UNIVERSITATEA DIN PETROȘANI
DOCTORAL SCHOOL

DOCTORAL THESIS

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Petroșani, 2024

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Contributions on the design and management of a bio-inspirational exoskeleton for the shoulder coupling

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INTRODUCTION

In recent decades, technological advances and advances in biomechanical engineering have led to the emergence of exoskeleton devices, representing innovative solutions for improving limb mobility and functionality, in the case of this research the upper limbs, affected by various diseases and traumas.

CHAPTER I
CONTEXT OF THE RESEARCH
ANATOMY OF THE SHOULDER JOINT

This chapter aims to provide a detailed look at the anatomy of the shoulder joint, the biomechanics of specific movements and associated conditions. The anatomy of the human shoulder joint is an essential field for understanding its functioning, involving both the bone structures and the soft elements that contribute to the complex movements of this anatomical segment.

The detailed study of the bone structure of the shoulder joint reveals its complexity, highlighting the importance of each bone in ensuring proper stability and mobility. In parallel, the investigation of soft elements, such as muscles, tendons, ligaments and cartilage, brings to light the intricate network that contributes to the functioning and support of the joint. Understanding this complex anatomical network is essential for assessing normal movements and identifying structural changes in shoulder conditions.

The biomechanics of shoulder movements is another aspect addressed in this study. Understanding how the shoulder joint allows for varied movements, such as abduction, adduction, flexion, and extension, contributes to the development of a conceptual framework for analyzing normal movements and deviations that can occur as a result of trauma or illness. This biomechanical perspective provides the necessary basis for the development of personalized and effective treatment strategies.

The particularity of this study also lies in the analysis of shoulder diseases, starting from those determined by genetic factors to those induced by trauma or degenerative diseases. Investigating how anatomical structures and biomechanics are affected in various pathological conditions is an essential component for identifying appropriate therapeutic interventions.

Objectives

The objectives of the chapter are:

- A Study of the Anatomy of the Human Shoulder Joint;
- Understanding the Biomechanics of Movements;
- Shoulder joint disorders.

CHAPTER II
EXOSKELETON DEVICES

In recent decades, the development of technology and biomechanical engineering has led to the emergence of exoskeleton-type devices to improve the mobility and functions of limbs injured by various ailments and traumas. In recent years, most of these exoskeleton devices are portable, fixed to the human body to support it in certain physical activities. These devices have a variety of destinations and roles, including: *Improving human performance* (they can be used to support and improve human performance in physical activities; for example, exoskeletons can be used in heavy industry to help workers carry heavy objects and reduce the physical effort required); *Physical rehabilitation* (helping patients regain mobility and muscle strength after injury or surgery; for example, an upper limb exoskeleton can help a patient regain the ability to grasp and manipulate objects or perform daily activities); *Injury protection* (can be used to protect the human body from injury; for example, exoskeletons can be used in the construction or mining industry to protect workers from falls or blows); *Military use* (they can be used in the military field to enhance soldiers' performance; for example, exoskeletons can help carry heavy equipment or reduce fatigue and physical stress); *Healthcare* (can be used to help medical personnel transport heavy patients or perform other difficult physical tasks in a medical environment). In general, exoskeletons can be used in any situation that requires human performance enhancement, injury protection, or assistance in difficult physical activities.

The shoulder joint is one of the most mobile and complex joints in the human body. Because it is so mobile, it is susceptible to a range of injuries, such as tendon tears or dislocations. These injuries can affect the patient's ability to use their shoulder, which can lead to loss of independence and decreased quality of life. The shoulder joint exoskeleton can be designed to help restore shoulder function and improve mobility for patients suffering from injuries or other conditions affecting the shoulder.

This device consists of an external skeleton, mounted on the arm and torso, which helps to support and stabilize the shoulder, and this skeleton is usually made of lightweight and resistant materials, such as carbon fiber or aluminum, to minimize weight and facilitate movement. The exoskeleton for the shoulder joint is operated and controlled by an actuation system (electric, hydraulic or pneumatic), together with a set of sensors and algorithms. Sensors are used to detect patient movements and send signals to the propulsion system, which then acts accordingly, and algorithms are used to interpret sensor signals and adjust the drive system in real-time to ensure that the device adapts appropriately to the patient's movements.

The devices on the market can be broadly classified according to how human subjects interact with them: handling the end effector and wearing the exoskeleton in daily activities. They do not have the ability to independently control or assist each human joint, as interactions take place at the anatomical level of the human arm.

Objectives

The objectives of the chapter are:

- A study of drive and control systems for exoskeletons;
- A comparative study of exoskeleton devices for the shoulder joint, with a focus on those operated with the help of cables.

CHAPTER III
MOVEMENT OF THE HUMAN ARM. MODELING AND SIMULATION

In the context of the development of exoskeletons and assisted technologies, the importance of sensors, with a focus on inertial units of measurement (IMU), is fundamental for accurately capturing the movement of the human arm. The data provided by the IMU sensors concern orientation, acceleration and speed, providing information for the analysis and interpretation of movements in real time. This detailed approach in motion capture is an essential step in the direction of building efficient and adaptable exoskeletons.

In parallel, understanding kinematics in the shoulder joint is an essential aspect in exoskeleton design, and the Denavit-Hartenberg mathematical model provides a robust method for describing the relative position of segments in a kinematic chain and is a useful tool for modeling the kinematics of motion of both the human arm and the exoskeleton device.

Capturing the movement of the human arm, in a way that respects kinetics and biomechanics, is a vital direction of research and development in the field, and the integration of

IMU sensors, efficient actuators and advanced mathematical models contributes to the creation of innovative exoskeleton devices, with the potential to significantly improve the quality of life of people with disabilities, in medical recovery or in industrial tasks.

Objectives

The specific objectives of the chapter are:

- Identification of the types of movements performed in the shoulder joint;
- Identifying the Arm Movement Space;
- Development of the Human Arm Motion Capture System Using IMU Sensors;
- Realization of a Denavit-Hartenberg mathematical model for the analysis of the kinematics of the human arm.

CHAPTER IV
EXOSKELETON DEVICE DESIGN

In recent decades, technological development has brought significant transformations in many fields, including biomedical engineering. One of the most promising research directions in this field is the development of exoskeleton devices, designed to support and improve the functionality of human limbs. This chapter begins with the evaluation and improvement of a modified version of the Stewart Platform, a bio-inspirational structure dedicated specifically to the human shoulder. This platform not only supports the upper limb, but also offers improved mobility, being a notable innovation in the field of assistive devices.

This chapter aims to explore in depth the technical and functional characteristics of a proposed exoskeleton for the right arm, comparing it with other similar devices on the market. Through comparative analysis, the study will highlight the essential similarities and differences, as well as the control methods used by each device. This is essential for identifying specific innovations and possible improvements that can be made to these technologies.

The chapter continues with the analysis of the exoskeleton driving system, including the Dynamixel AX-12A motors and the DFRobot SEN0386 IMU sensors, which, together with a control algorithm adapted and implemented for prototyping through an Arduino code, ensure precise and efficient operation. These components are vital for the overall performance of the device and its adaptability to the specific needs of users.

By addressing these topics, this chapter lays the foundation for further discussions in the thesis, related to the application potential of exoskeleton devices in the field of healthcare and rehabilitation. The ultimate goal is to contribute to the development of innovative solutions that can transform the lives of people with locomotor disabilities, giving them greater independence and quality of life.

CHAPTER V
EXOSKELETON CONDUCTION SYSTEM

In this chapter, we will explore two innovative methods of exoskeleton control, the design of which was detailed in the previous chapter. The first method involves the use of an IMU-type sensor, which captures the movements of the trunk and converts them into control commands for the movement of the exoskeleton arm, functioning similarly to a joystick. The second proposed method uses advanced *machine learning* techniques to predict arm movements based on trunk dynamics. These approaches are necessary to improve the interaction between the user and the robotic device, providing a detailed perspective on its application potential.

In Chapter V, the development and validation of a conduction model for exoskeletons is explored, focusing on the use of advanced data analysis and control techniques. The study focuses on the implementation and testing of a control system based on IMU (Inertial Measurement Unit) sensors, intended to monitor and adjust arm movements in real time. A central element of the research is the use of Principal Component Analysis (PCA) to reduce the size of the dataset and determine its relevance. By rigorously collecting and analyzing motion data and testing the model in MatLab-Simulink simulations, the study demonstrates the efficiency of the control algorithm and the relevance of the cumulative variability explained. These main ideas emphasize the importance of an interdisciplinary approach to optimize the performance and interpretability of the model, ensuring a responsible and efficient integration of exoskeleton technology.

The main steps of this exoskeleton driving model:

1. Analysis of the main components (PCA):

- PCA is used to determine the relevance of input data and reduce the size of the dataset;
- The first two main components are sufficient to describe the desired pattern, with the first component explaining an overwhelming majority of the variation (95.432%) and the second component adding another 3.5269% to the explained variance.

2. Data collection methodology:

- Data were collected by repeating arm movements synchronized with trunk movements in different planes (vertical, front-back, and circular movements);
- The collected dataset was divided into 80% for model training and 20% for validation, to ensure realistic evaluation of model performance.

3. Exoskeleton control:

- A control system based on IMU (Inertial Measurement Unit) sensors is used to monitor and adjust arm movements in real time;
- The specific driving algorithm uses the angles of movement of the torso to control arm movements, ensuring that they respect the natural amplitudes of human joints.

4. Driving model simulation and testing:

- Simulations in MatLab-Simulink were used to test and adjust the parameters of the control algorithm, ensuring optimal functioning of the exoskeleton under different conditions;
- The implementation of exoskeleton control was carried out in the embedded C language, using dedicated libraries for the management of servo motors.

5. The Importance of Cumulative Variability Explained:

- The cumulative variability graph explains how each main component contributes to explaining the total variance of the dataset, emphasizing the importance of the first component;
- The trade-offs between the inclusion of additional components and the complexity of the model are analyzed to optimize the efficiency and interpretation of the model.

CONCLUSIONS

In Chapter I, we conducted a detailed study of the anatomy of the human shoulder joint and the biomechanics of movements to highlight their complexity and diversity. The organization of the nineteen muscles into four main groups, together with the formation of secondary groups from neighboring muscles, allows combined movements to be performed, such as driving the arm diagonally-front upwards, a combination of flexion and abduction (vertical and horizontal). These complex arm circumduction movements are the result of the sum of the series of movements, both the main and the secondary ones. Thus, a promising direction has emerged in the development of exoskeletons intended for the recovery of natural arm movements in the shoulder joint, thus making significant contributions in the field of functional recovery.

Exoskeleton systems for the upper limbs tend to have a wide range of applications, from medical rehabilitation of patients with neuromuscular conditions to their use as assistants in physical or industrial activities. Following the study carried out in Chapter II, I understood that the exoskeletons for the shoulder joint, developed in the last decade, use components fixed on immobile supports, intended for mounting in medical rooms or offices or on textile supports for portability. They are driven by pneumatic or electric motors, and the transmission of movement is carried out with the help of cables, especially in the case of devices that aim for bio-mimicry.

Research and development in this field is facing new challenges, and the trend is to create exoskeletons as similar as possible to human anatomy, from lightweight and resistant materials. The researchers' goal is to create wearable and autonomous devices that become an integral part of people's daily lives, just like the clothes worn today.

By simulating the movements of a human arm in the shoulder joint and creating a virtual arm that mimics these movements in the context of everyday activities such as drinking water or putting a chain around the neck, we explored the possibility of using this information to make an exoskeleton system. The aim is to help people with reduced mobility to carry out these daily tasks without difficulty. By integrating technology into everyday life, we can improve the quality of life and independence of these people.

Based on the experiments, we developed and presented in Chapter IV, an innovative device called the ExoWare exoskeleton (now in version 4.0), designed to assist the movement of the human arm using only four cables. This device is a simple system of control of the human arm, acting similarly to the four muscle groups that generate the movements of the arm. Using servo motors as "muscles" attached to the back of the device and cables that move along controlled paths as "ligaments" that adapt to the user's body shape, the exoskeleton provides support and mobility. Control of the device is carried out with the help of IMU sensors, which detect the movements and orientation of the arm, translating them into commands for the exoskeleton. This device is a useful solution for people with difficulties in arm movement, helping them to regain or improve their mobility lost due to a medical condition or following an accident.

CONTRIBUTIONS

As for the part of the contributions made within the doctoral thesis, I would mention, first of all, the contributions in terms of bibliographic research and the analysis of the current state of the topic addressed.

- I make a detailed introduction to the field of research of the anatomy of the human shoulder and a brief description of the elements of the shoulder joint and the biomechanics of specific movements and associated conditions is made based on the bibliography;
- Based on scientific papers in the literature, I have presented several models of exoskeleton devices, developed in the last decade, which present technologies similar to the one presented by me.

From the point of view of establishing the objectives of the research, I would notice several contributions that are related to the development of an exoskeleton type device.

- Noting that the movements of the human arm can be divided into two moments of movement, the first moment in which the arm is raised laterally horizontally plus another 15°, in the Glenohumeral joint, and then continuing with the second moment until reaching 170-180°, in the Scapulothoracic joint; made in the shoulder joint with the help of four large muscle groups. Abstracting we decided that the human arm could have its movements controlled with the help of four cables, and to accomplish this we carried out some experiments:
  - In the first experiment we made a measurement of the cables needed to find out what is the optimal length to be able to perform any of the basic movements of the arm.
- With the second experiment we found that the positioning of the cable attachment point on the arm, in order to lift it with maximum efficiency and with the lowest energy consumption, is the one near the deltoid tuberosity on the humerus, at one third of the base and two thirds of the tip. Also in this experiment we found that the way the shoulder joint is constructed in the Glenohumeral region resembles a Stewart platform, but with some major modifications, by using four actuators, not six, and using a central fulcrum for more efficient control of the two planes of the platform.

- Conducting a series of experiments to capture angular values of arm movements by using IMU sensors during recreations of some of the daily activities of a healthy person. This led to the realization of mathematical models of control and conduction of the device arm, to the establishment of the control algorithm and to the realization of the simulation in MatLab-Simulink of the control with the help of Artificial Intelligence.
- After the exoskeleton device was made, some clear directions of use were established. Its main use is in the medical field, for the rehabilitation of natural arm movements of people with various conditions or traumas of the shoulder joint; Secondary uses could be to assist in everyday life for people who have suffered a stroke and are no longer able to move their arm, or to augment work in the industrial or military field.
- Am definit un concept de control autonom, bazat pe *machine learning*, pornind de la identificarea metodelor de control al celorlalte prototipuri analizate, am implementat un algoritm care utilizează valorile achiziționate de la doi senzori IMU.

The objectives proposed to be solved within this doctoral thesis have been achieved and implemented, thus creating an exoskeleton-type device driven with the help of an Artificial Intelligence model, which can be created different operating scenarios, from the repetition in a certain plane of a single movement, to the realization of series of complex movements such as the circumduction movement of the human arm. The values acquired from the two IMU sensors used can be both control and feedback values, to verify the correctness of the arm movements performed by the various patients. Testing the functionality of the device under laboratory conditions highlighted the reliability of the system and thus validated the prototype made. For the actuation and construction part of the device for performing specific movements in the shoulder joint of a human arm, an application for a patent was registered with OSIM under the number A/00813/30 Dec 2021, under the name: *Device attached to a human garment, intended to support or move the upper limb of a person*.

Contributions detailed by chapters

Chapter I:

1. We conducted a detailed study to understand the anatomy and biomechanics of the shoulder joint, examining both the bone structure and the soft elements that support and enable the complex movements of this joint. This detailed analysis of bone structure emphasizes the complexity and importance of each element in maintaining stability and mobility, while investigating muscles, tendons, ligaments, and cartilage highlights the interconnected network that contributes to the optimal functioning of the shoulder joint.

2. We conducted a study of the biomechanics of shoulder movements to provide an essential conceptual framework for understanding various movements such as abduction, adduction, flexion and extension, important for the development of personalized and effective treatment strategies.

3. We conducted a study of shoulder conditions, from those caused by genetic factors to those resulting from trauma or degenerative diseases. This study is essential for identifying appropriate physical therapy interventions, in which the use of exoskeleton devices are of real help.

4. Following the understanding of the kinesiotherapeutic and treatment methods applied in different shoulder conditions, we have identified the ways to use an exoskeleton type device, with passive actuation, in immobilizing the arm in a certain position, or with active actuation, in the movement of the arm in a certain space of movement.

Chapter II:

5. Following the analysis of specialized publications, we have identified several areas of application of exoskeleton devices, namely, in that of improving human performance during physical activities, where arm strength and endurance are required; in physical rehabilitation after a medical intervention, by immobilizing the arm or to regain the natural physical capacities of the arm; assisting the user as a security companion or assisting in carrying various heavy objects.

6. We defined this device as bio-inspirational, following the study of bio-inspirational technologies, identifying them and inserting them into this device, so that through biomimetics we reconstructed the elements of the shoulder joint, through bionics we achieved the set of specific movements of the arm in performing the first moment of movement, through neuroprosthetic technology we achieved arm control by integrating an artificial intelligence module.

7. Also following this study, we divided the types of exoskeletons into two categories, namely, bio-mimetic, which constructively attaches to the human body, by imitating the exoskeleton of insects, and bio-inspirational, which takes into account muscle groups, as actuating elements, and the servomotors will be positioned on the user's back.

8. As exoskeleton control methods are important for optimizing the performance and safety of these complex devices, following the study we identified the following control methods: control based on IMU sensors, for real-time movement monitoring; based on electromyography (EMG), for predicting the user's movements by measuring muscle activity; and with the help of machine learning algorithms, which allow adaptation to the user's specific movement styles.

9. We have defined the hardware elements of an exoskeleton for the human shoulder joint, which involves the design and construction of components to support and facilitate arm movements. Key components include the exoskeleton structure, which is made of textiles, aluminum or plastic to reduce weight, and the drive system, which can use electric motors, hydraulics or pneumatic systems. Sensors and control systems monitor the user's position, strength, and movements, ensuring precise control of the exoskeleton. The transmission system can use belts, chains or cables, and transmits the torque of the motor to the positioning and orientation mechanisms.

10. An exoskeleton must mimic the capabilities of the human arm, which has 7 degrees of freedom (DoF), but in the case of exoskeletons it can vary between 5 and 9 DoF, depending on the design and application, to allow the device to control and rehabilitate the human arm in the event of malfunctions, assisting or improving movements. We have transposed into tabular form the degrees of movement, depending on the joint and the type of movement performed, as well as the range of motion related to the movements in the joints.

11. We have structured in tabular form some aspects that present the hardware and software design of an exoskeleton for the upper limb, aspects that present the mechanism, drive, transmission or control.

12. We conducted a study of the actuation modes of an exoskeleton intended for the shoulder joint, presenting the advantages (+) and disadvantages (-) in terms of power, control, mobility and maintenance of the system, for different drive systems, namely electric, hydraulic, pneumatic, mechanical and elastic.

13. We identified the characteristics of an ergonomic exoskeleton, which include low weight, balanced weight distribution, the ability to perform a wide range of motion, and comfort adjustment systems.

14. Based on the analysis of similar devices, we have made a synthesis of the transmission methods by direct drive, mechanical drive (belts, chains, cables), and indirect drive (gear systems), each with advantages and disadvantages, such as the need for regular maintenance and the difficulty of design. Cable transmission, in particular, allows for an ergonomic design by placing heavy components on the user's back and light ones on the arm, but requires strong cables, optimal routes, and maintaining proper tensioning.

15. We conducted an analysis to identify the types of sensors needed to detect the motion and estimate the position in space of a human arm and concluded that current IMU sensors, which provide speed and acceleration data, are a sufficient solution. Sensor data allows exoskeletons to correct user movements, assist workers in strenuous tasks, execute predetermined movements for incapacitated patients, help lift and carry heavy objects, or perform a user's intended movements.

16. Based on the analysis of similar devices, we have observed that an exoskeleton device can be controlled "in mirror" in the form of a human-master arm/exoskeleton-slave arm, by direct actuation, with the help of a joystick, for example, or by indirect actuation, by creating scenarios or based on machine learning, by integrating an artificial intelligence system.

17. Following the study of specialized publications, we deduced that the biomechanics of a wearable exoskeleton device must interact with the human body, that a bio-inspirational model must mold to the human musculoskeletal model, so as not to obstruct the user's movements, to be compact, light and resistant.

18. We have conducted a detailed analysis of wearable exoskeleton devices, intended for the upper limb, to understand the role of these devices, and they can be classified as having a medical purpose, to recover the natural movements of the human arm and to increase the strength, security and mobility of the user.

19. We conducted a study of wearable exoskeleton devices, in terms of areas of use, based on what such a device can offer. Thus, we have made a classification of them in three directions of use, as a device for augmenting human work, in the industrial or military sector, by supporting the arms to perform exhausting work or to provide the additional force necessary to carry out an operation; as a passive assistive device for immobilizing the arm in a certain period of time and as an active device for rehabilitation and restoration of the natural movements of the human arm in the shoulder joint, a support device in physical therapy. The model proposed by me can be applied in each of the three directions of use:

- as a work augmentation device, as the arm can be kept active, with the help of servomotors (in this case voice commands can also be added);

- as an assistive device, as it can actively immobilize the arm in a predetermined position with the help of servo motors;
- as a rehabilitation device, since it can lead the arm in a certain predefined range of motion, following the correctness of the execution, the limits achieved and the force exerted by the user.

Chapter III:

20. We conducted an analysis of the types of sensors used to perform closed-loop control of an exoskeleton intended for the shoulder joint. It requires the use of specific sensors to accurately measure the movements and forces involved, such as position sensors measure the position of the joint, force sensors measure the force exerted by the exoskeleton, IMU sensors measure the speed and acceleration of arm movement, electromyographic (EMG) sensors measure the activity of the user's muscles, and pressure sensors monitor the pressure on the skin to prevent injury. Computer control systems use the data from these sensors, applying machine learning algorithms to tailor exoskeleton movements to the user's needs. Commands can also be given via joystick or voice commands. In these versions of the prototype we used only IMU sensors, and the position sensors are integrated into the servo motors.

21. We performed an analysis of the kinematics of the elements of the skeletal system, in this case the shoulder joint, without considering the forces involved, in order to understand the type, direction, spatial positioning and speed. Even if there are several types of movement in the shoulder joint (translation/sliding, rotation, rolling), we have only considered the rotational movement, found in the glenohumeral joint, to achieve the first moment of movement.

22. We performed an analysis of the types of movements for flexion-extension, abduction-adduction, internal-external rotation, as well as complex movements such as circumduction and circumflexion. (Part of joint biomechanics, arthrokinetics studies the normal functioning of joints and is essential for diagnosing and treating joint conditions).

23. We conducted a study of osteokinematics (osteokinematics is a subdiscipline of joint biomechanics, which focuses on how bones move together, chained, contributing to the normal functioning of joints) for the glenohumeral joint, and an experiment to understand what is the optimal point of mounting the grip on the sleeve and the sleeve on the arm. We mounted the "front-back-down" sockets close to the glenohumeral wrist and the "top" socket at 1/3 base and 2/3 tip, for optimal control and low power consumption.

24. We carried out a study of the opening of movements in the glenohumeral joint in order to find out what the necessary length of the cable is, from the winding on the motor pulley

to the socket on the sleeve mounted on the arm. The opening of the movement refers to the arc, in degrees, described between the beginning and the end of a movement performed by an element in a joint, in a specific plane. It can be applied to a single bone element or a chain of bone elements. For example, in the case of horizontal abduction-adduction of the arm in the Glenohumeral joint, if only the movement of the humerus is considered, the opening is about 130°. The opening of the movement can be active, if the movement is performed by the user, or passive, if the movement is performed by a physical therapist, who leads the user's arm. Knowledge of the opening of movement is necessary during the period of rehabilitation/restoration of natural movements, but also for increasing labor, especially if the arms are held up or sideways, for a long time.

25. We conducted a study to identify the types of movements involved in daily activities and the related movement space. In daily activities, the arches of the bony elements in both joints of the arm, plus the wrist, add up, including movements in one plane and transitions in other planes. The starting positions for measuring the openings of movements in the shoulder joint can be either from the anatomical position (with the arm lowered freely by the side of the body, with the palms facing forward), or from the neutral position (with the arm lowered by the side of the body, with the palms facing the body) or horizontally, at the side of the body, with the palms facing forward. In the simulations carried out, in which we used two or three IMU sensors, we started with the movement of the right arm from the neutral position, horizontally, with the palm facing downwards. There were three simulated activities, "drinking water while sitting on a chair", "drinking water while standing" and "putting a chain around the neck". I only performed these three activities because several types of movement with rotations on the three axes and several plane changes are involved in arm movements. In general, measurements are made only for the right arm, considering that the left arm has the same values, but "mirrored".

26. We conducted a study to identify, based on the literature, shoulder movements (expressed in degrees) during usual daily activities. Most of the daily activities are carried out in the range of movement between (F) [124°/60°], (E) [-90°/-27°], (Abd) [0°/23°] and (Add) [66°/42°].

27. We have carried out an analysis of the principles of capturing the movement of the human arm using IMU sensors, since the movements of the human arm are carried out on different planes and axes and at different speeds, for example "greeting an acquaintance at a distance" and "defending from an approaching object" are carried out with small variations in planes and axes, but with high speed, and "floor sweeping" or "table cleaning" is carried out on several planes and axes, but at low speed.

28. We conducted an experiment in which we designed a device with two MPU6050 IMU sensors to capture arm movement in the shoulder and elbow joints. In this experiment we considered the position of the torso as fixed on the three axes, in which only the values of the angles for the shoulder and elbow are those taken into account to achieve the control of a virtual arm.

29. We conducted an experiment in which we designed a device with three IMU MPU6050 sensors to capture the movement of the arm, in the shoulder and elbow joints. In this experiment we considered that the trunk is also mobile on the three axes and becomes a support for the shoulder-elbow system. Angular values were used to control a virtual arm to perform the daily activity of "grabbing and drinking water from a cup".

30. We have developed an application for processing the data received from the IMU sensors using the quaternions format for representing the animation with the movement of a virtual arm. Quaternion data is used in the control of a virtual arm to represent the spatial orientation and movements of IMU sensors with accuracy and stability superior to Euler angles. Quaternions use a direction vector to define the axis of rotation, combined with an angle of rotation, to describe rotations efficiently and accurately avoiding singularity problems and the "gimbal lock" effect, allowing smooth and efficient interpolation of orientations, essential for precise control of the virtual arm.

31. We developed a Denavit-Hartenberg kinematic model through a simplified diagram of the human arm having three rotational couplings in the shoulder position and two rotational couplings in the elbow position, and in order to approximate the movements of the human arm precisely enough, the distances between the first three couplings and between the last two couplings were considered to be length 0. The complete arm motion matrix has the form determined by the successive multiplication of the relative motion matrices of the component elements of the human arm. Based on the determined matrix we can calculate the resulting position of the arm.

32. We performed the modeling and simulation in MatLab-Simulink-SimMechanics by processing the data acquired from the IMU MPU6050 sensors, in order to reproduce the movement of the skeletal elements of the virtual arm. Following the simulated interpretations, we created the movement profile for trajectory, speed, acceleration and posture, in the case of the daily activity of "grabbing and drinking water from a cup".

33. Based on the research of the biomechanics of the shoulder joint, we conducted an experiment to simulate the movement of a virtual human arm synchronous with the movement of a real human arm based on data taken from IMU sensors. In the experiment we also used the values

of the angles of movements in the elbow joint, to complete the movement of the arm. The results of the experiment can be used in the creation of rehabilitation, assistance or labor augmentation scenarios.

34. Following the analysis of movements in human daily activity for three examples (of "drinking water while sitting in a chair", "drinking water while standing" and "attaching a chain to the neck"), we identified the movement steps and angles of each couple. In each series of movements I started from the neutral position, with the arm in a horizontal position with the palm down, as position 0. We reconstructed the movements of the activity in the simulation by following the rotations on the three axes and performing between 4 and 6 steps. The results of the experiment can be used in the creation of use scenarios for the device intended for rehabilitation.

35. In the simulation of the arm movement based on the steps of realization, the values of the previously identified angles were used as inputs. Thus, for the first simulation (the one of "drinking water while sitting on a chair") the movements were vertical adduction-shoulder flexion-elbow flexion, vertical abduction-elbow flexion, with rotations on the local X-Y-Z local axes; for the second simulation (the one of "drinking water while standing") the movements were horizontal abduction-vertical adduction-elbow flexion-shoulder flexion-internal rotation-shoulder flexion, with rotations on the X-Y-Z axes local-Z local-X local; for the third simulation (the one of "attaching a chain to the neck") the movements were of supination hand-elbow flexion-vertical abduction, with rotations on the local Y-Z-X local-local Z axes. The results of the experiment can be used in the creation of use scenarios for the device intended for rehabilitation.

Chapter IV:

36. We proposed a design model for an exoskeleton device based on the principle of a modified Stewart platform, so that instead of two horizontally positioned platforms, controlled by six movable arms, two vertically positioned platforms would be used, with only four movable arms and a central pillar. This model is inspired by that of the natural human shoulder, which is operated by four muscle groups, and the mobile element pivots centrally in the glenoid cavity.

37. We conducted an experiment to identify the attachment points of the cable fixing sockets on the mobile element controlled using a modified Stewart platform. On the mobile arm we mounted three sockets, one at the base, the second at 1/3 of the base and 2/3 of the tip, and the third halfway between the second socket and the tip. The experiment consisted of validating the idea that at 1/3 of the base and 2/3 of the peak, optimal control of the mobile arm and a reduced energy consumption are achieved.

38. We developed a mathematical model for the proposed platform. If in the classic version of the Stewart platform AO_1O_2M (the corners and centers of the planes) it represents a parallelogram, in the modified version it represents$AO_1O_2M_1$an irregular trapezoid. The vector $\vec{d}$ (the central pillar) has a known and constant length, and the orientation is given by the angles of movement of the shoulder (α, β, γ). Because the planes are square in shape and the distance from the corners to the center is known. The reference system is rotated with the angles $O_2x_2y_2z_2(\alpha, \beta, \gamma)$ with respect to the reference system having the rotation matrix (see page 146) and displaced with the vector $O_1x_1y_1z_1\vec{d}$. After determining $\overrightarrow{c_2}$, $\overrightarrow{c_3}$and $\overrightarrow{c_4}$, the commands of the four motors for driving the arm in orientation are obtained (α, β, γ).

39. AA device for measuring the length of the cables necessary for the transmission of motion for the designed coupling has been made. We considered that the arm is in a neutral position, horizontally, and the servo motors are mounted on the user's back. The total length of the cable is composed of the lengths of the cable wound on the motor pulley, the cable on the route, and the cable from the point of exit of the trunk to the socket fixed on the sleeve mounted on the arm. This resulted in a total usable length of 42cm, which ensures that the movements of the arm are carried out normally.

40. I have carried out a detailed analysis of the existing exoskeleton devices for arm management, in terms of similarities and differences from the model proposed by me and their methods of control, for the three general models of exoskeleton devices, human work augmentation, rehabilitation and assistance, namely:

a. Human Labor Augmentation Exoskeletons:
- Similarities: The main stand is mounted on the user's back
- Differences: The arm support is made of bars, mounted on the outside of the arms
- Control: Most have a passive control, activated when raising the arms

b. Rehabilitation exoskeletons:
- Similarities: Most of them use cables, but also wearable structure
- Differences: Uses Bowden cables, up to seven cables and three sleeves or even pneumatic cylinders
- Control: In some models, the continuous cable tensioning method is implemented

c. Assistive exoskeletons:
- Similarities: Most provide assistance with shoulder movements, but some also provide assistance with elbow movements

- Differences: Most provide assistance in performing shoulder flexion and abduction and elbow flexion movements
- Control: Some have an active control of the cable tension, and in other cases the adjustment is done manually

41. Based on the analysis of identifying the common elements with the device proposed in the thesis, we found that in recent years wearable, relatively light devices have been made; some having cables fixed on sleeves mounted along the arm, operated by linear actuators; most of them are intended for the medical rehabilitation of users, generally those affected by stroke and almost all of them have control and actuation elements mounted on the user's back.

42. We have designed an exoskeleton-type device that can attach to a human garment, intended to support or move the upper limb of a person who is unable to support or move their upper limb. The device acts in the area of the shoulder joint and supports in particular the movements of the glenohumeral joint. The device is mounted on a textile stand tailored in the form of a garment. Below this layer is the resistance layer on which all the hardware elements are mounted. This resistance layer is a flexible mesh created from 44 hexagonal plates. On the textile layer are mounted the control and drive systems, and the 4 cable routes. Underneath these two layers is the comfort layer, the one that will come into contact with the user.

43. We designed and manufactured a flexible mesh to be the support on which to mount the hardware elements of the device. This flexible mesh is composed of 44 hexagonal plates, and has a relative rigidity, because it creates a resistance, left-right/up-down and diagonally, large enough to hold the motors in the same place, but which has some front-to-back flexibility, to be able to mold to the shape of the user's back. Until version 3.0, the four motor sockets were also mounted in the mesh body. Up to this point the mesh covers a small part of the user's back surface, and in a later approach I will complete the mesh to cover the entire surface of the user's torso.

44. To route the cables to the sockets on the sleeve mounted on the arm, we designed the routes of the cables for the transmission of arm movements, taking into account the positioning of the muscles that contribute to the movement of the human arm. Thus, we established four cable exit points on the user's torso. Then we completed the routes by installing a few small guides to smooth the movement of the cable along the route.

45. For this device we have designed four versions. In the *first version* we sketched the place of the servo motors, the points that will form the routes, we made the elements that will form the "shoulder" and "arm" of the device, the sleeve, the sockets and the flexible mesh. In *the second version*, we guided the cables with the help of metal elements, and the steel cables were fixed in the sockets on the sleeve. On the textile support I mounted two IMU sensors, one in the nape of

the neck area and the second at the end of the "arm", in the elbow joint area, for movement feedback. In *the third version*, we made a central element of direct cable guidance to the motor pulleys, because after many rehearsals the cables tended to behave like a spring coil and jump off the motor pulleys. In *the fourth version*, we have made a number of essential changes, such as reconfiguring the position of the servo motors to facilitate the movement of the cables; we have replaced the socket of the servo motors integrated into the flexible mesh with independent elements fixed to the mesh; we have replaced the metal guide elements with passive guide elements, in which we have fixed the Teflon tubes, and active elements with pulleys with bearings, In order to be able to change the direction of the cable even at 90° without affecting the fluidity of the movement; we replaced the steel cables with braided silk threads for the fluidity of movement; we replaced the sockets for the steel cables, on the sleeve mounted on the arm, with sockets for the silk threads. The common elements of all versions are: a "male bust" mannequin as a support for the device, at the bottom of the mannequin we placed the power supply, and on the textile support, under the motor area we fixed the control plates.

Chapter V:

46. We have made a brief presentation based on the technical sheet of the servo motors used:

- *The "Dynamixel AX-12A" servo motor*, produced by Robotis, is a complete actuator, offering improvements over the previous AX-12 model, but maintaining full compatibility with it.
- *Technical specifications*: *Communication speed*: 7.843 bps - 1 Mbps, *Running rate*: 0 - 300° (with endless running), *Gear ratio*: 254:1, *Locking torque*: 1.5 N.m at 12V, 1.5A, *Input voltage*: 9.0 - 12.0 V, ID: 0-253 (254 reserved for broadcasting), *Feedback* for position, temperature, load, input voltage.
- *Features & Limits*: *Angular Limit*: Restricts movement using CW and CCW limits, *Temperature Limit*: Protects against overheating, *Voltage Limit*: Adjusts voltage range for protection, *Maximum Torque*: Adjustable for optimal performance, *Lens Position & Travel Speed*: Precise Motion Control, *Torque* Limit: Adjustable for protection and performance.
- *Data size and access*: *Data size* ranges from 1 to 2 bytes, with "RW" (read and write) or "R" (read-only) access. Initial values are restored when the device is turned on for consistency.

47. We have made a brief presentation based on the technical sheet of the IMU sensor used:

- *Device Type*: *6-axis serial* accelerometer, *high-precision* gyroscopes, *Filter technology*: Kalman algorithms for noise reduction and accuracy improvement, *Functions*: Real-time motion tracking and attitude determination in dynamic environments.
- *Performance*: *Accuracy*: *Static* up to 0.05° and *Dynamic* up to 0.1°, *Voltage*: 3.3V - 5V, *Current*: < 40mA, *Measuring ranges*: *Acceleration* ±2/4/8/16g, *Angular velocity* ±250/500/1000/2000°/s, *Angular attitude* ±180°.
- *Benefits*: *Accurate and stable measurements*: Optimized performance in dynamic environments, *Versatility*: Effective in various environments and conditions, suitable for wearable devices, autonomous vehicles, and industrial equipment.

48. We designed an exoskeleton loop conduction system. To ensure precise control of an exoskeleton, it is essential to use an advanced system of sensors and decision algorithms. We have implemented an IMU sensor mounted on the user's torso, which controls the vertical and horizontal movement of the arm based on the inclination of the torso.

- *Movement control*: *Trunk sensor*: Left-to-right trunk movement controls vertical arm abduction-adduction, while front-to-back movement controls horizontal abduction-adduction; *Tonearm sensor*: The second IMU sensor placed on the user's arm monitors the tonearm's response to commands in real-time, facilitating instant adjustments.
- *Algorithms and simulations*: We presented a specific control algorithm and simulation scheme in MatLab-Simulink. This allows the testing and adjustment of the parameters of the control algorithm, ensuring the optimal functioning of the exoskeleton.
- *Implementation in C Embedded language*: Exoskeleton control was implemented using specialized libraries for servo motor management. These libraries allow precise and efficient handling of servo motors, ensuring coordinated and fluid movements. Advanced control algorithms dynamically adjust the exoskeleton's mechanical behavior based on commands and sensory feedback, optimizing user performance and comfort.

49. We proposed a driving model based on the operating principle of a joystick, which considers the movement of the trunk as the intention to move the arm.

50. We designed the logical scheme of driving the exoskeleton based on the movement of the trunk. This is based on the tilt angles of the user's torso measured by IMU sensors:

- *Lateral movement* (): If the torso is tilted to the left between [5° and 30°], the exoskeleton raises the arm; If the trunk is tilted to the right between [-30° and -5°], the arm is lowered; These movements respect the natural amplitudes of human joints, limited to a range of [-90°, 90°] for vertical movementsα_x.
- *Anteroposterior movement* (): The inclination of the torso towards the front between [5° and 30°] causes the arm to move forward; Tilting the torso backwards between [-30° and -5°] causes the arm to retract; The limits of movement on this axis are set between [-30°, 150°], preventing the natural movement capacity of the arm from being exceededβ_y.

51. For evaluation and testing, we developed a simulation in MatLab-Simulink that uses a simplified model of the IMU. The simulation uses SliderGain elements to simulate the response of IMU sensors, ensuring optimal exoskeleton operation under various conditions of use.

52. We have made an exoskeleton driving application based on the logic scheme presented above. The implementation of exoskeleton control was carried out using the embedded C language and dedicated libraries for servo motor management, ensuring precise and efficient movements. Advanced control algorithms adjust the mechanical behavior of the exoskeleton according to the given commands and sensory feedback, optimizing performance and user comfort. The Arduino code (shown in Appendix 1) uses the `Dynamixel2Arduino` library for controlling Dynamixel servo motors and `SoftwareSerial` for serial communication. Hardware configurations and rotation values are defined in code, and setup and `loop functions` manage the initialization and operation of servo motors, including setting target positions.

53. We built a dataset to train a machine learning model to drive the exoskeleton based on trunk movement. The data collection process for the constitution of the training dataset was structured in three distinct sessions, each aimed at capturing specific types of arm movement in coordination with the trunk. The goal of this approach was to diversify the data to train a *machine learning model* capable of correctly interpreting the different types of human movements.

- *In the first session*: The subject performed the movement of the arm from top to bottom approximately 10 times, synchronized with the movement of the trunk; This session aimed to collect data on vertical movements, which simulate the raising and lowering of objects or natural gestures in a vertical plane.

- *In the second session*: The subject performed the movement of the front-back arm 10 times, synchronized with the trunk; The goal was to capture the dynamics of the arm in anteroposterior movements, such as pushing or pulling an object.
- *In the third session*: The subject repeated the circular movement of the arm 10 times, in coordination with the trunk; It aimed to collect data on complex, rotational movements, useful in assessing arm coordination and agility.
- After the completion of the three sessions, the collected data was gathered into a consistent dataset. Of these, 80% will be used for training the model, and the remaining 20% for its validation. Random selection of training and validation subsets ensures that the model is tested on data unseen during training, providing a realistic assessment of its performance and generalization. This systematic methodology not only optimizes the training process, but also contributes to increasing the accuracy and reliability of the *machine learning model* developed.
- 12 volunteers participated in the data collection sessions.

54. For the design and construction of the device with the two IMU sensors for collecting data sets, we used equipment designed to rehabilitate the posture of the back, as it has solid parts and fasteners around the torso. On the solid elements we mounted the sensor on the back and the control plate, and the sensor on the arm was mounted on a sleeve that is fixed on the arm with velcro.

55. Dataset analysis by the PCA (Principal Component Analysis) method applied to a dataset to determine the main components that capture the variation in the data. Key results include:

- *First Principal Component (FP1):* Explains 76.9144% of the total data variance; Captures most of the essential information related to trunk and arm movements, suggesting a general movement or main trend in the data.
- *Second main component (FP2):* Explains another 23.0856% of the total variance; Captures outstanding information that is not explained by FP1, representing variations independent of those captured by the first component.
- *Cumulative Variability Plot*: Demonstrates that adding the first component provides a complete representation of the data; The second component captures the entirety of the variation in the data set, and after this the curve flattens out, indicating marginal gains from the inclusion of the third component; The PCA shows that the variability of the dataset can be largely explained by the first two components,

suggesting that for further analyses, data complexity can be significantly reduced without losing essential information.

- PCA allows data to be simplified by using key components to build simpler and more efficient models, while providing a clear understanding of the main factors influencing the dataset.

56. We trained and evaluated a support vector regression (SVR) model to predict arm movement values based on trunk movement, and involving the following steps:

- *Data collection and preparation*: In this step, data is collected from sensors that monitor trunk and arm movements. For example, the inclination angles of the trunk and the angles of movement of the arm during specific activities are recorded.
- *Data exploration and visualization*: Examines data distributions, relationships between variables, and identifying any anomalies; Data resizing: Using PCA to reduce the dimensionality of the dataset and identify the main components that explain most of the variation in the data.
- *Split the training and test dataset*: The data is divided into training (usually 80%) and test (20%) sets to evaluate the model's performance on unseen data. This division can be done randomly or using cross-validation techniques.
- *Training the SVR model*: Choosing the kernel (linear, polynomial, radial-basis function - RBF), the regularization parameter (C) and the epsilon parameter (ε) that defines the accepted margin of error; The SVR model is trained on the training set using input data (trunk movement) and target values (arm movement); The SVR algorithm finds the regression function that minimizes the prediction error within the specified margin of error.
- *Model evaluation*: The model's performance is evaluated using metrics such as Mean Squared Error (MSE), Mean Absolute Error (MAE), and Coefficient of Determination (R^2, is an indicator that shows how well the model's predictions match the actual data, with a maximum value of 1). These metrics help quantify how well the model predicts arm movements on the test set; Cross-validation: Performing cross-validation to ensure that the model is not overtrained (overfitting) and that it generalizes well on new data.
- *Model optimization*: Based on model performance, hyperparameters are adjusted to improve the accuracy and robustness of predictions. This process may involve grid

search or random search; The final model, with the optimal hyperparameters, is re-evaluated on the test set to confirm performance improvements.

- *Implementation and use of the model*: The final model is implemented in a real-time prediction system that takes data from sensors and provides predictions of arm movements; The model's performance is continuously monitored, and the model is periodically retrained with new data to improve accuracy and maintain relevance over time.

57. We developed a MatLab model for SVR for training with the built dataset. The MatLab code performs the process of training and evaluating the support vector regression (SVR) model to predict arm movements based on trunk movements. The data is loaded from three CSV files and concatenated to form a complete data set. The input and output (label) variables are extracted, indicating that the model uses two *predictor variables* to estimate three response variables. The SVR model is trained for each output (response), using a Gaussian kernel and optimized parameters. After training, predictions are made and accuracy metrics such as *mean square error* (MSE), *mean absolute error* (MAE), and *coefficient of determination* R^2 are calculated to evaluate the model's performance.

58. We analyzed the accuracy results, namely MAE and R^2: The results of the trained SVR model for predicting arm movements based on trunk movement were evaluated using two main metrics: Mean Absolute Error (MAE) and Coefficient of Determination (R^2).

- *Mean Absolute Error (MAE):* The first dimension of the output has MAE = 8.89; Interpretation: On average, the model's predictions deviate by about 8.89° from the actual values. Given the scale of measured values [-90, 90°], this error is average; The second dimension of the output has MAE = 4.778; Interpretation: The predictions are more accurate compared to the first dimension, with an average deviation of 4.78°; The third dimension of output has the MFA: 8.60; Interpretation: The error is similar to that of the first dimension, suggesting a medium accuracy for the value range [-30, 120°].

- *Coefficient of Determination (R^2): The* first dimension of the output has R^2 = 0.921; Interpretation: The model explains 92.14% of the observed variance in this dimension, which indicates an excellent match between predicted and actual values; The second dimension of the output has R^2 = 0.883; Interpretation: With an R^2 of 88.34%, the model demonstrates a good performance, although slightly inferior compared to the first dimension; The third dimension of the output has R^2 = 0.836;

Interpretation: This is the lowest R^2 coefficient of the three dimensions, indicating that the model is less efficient in explaining variance in this part of the dataset.

- *Conclusions*: The EAW varies between 4.78° and 8.89°, indicating different levels of precision depending on the size of the movement; The R^2 ranges from 0.836 to 0.921, showing that the model fits well with the data, but there is room for improvement, especially in the third dimension. These results suggest that the support vector regression (SVR) model has a solid performance in predicting arm movements, but the accuracy varies depending on the specific size of the movement.

59. I filed a patent application with OSIM with the title: *Device attached to a human garment, intended to support or move the upper limb of a person*, and the registration number: **A/00813/30 dec 2021**

FURTHER DEVELOPMENTS

As for future research directions, I can define some main proposals:

- I am considering the development of the support placed on the patient's back in order to be able to perform the second moment of movement, by fragmenting the sector in the shoulder area, which will have an independent mobility, like the shoulder blade in its movement on the rib cage, in order to perform vertical abduction and adduction movements up to the maximum limits of movements.
- Then I consider increasing the power of the arm by using two servo motors in tandem to perform each type of movement, so that the servo motor that leaves the wire free to climb the arm, will also lift it, by using two pulleys to wind the cable on each servo motor.
- With the third proposal, I am considering making sockets on the sleeves mounted on the arm, which would also have the function of checking the cable tension and adjusting it, in order to be in the optimal parameters.
- In the fourth proposal, I envisage extending the control of movements to the elbow joint and perhaps even to the wrist, and to achieve the three types of control, through scenarios, through user action and through Artificial Intelligence.
- Then I want to complete the device, so that I can control the movements of the left arm, in addition to those of the right arm, and all the hardware components attached to the support mounted on the patient's back are integrated inside that support.

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