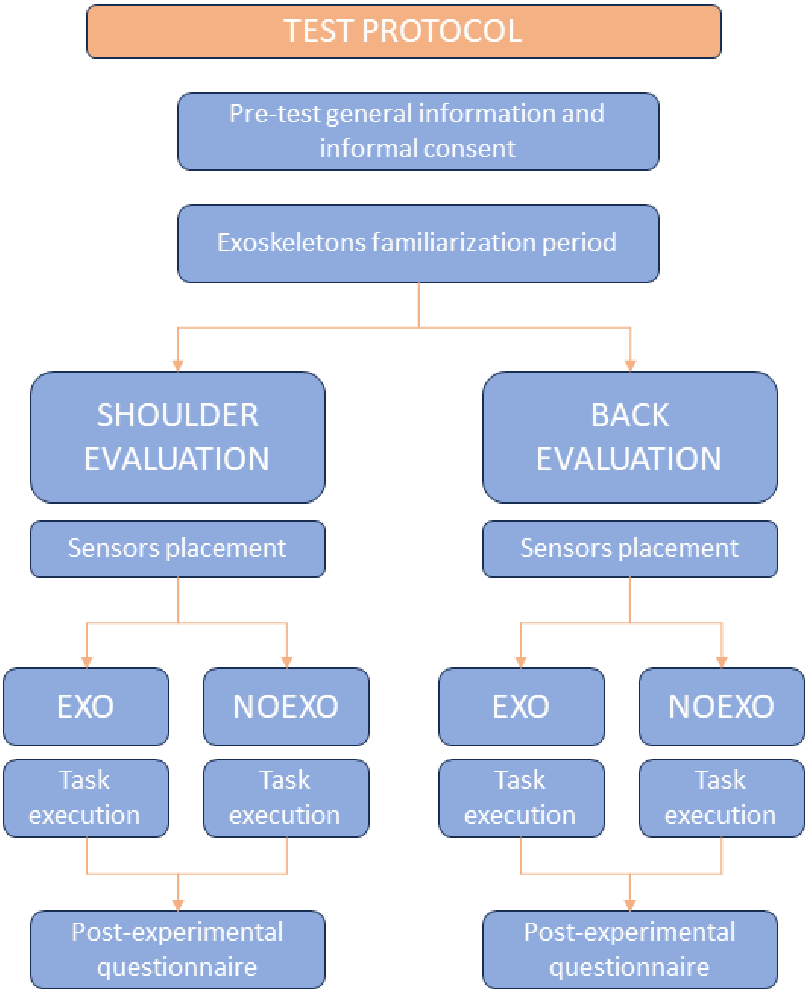


Figure 2.17: Schematic representation of the test protocol

Chapter 3

ON FIELD TESTING

To enhance the study, we conducted an on-field testing phase in collaboration with a local company. This test followed a different protocol compared to the one described above for the laboratory tests. The divergence was primarily due to time constraints associated with on-field testing, including worker availability, the company's work shifts, and the practicality of executing specific tests within those constraints. Furthermore, the effectiveness of only the PAEXO back was assessed. This was because the test was conducted in the company's warehouse, where the tasks primarily involved lifting and moving, rather than overhead work. In this on-field test, data from EMG, Empatica, and intermediate as well as final questionnaires were analyzed. Due to limitations arising from on-field tests and the workers' work attire, it was only possible to analyze the muscles of the back. Therefore, EMG electrodes were applied to the erector spinae longissimus (ESL), erector spinae ileocostalis (ESI), and latissimus dorsi (LD) muscles.

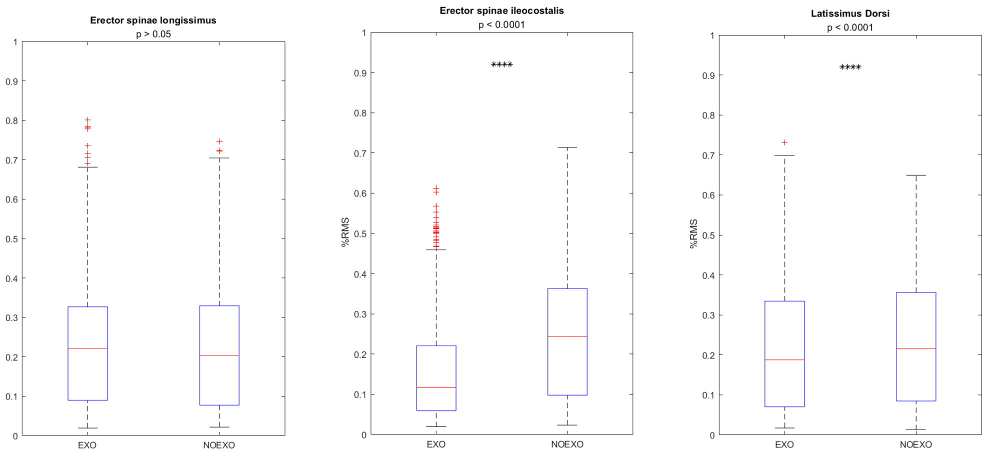
The on-field protocol commenced similarly to the laboratory procedure, where participants provided general information and explicit consent. This was followed by familiarization with the exoskeleton and the application of sensors. The actual test involved lifting a 25 kg package continuously for eight minutes, both with and without the exoskeleton, to evaluate its effectiveness.

Throughout the tests, participants responded to the Perceived Exertion Questionnaire using the BORG CR-10 scale. Finally, after the test, participants completed the post-experimental questionnaire.

Due to limitations, only two healthy males were available for the on-field experiment. On average, their age was 37.5 years (SD = 9.2 years), with a height of 184.5 cm (SD = 6.4 cm), and a body mass averaging 81.0 kg (SD = 11.3 kg). Both participants were right-handed and had no prior experience with exoskeletons. All volunteers provided informed consent and affirmed the absence of any orthopedic issues.

Below are the results obtained from this on-field test.

Figure3.1a, Figure3.1b and Figure3.1c shows the muscles activation, for all participants for both trial: when utilizing the exoskeleton (EXO) and when not using it (NOEXO). Using the exoskeleton resulted in a notable decrease in muscle activation. The erector spinae ileocostalis (ESI) showed a significant reduction ($p < 0.001$), as did the latissimus dorsi (LD) ($p < 0.0001$), when compared to not using the



(a) (b) (c)

Figure 3.1: Muscle activity with the exoskeleton (EXO) and without it (NOEXO) during on field testing of: a)erector spinae longissimus, b) erector spinae ileocostalis, c)latissimus dorsi. Stars indicate significant differences (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p < 0.0001$).

exoskeleton. While, any statistically relevant differences were found in the erector spinae longissimus (ESL) activation.

In terms of metabolic cost, Figure3.2 presents the heart rate (HR) and electrodermal activity (EDA) measured during the test, with and without the exoskeletons. The results indicate a non-significant difference for HR ($p > 0.05$), but a significant increase in EDA ($p < 0.0001$) during the task with the exoskeleton compared to without.

Table3.1 report the global scores of the perceived exertion questionnaire at two instant of the test, both with and without the exoskeleton.Using the BORG CR-10 scale, it was observed that the exoskeleton provided support, resulting in a 35% reduction in perceived fatigue when utilizing compared to conditions when the exoskeletons were not employed.

Lastly, Table3.2 presents the overall and detailed scores (across the 4 factors) of the post-experimental questionnaire for the participants. The global scores, calculated as the average of the scores across the 4 factors for each participant, were 6.7 (SD = 0.6). Of particular interest are the scores for confidence (CO) and physical effort (PE), which were 7.3 (SD = 1.8) and 7.3 (SD = 2.7), respectively.

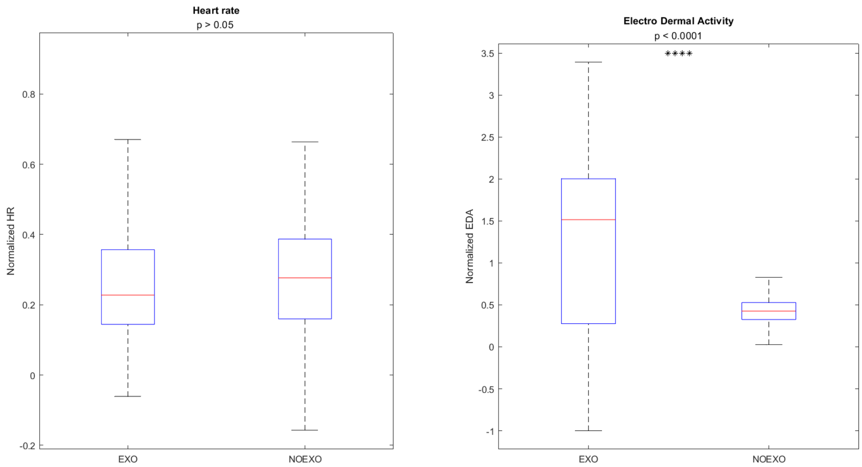


Figure 3.2: Heart rate and electro dermal activity, during both exoskeletons evaluation, with and without exoskeleton. Stars indicate significant differences (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

	BACK					
	EXO			NOEXO		
	I	II	TOT	I	II	TOT
Mean	4.0	4.0	4.0	6.0	6.3	6.1
Std	1.4	0.0	0.7	1.4	1.8	1.6

Table 3.1: Global scores of the perceived exertion questionnaire with the exoskeleton (EXO) and without it (NOEXO)

	BACK				
	CO	FU	CL	PE	TOT
SUBJECT 1	8.5	7.8	6.9	9.2	8.1 (1.0)
SUBJECT 2	6.0	4.4	5.8	5.3	5.4 (0.7)
TOT	7.3 (1.8)	6.1 (2.4)	6.4 (0.8)	7.3 (2.7)	6.7 (0.6)

Table 3.2: Post-experimental questionnaire detailed scores, across the 4 factors: CO: Confidence, CL: Cognitive Load, FU: Functionality, PE: Physical Effort

Chapter 4

RESULTS

In this chapter, the results obtained in the study are presented. The results are organized based on the various evaluation criteria defined earlier.

4.1 Analysis of muscular activity

Figure4.1 display all the muscles activation, in the case of the PAEXO back evaluation, for all participants for both trial: when utilizing the exoskeleton (EXO) and when not using it (NOEXO). The results take in consideration all the three phases (6 Kg, 12 Kg and 20 Kg). Using the exoskeleton resulted in a notable decrease in muscle activation. The erector spinae longissimus (ESL) showed a significant reduction ($p < 0.001$), as did the erector spinae ileocostalis (ESI) ($p < 0.0001$), when compared to not using the exoskeleton. Additionally, the semitendinosus (SE) displayed a substantial reduction with the exoskeleton ($p < 0.0001$). It's important to note that although the rectus abdominis (RA) exhibited a significant reduction, it was not considered due to challenges with electrode attachment during signal acquisition.

In addition, the muscles activation were analyzed and reported separately for each phase.

Figure4.2 shows the muscles activation for 6 Kg lifting phase. In this case the back muscles, ESL and ESI, had a significant increase wearing the exoskeleton ($p < 0.0001$). However, the SE had a significant reduction wearing the exoskeleton ($p < 0.0001$). Figure4.3 display significant difference in all the three muscles responsible for the lifting using 12 Kg, with a lower activation of ESL and SE, and an higher activation of ESI using exoskeleton. At last, Figure4.4 shows the muscles activation for 20 Kg lifting phase, and resulted in a reduction of all the three muscles (ESL ESI SE) using the exoskeleton, when compared to not using the exoskeleton. Table4.1 presents the results of this analysis, highlighting the % change between the two trials of the PAEXO back evaluation.

Figure4.5 shows the muscles activation, in the case of the PAEXO shoulder evaluation, for all participants for both trial: when utilizing the exoskeleton (EXO) and when not using it (NOEXO).Using the exoskeleton resulted in a statically significant difference ($p < 0.0001$) for all the muscles, ESL, deltoideus medius (DM), trapezius descendens (TD) and biceps brachii (BB). An analysis specifically focused

	Back muscle activity (%RMS)					
	6 Kg					
	EXO		NOEXO			
	mean	sd	mean	sd	NOEXO - EXO (%NOEXO)	P-val (U-stat)
Erector Spinae Longissimus	0.25	0.21	0.22	0.22	-16.3	7.653e-45 (1.075e+08)
Erector Spinae Ileocostalis	0.24	0.21	0.22	0.21	-11.4	9.076e-86 (1.113e+08)
Semitendinosus	0.23	0.21	0.24	0.22	4.1	1.383e-05 (9.508e+07)
	12 Kg					
	EXO		NOEXO			
	mean	sd	mean	sd	NOEXO - EXO (%NOEXO)	P-val (U-stat)
Erector Spinae Longissimus	0.23	0.21	0.24	0.24	3.0	7.838e-36 (2.766e+07)
Erector Spinae Ileocostalis	0.22	0.20	0.21	0.22	-3.1	2.415e-04 (3.020e+07)
Semitendinosus	0.18	0.18	0.26	0.24	32.0	2.106e-04 (3.232e+07)
	20 Kg					
	EXO		NOEXO			
	mean	sd	mean	sd	NOEXO - EXO (%NOEXO)	P-val (U-stat)
Erector Spinae Longissimus	0.23	0.22	0.26	0.25	11.5	8.979e-14 (6.902e+07)
Erector Spinae Ileocostalis	0.20	0.21	0.24	0.23	15.9	4.195e-03 (6.673e+07)
Semitendinosus	0.25	0.21	0.25	0.23	1.5	8.577e-93 (5.511e+07)
	6 Kg + 12 kg + 20 Kg					
	EXO		NOEXO			
	mean	sd	mean	sd	NOEXO - EXO (%NOEXO)	P-val (U-stat)
Erector Spinae Longissimus	0.18	0.17	0.21	0.21	12.2	4.217e-24 (5.327e+08)
Erector Spinae Ileocostalis	0.16	0.15	0.17	0.18	11.3	4.839e-03 (5.509e+08)
Semitendinosus	0.13	0.15	0.21	0.20	35.9	0.000e+00 (4.278e+08)

Table 4.1: Mean and standard deviations (sd) of the RMS muscle activity during the two trail (EXO and NOEXO) and the % change, the p-value of the Mann-Whitney-Wilcoxon test two-sided and U-stat when analysing PAEXO back.

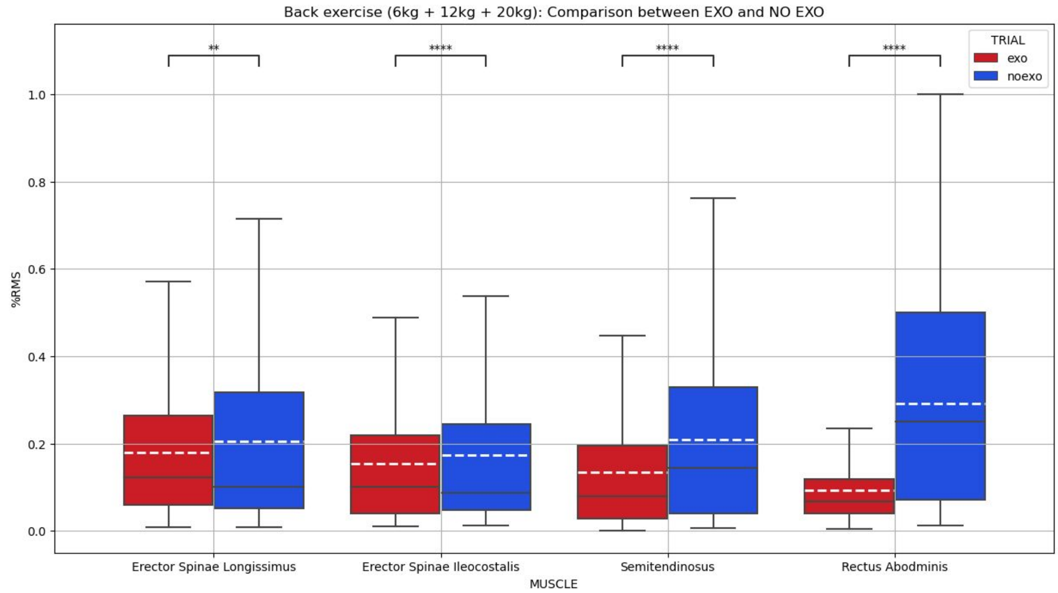


Figure 4.1: Muscle activity, during PAEXO back evaluation, with the exoskeleton (EXO,red) and without it (NOEXO,blue). Stars indicate significant differences (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

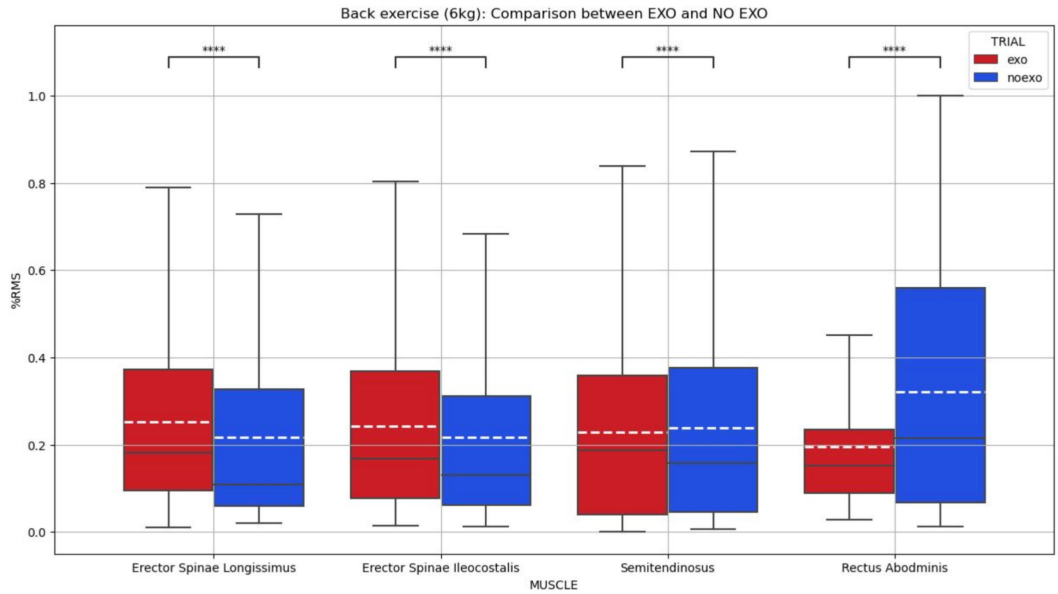


Figure 4.2: Muscle activity of 6Kg lifting phase, with the exoskeleton (EXO,red) and without it (NOEXO,blue). Stars indicate significant differences (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

on the dominant hand (side) confirmed the previously obtained results, as it shown in Figure4.6. Table4.2 presents the results of this analysis, highlighting the % change between the two trials of the PAEXO shoulder evaluation.

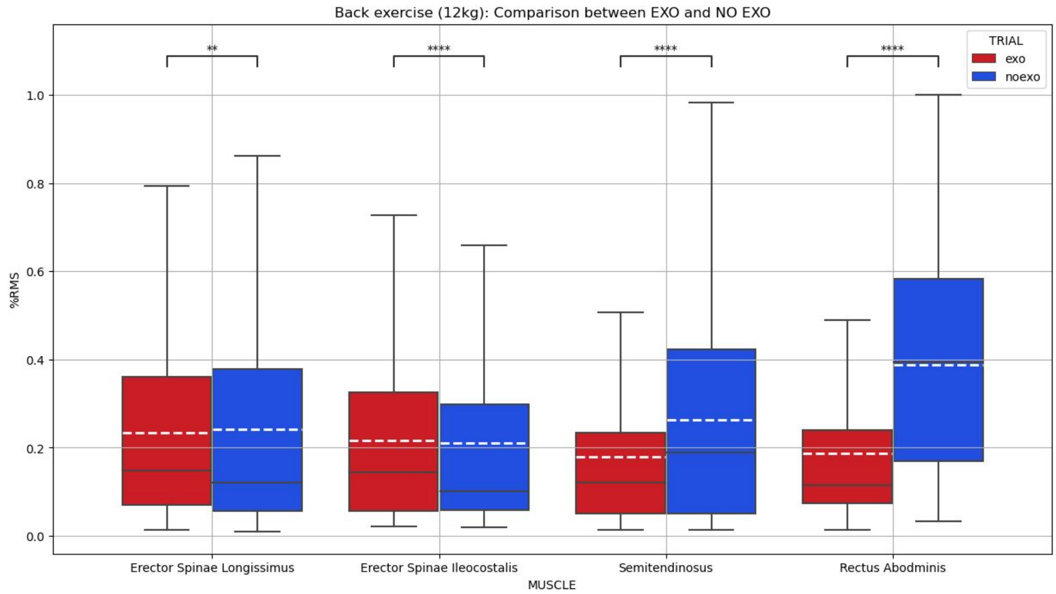


Figure 4.3: Muscle activity of 12Kg lifting phase, with the exoskeleton (EXO,red) and without it (NOEXO,blue). Stars indicate significant differences (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

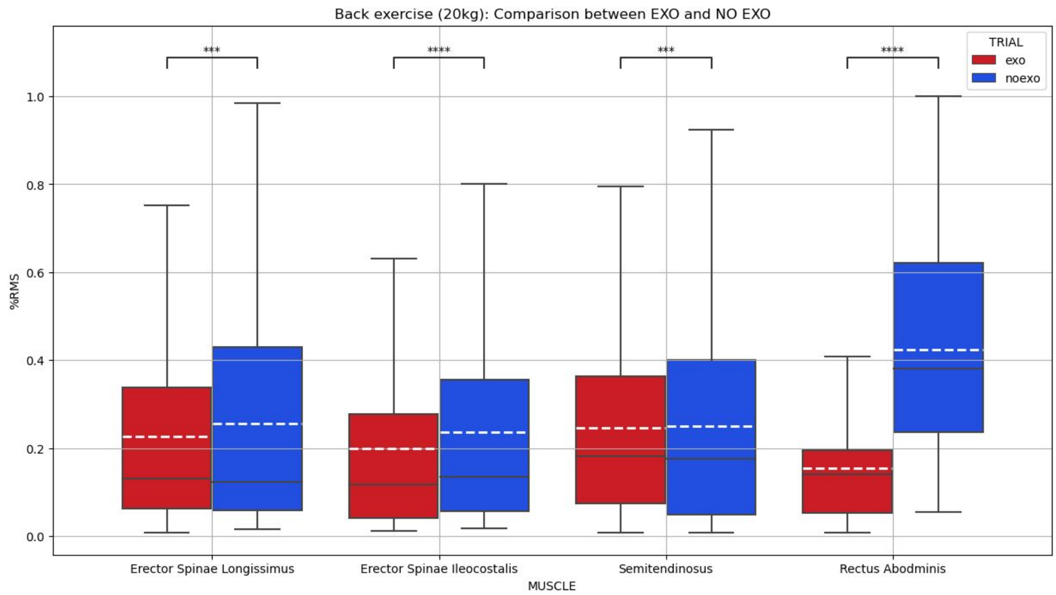


Figure 4.4: Muscle activity of 20Kg lifting phase, with the exoskeleton (EXO,red) and without it (NOEXO,blue). Stars indicate significant differences (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

	Shoulder muscle activity (%RMS) (Dominant side)					
	EXO		NOEXO			
	mean	sd	mean	sd	NOEXO - EXO (%NOEXO)	P-val (U-stat)
Erector spinae longissimus	0.18	0.15	0.21	0.15	12.6	6.008e-56 (5.704e+08)
Deltoideus medius	0.25	0.19	0.28	0.21	10.4	1.222e-224 (5.270e+08)
Trapezius descendens	0.44	0.16	0.47	0.16	6.4	1.513e-214 (5.290e+08)
Biceps brachii caput longus	0.19	0.13	0.21	0.13	10.0	5.547e-169 (5.385e+08)

Table 4.2: Mean and standard deviations (sd) of the RMS muscle activity during the two trail (EXO and NOEXO) and the % change, the p-value of the Mann-Whitney-Wilcoxon test two-sided and U-stat when analysing PAEXO shoulder.

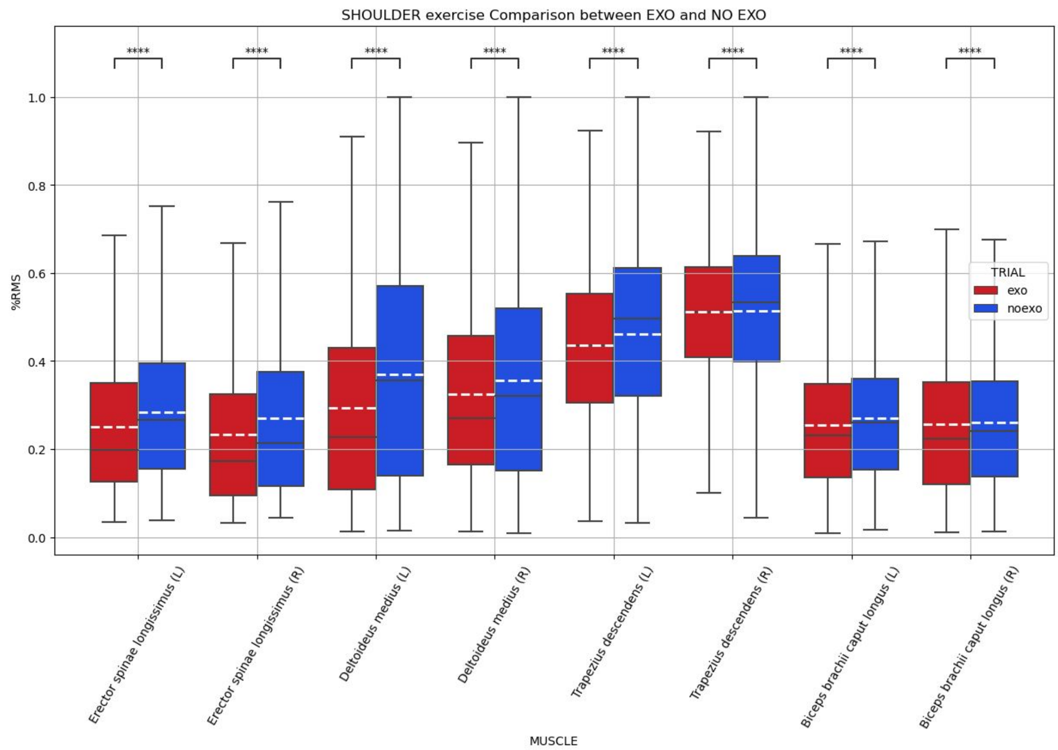


Figure 4.5: Muscle activity, during PAEXO shoulder evaluation, with the exoskeleton (EXO,red) and without it (NOEXO,blue). Stars indicate significant differenceso (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

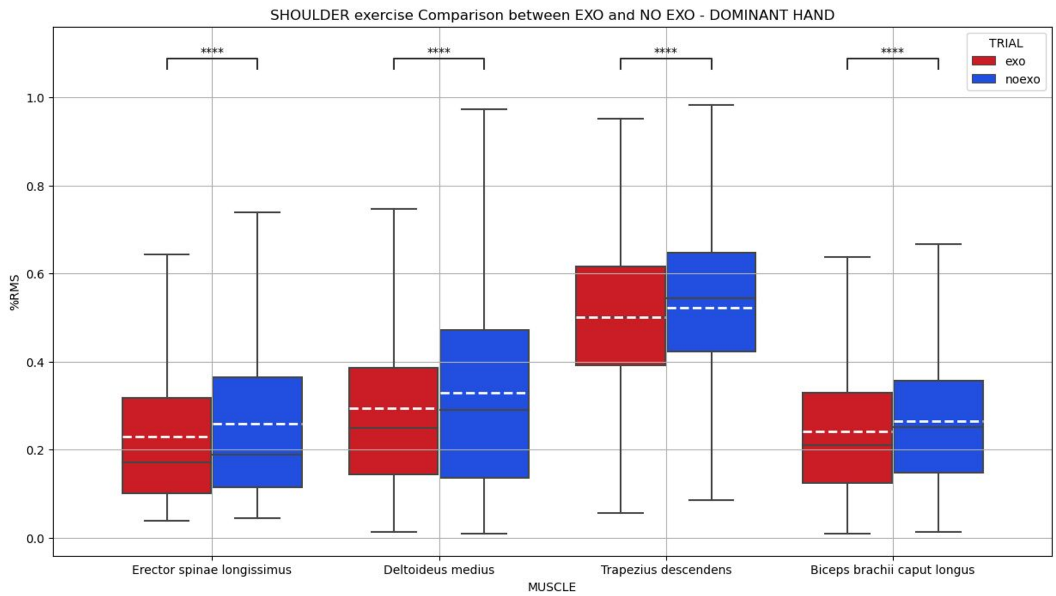


Figure 4.6: Muscle activity, during PAEXO shoulder evaluation, with the exoskeleton (EXO,red) and without it (NOEXO,blue), considering only muscles of the dominant hand (side). Stars indicate significant differences (*p $<$ 0.05, **p $<$ 0.01, ***p $<$ 0.001, ****p $<$ 0.0001).

4.2 Energy consumption analysis

The analysis shows significant differences between the two trail (EXO and NOEXO) in the case of HR only for the PAEXO shoulder evaluation (Figure4.7). The heart rate measured during the back evaluation, resulted with no statistically relevant differences ($p > 0.05$) between the two trial, using the exoskeleton and performing the test without it. While, during the shoulder evaluation, the heart rate when using the exoskeleton (EXO) shows a significant reduction ($p < 0.01$) compared to not wearing the exoskelton.

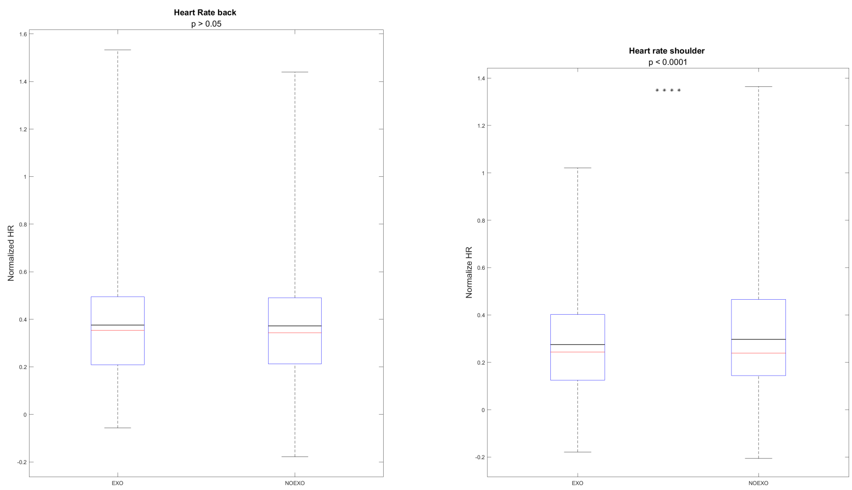


Figure 4.7: Heart rate, during both exoskeletons evaluation, with and without exoskeleton. Stars indicate significant differences (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p < 0.0001$).

Regarding electro dermal activity (EDA) results show that differences between the two trail (EXO and NOEXO) are statistically significant ($p < 0.05$) for both the back and shoulder evaluation, see Figure4.8.

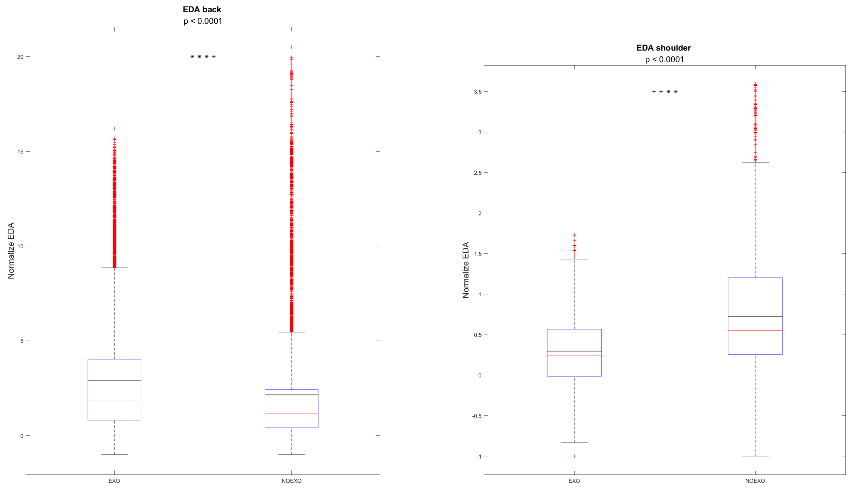


Figure 4.8: Electro dermal activity, during both exoskeletons evaluation, with and without exoskeleton. Stars indicate significant differences (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

4.3 Motion analysis

Joint angles are analyzed for each subjects and test. They are time-scaled to a common duration and displayed as time-series.

Figure4.9 presents the time-series data for the hip joints throughout the entire duration of the test. Hip joint movements vary between the two trials. It is noticeable that utilizing the exoskeleton significantly reduces the hip angle during the bending phase when participants were handling the box.

Data for the knee joints throughout the entire duration of the test is representes in Figure4.10. Differences in knee joint movements were observed between the two trials. Specifically, the utilization of the exoskeleton decreased the knee angle during the bending phase, especially, when participants were engaged in box lifting (the first peak of the time-series).

Significant differences ($p < 0.05$) in both hip and knee flexion maximum angles were observed between the two trials (EXO and NOEXO) (Figure4.10).

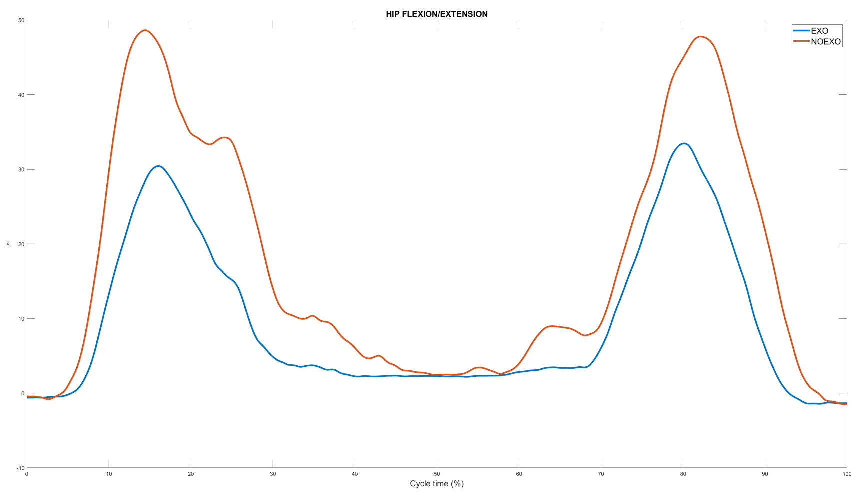


Figure 4.9: Time-series of the hip joints. Time-series represent the movement of a complete cycle of lifting and placing the box.

Figure4.13 illustrates the time-series data of flexion/extension and abduction/adduction angle of the shoulder joint, considering only the dominant hand (side) for the analysis. The flexion/extension angle showed an increase when moving the drill to the front, while it decreased during the overhead movement when using the exoskeleton. The increase in flexion/extension angle when the exoskeleton is not used during the overhead movement corresponds to a decrease in the abduction/adduction angle, consistently observed when the exoskeleton is not utilized.

Any significant differences ($p > 0.05$) were observed in the maximal flexion/extension and minimal abduction/adduction shoulder angle.

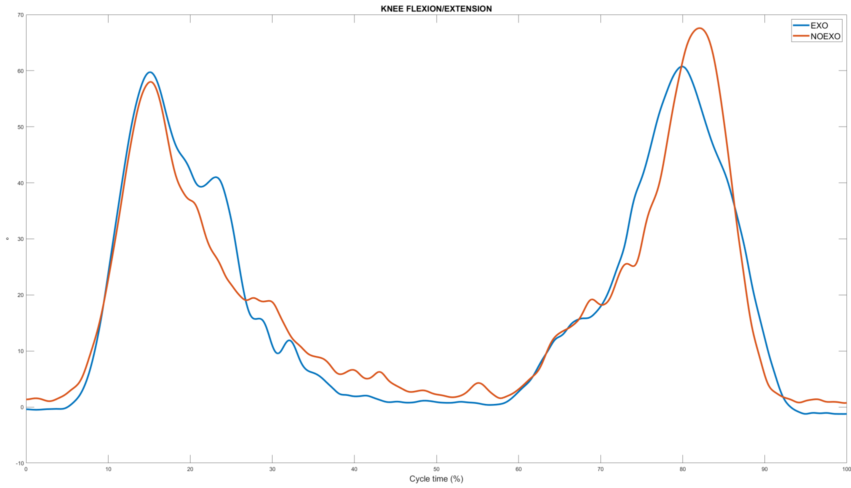


Figure 4.10: Time-series of the hip joints. Time-series represent the movement of a complete cycle of lifting and placing the box.

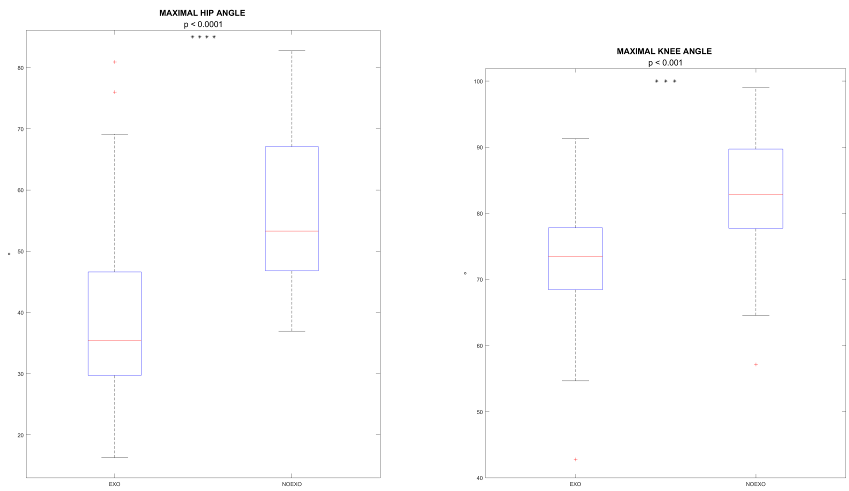


Figure 4.11: Maximal hip and knee joint angles while lifting. Stars indicate significant differences (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

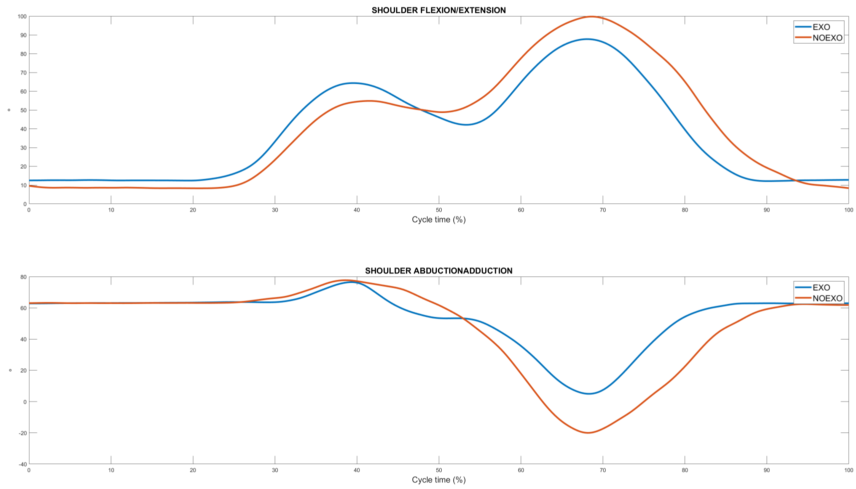


Figure 4.12: Time-series of the shoulder joints (dominant hand side). Above flexion/extension angles and below abduction/adduction angle. Time-series represent the movement of a complete cycle of moving the drill in front and then overhead.

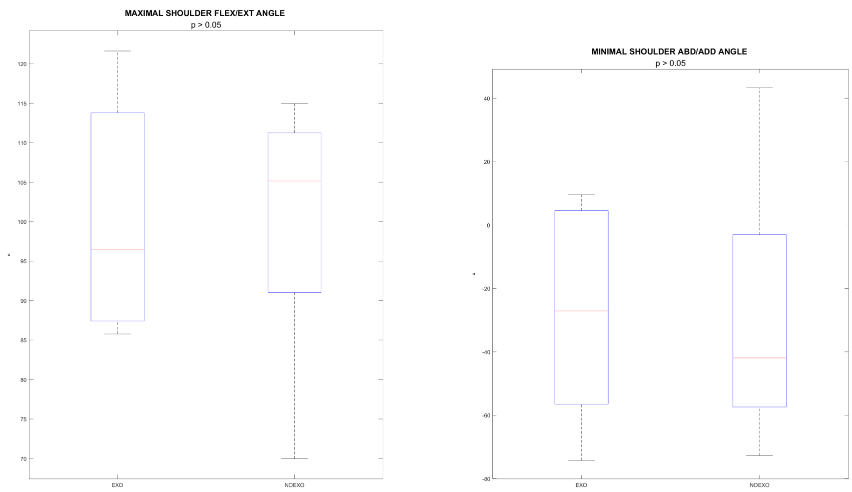


Figure 4.13: Shoulder maximal flexion and minimal adduction joint angles. Stars indicate significant differences (*p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

4.4 Subjective assessment

Table 4.3 and Table 4.4 report the global scores of the perceived exertion questionnaire at two instant of the test, both with and without the exoskeleton.Using the BORG CR-10 scale, it was observed that both exoskeletons provided support, resulting in a 11% reduction in perceived fatigue when utilizing PAEXO back and an 29% decrease when using PAEXO for the shoulder, compared to conditions when the exoskeletons were not employed. However, only the decrease with the PAEXO shoulder is statistically significant, see Figure4.14.

Table 4.5 displays the overall and detailed scores (across the 4 factors) of the post-experimental questionnaire for all participants. The global scores, calculated as the average of the scores across the 4 factors for each participant, were 6.8 (SD = 0.9) when evaluating PAEXO for the shoulder. In contrast, when evaluating PAEXO for the back, the global scores were 5.3 (SD = 1.0).

	BACK					
	EXO			NOEXO		
	I	II	TOT	I	II	TOT
Mean	3.8	6.2	5.0	4.1	7.2	5.6
Std	1.9	2.4	2.0	1.9	2.6	2.1

Table 4.3: Global scores of the perceived exertion questionnaire with the exoskeleton (EXO) and without it (NOEXO). PAEXO back evaluation.

	SHOULDER					
	EXO			NOEXO		
	I	II	TOT	I	II	TOT
Mean	4.3	4.7	4.5	5.9	6.6	6.3
Std	1.8	1.5	1.6	2.3	2.5	2.3

Table 4.4: Global scores of the perceived exertion questionnaire with the exoskeleton (EXO) and without it (NOEXO). PAEXO shoulder evaluation.

SUBJECTS	**SHOULDER**					**BACK**				
	CO	FU	CL	PE	TOT	CO	FU	CL	PE	TOT
S1	6.5	5.6	6.8	5.3	6.1	4.5	6.0	5.5	6.0	5.5
S2	7.0	7.2	6.5	7.3	7.0	6.0	6.2	5.6	6.3	6.0
S3	7.5	7.0	6.7	7.3	7.1	6.5	6.2	5.0	6.3	6.0
S4	5.0	6.6	8.5	7.0	6.8	2.0	3.8	6.2	4.7	4.2
S5	6.5	7.5	6.1	7.2	6.8	6.0	4.1	3.0	6.7	5.0
S6	5.5	5.0	5.0	5.0	5.1	3.0	3.8	4.7	3.3	3.7
S7	10.0	8.8	6.8	7.3	8.2	7.0	7.6	5.2	8.0	7.0
S8	7.0	6.4	6.2	6.3	6.5	5.0	5.6	4.7	5.3	5.2
S9	7.5	8.0	8.3	7.3	7.8	6.0	7.0	7.2	5.3	6.4
S10	6.5	5.4	6.3	7.3	6.4	3.5	5.0	4.0	5.0	4.4
TOT	6.9 (1.3)	6.8 (1.2)	6.7 (1.0)	6.7 (0.9)	6.8 (0.9)	5.0 (1.7)	5.5 (1.3)	5.1 (1.2)	5.7 (1.3)	5.3 (1.0)

Table 4.5: Post-experimental questionnaire detailed scores, across the 4 factors: CO: Confidence, CL: Cognitive Load, FU: Functionality, PE: Physical Effort

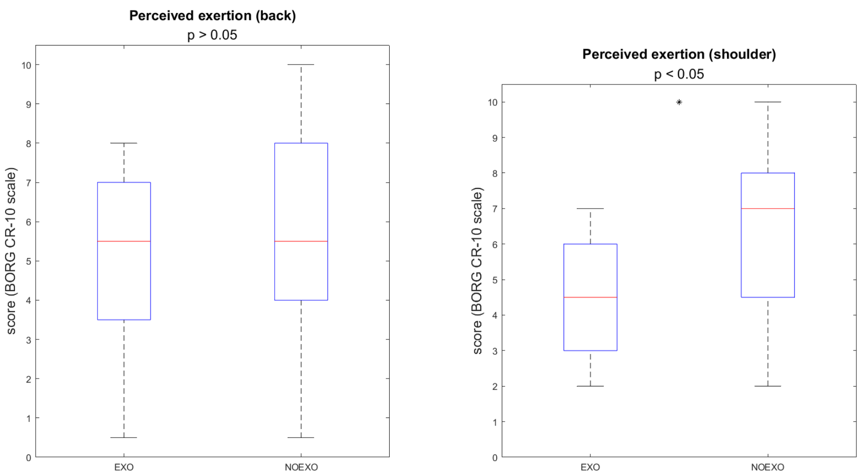


Figure 4.14: Ratings of perceived exertion

Chapter 5

DISCUSSION

In this study, ten non-expert participants performed a series of different task with and without the assistance of PAEXO back and PAEXO shoulder, in order to assess their effectiveness. The results obtained are discussed separately for each exoskeleton.

5.1 PAEXO back

The PAEXO back reduces muscle activity of the main back and leg muscles. Specifically, during the lifting activity, the muscle activity of the erector spinae longissimus (ESL) and erector spinae ileocostalis (ESI) were reduced respectively by 12.2% and 11.3% when using the exoskeleton. The reduction were seen clearly in the muscle activity of the semitendinosus, that presented a reduction of 35.9%. The findings obtained in this study relate to values documented in literature, underlining the consistency and reliability of our results [13] [9]. The on-field test further confirms our laboratory findings, highlighting a significant reduction in muscle activity for all the back muscles (ESI and LD), although no significant differences were observed for the ESL. It's important to note that the on-field test was conducted with a relatively small population. Nonetheless, it provides valuable insights into the actual values and trends of muscle activity in a real workspace setting.

The exoskeleton not only mitigated the onset of muscular fatigue but also likely influenced metabolic consumption during the tasks. Significant differences were found in electro dermal activity (EDA). Contrary to expectations, EDA increased while using the exoskeleton, showing a 25.7% augmentation. However, the heart rate did not exhibit a statistically significant difference between the two trials - with and without the exoskeleton. This indicates that the PAEXO back did not significantly reduce metabolic cost during work. This results were confirmed by the on field test. Possible factors contributing to this could be the relatively short familiarization period with this less user-friendly back support, or factors related to its weight and comfort.

Interestingly, significant results emerged from the analysis of joint motion patterns and their maximal angles. Notable differences were observed in the trajectories of hip and knee flexion/extension angles, with significant disparities found in their respective maximal angles. The exoskeleton played a significant role in reducing the maximal flexion/extension joint angle of the hip. This assistance enabled participants to perform the task in a more appropriate manner, requiring less flexion of the trunk and exerting less strain. These results regarding joint angles could potentially be affected by marker positioning, particularly considering the placement of the exoskeleton. Further analyses may be necessary to ensure a more comprehensive and accurate evaluation in this regard. Nevertheless, qualitative observations made during the tests did reveal some noticeable differences.

The subjective measures, especially regarding perceived exertion, indicated minor differences between the two trials, although they did not reach statistical significance, possibly owing to the relatively small study population. However, this observation aligns with the metabolic cost analysis, where no significant difference in heart rate was noted.

At last, the post-experimental questionnaire gave some interesting results that help to understand better all the results previously reported and discussed.The overall score, considering all participants and four factors, was 5.3 (SD = 1.0), which is relatively low. Notably, the factors related to confidence and cognitive load, encompassing questions about trust, usability, and independence with the exoskeleton, scored particularly low. This suggests discomfort with the exoskeleton, aligning with the other parameters evaluated earlier. However, upon detailed analysis of the post-experimental questionnaire conducted in the field, a distinct response to these questions is observed. In fact, the results for the same factors are consistently higher. These findings suggest that actual workers are more adept at using the exoskeleton and have greater confidence in using it, perhaps because they already know which movements to make and how they can be assisted.

5.2 PAEXO shoulder

The shoulder exoskeleton examined in this study (PAEXO shoulder) significantly reduced muscular load during the simulated tasks that involved elevating the arms above shoulder level. These findings align with prior research assessing passive devices' potential to reduce muscle load during static tasks [11][10][8][26]. PAEXO shoulder, in the present study, offered support slightly below the ranges reported in the literature: deltoideus medius activity was reduced by 10.4% (25,3% [10] and 38% [8]), trapezius descendens was reduced by 6.4% (32% [8] and 10% [26]) and biceps brachii activity was reduced by 11% (31.8% [10]). A difference between previously study was found in the erector spinae activation. The reduction in shoulder strain is a positive outcome. However, it's important to note that passive systems, by design, do not input energy. Therefore, the assistive force they provide needs to be redirected to another part of the body, typically a stronger one [27]. In the case of the PAEXO shoulder the pelvis. So, it would be expected an increased or similar muscle activation of the erctor spinae [11]. However, in our evaluation, using the exoskeleton resulted in a decrease in strain in the surrounding low back area.

The alterations in muscle activity not only reduced the onset of muscular fatigue but also likely influenced metabolic consumption. During the task, the heart rate and electro deramal activity, were reduced respectively by 8% and 60% , which confirms our hypothesis that using such a passive exoskeleton reduces metabolic cost while working. Reductions in heart rate when using passive shoulder support exoskeleton have been previously reported [24] [11] [10]. Although the parameter of electrodermal activity has not, to our knowledge, been previously employed in exoskeleton evaluation, its application in this study has demonstrated promising results.

Furthermore, the study demonstrated that the exoskeleton did not influence the movement of the arms. Although there were slight differences observed in the shoulder flexion/extension and abduction/adduction angle trajectories, no significant differences were found in the maximal and minimal angles.

The subjective measurements further confirm the support provided by PAEXO shoulder. Specifically, the global scores from the perceived exertion questionnaires exhibited a significant 29% reduction in perceived fatigue when utilizing the passive support exoskeleton, changing the rating from "Very strong" to "Strong (heavy)". This reduction aligns with findings from a previous study that reported a similar decrease [10].

Lastly, the post-experimental questionnaire reaffirmed the benefits provided by the exoskeleton across all four factors. The collective global score, taking into account all participants, was notably high at 6.8 (SD = 0.9), indicating a strong level of satisfaction. Participants expressed particular contentment in the 'confidence' response, emphasizing that the studied exoskeleton was user-friendly and easy to utilize.

Chapter 6

CONCLUSION

In this study, it has been conducted a comprehensive evaluation of two passive exoskeletons: PAEXO back and PAEXO shoulder, aimed at understanding their effectiveness in reducing muscle activity and metabolic cost during physically demanding tasks. The primary objectives were to analyze muscular activity, metabolic consumption, joint angles, and subjective perceptions to determine the impact of these exoskeletons on human performance and well-being.

The PAEXO back was found to significantly reduce muscle activity in the erector spinae longissimus (ESL), erector spinae ileocostalis (ESI), and semitendinosus (SE) muscles during lifting tasks. Additionally, it affected joint angles, notably reducing maximal flexion/extension angles of the hip, thus enhancing task performance and potentially mitigating musculoskeletal strain. While certain parameters in the metabolic cost analysis showed a noticeable increase, suggesting a potential but not entirely clear reduction in overall energy consumption, this study acknowledges its limitations. These findings were further supported by the subjective responses, indicating that a more extended period of familiarization with the exoskeletons might be necessary to fully realize their energy-saving potential. Understanding that participants' initial experiences could have been influenced by the novelty of the exoskeletons, extended exposure and adaptation may reveal more pronounced and conclusive benefits.

On the other hand, the PAEXO shoulder effectively reduced muscle activity in the deltoideus medius (DM), trapezius descendens (TD), and biceps brachii (BB) muscles during tasks involving arm elevation. This reduction in muscular load, combined with a decline in heart rate and electrodermal activity, supported the hypothesis that this passive exoskeleton contributes to a decrease in metabolic cost during work. Furthermore, the analysis of joint angles indicated that the exoskeleton did not impede arm movements, affirming its ergonomic design and usability.

Subjective assessments through questionnaires revealed a notable reduction in perceived fatigue and increased confidence levels when participants utilized the exoskeletons. Participants expressed satisfaction with the ease of use and ergonomic design of the exoskeletons, corroborating the objective measurements.

In conclusion, both PAEXO back and PAEXO shoulder have shown promising results in reducing muscular load and potentially lowering metabolic cost during physically demanding tasks. Despite some observed challenges, especially in the subjective assessments related to comfort and usability, these exoskeletons present valuable contributions to the field of wearable robotics. Further research and development efforts should aim to address user concerns, optimize the design, and conduct longitudinal studies to assess long-term effects and usability in real-world work environments.

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Acknowledgments

I would like to thank everyone at the Università Politecnica delle Marche for providing me with every component I needed to finish my thesis. I would like to express my sincere thanks to my advisor, Professor Giacomo Palmieri, my coadvisor, Cecilia Scoccia and my colleague Serenella Terlizzi for their assistance and support throughout my working experiment. The purpose of this thesis probably not have been achieved if I don't get their continual assistance and support.

To my family, my strongest pillars of support, thank you for being there every step of the way. Your love and understanding fuelled my determination to see this through.

To my friends, your friendship has been a guiding light, illuminating both the joys and challenges of academic life and the beautiful moments that make life extraordinary. Your encouragement, understanding, and belief in me have been a wellspring of strength throughout this journey. Thank you for standing by me, celebrating my triumphs, and providing comfort in times of defeat. Your friendship is a precious gift that I hold close to my heart.

This achievement is a culmination of collective effort and support from everyone mentioned and more. Thank you for believing in me and contributing to this significant milestone.

Ancona, Ottobre 2023

Samuele Tonelli