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Research and Development on Mobile Powered Upper-Body Exoskeletons for Industrial Usage

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Abstract— **This work is completed as a part of an exoskeleton project that was started to solve a specific problem. The scope covers the research and development of a lightweight mobile active upper-body exoskeleton for industrial workers who are lifting heavy loads on daily basis. It shall be a powered electromechanical device to decrease the musculoskeletal fatigue on the user with human augmentation properties. There will be certain constraints such as body part, mobility, and activity. The proposed design is the most optimized version that can be produced with the current state of the related studies.**

Keywords- exoskeleton; upper-body; research; development

I. INTRODUCTION

The heavy lifting operations on daily basis can cause several injuries on muscles and bones of the workers. Especially in automation factories, where carrying loads are a part of the job, there is a need for extra precautions for health and safety. However, the solution should not cause more stress or demotivation on the user, but it must increase the efficiency. Many workers report they have injuries or health risks due to their work. A considerable amount of these are physical hazards, mainly upper-body problems, and there should be preventive measures. An exoskeleton is an innovative and efficient solution for such situations.

The scope of this project concerns in an active mobile upper-body exoskeleton that will be used by industrial workers during heavy lifting operations [1]. This lightweight electromechanical wearable device must result in human augmentation when required. After comprehensive research on developed exoskeletons, even though similar goals are achieved with certain projects, it is concluded that the optimum design is not yet developed. The concept of exoskeleton itself still has no standards for itself. Also, even though power and communication aspects are similar to physical assistance robots, an exoskeleton must have exclusive design and control architecture developed for the specific work process. The optimized device shall be prototyped after this study.

II. LITERATURE REVIEW

In the beginning of this study, a comprehensive literature review on exoskeletons is conducted including the history and state of art [1]. In general, an exoskeleton is a multipurpose robotic device which can be used in various fields. For example, exoskeletons for industrial usage are designed for supporting manual labour tasks in production factories are now available commercially [2]. They are considered as ergonomic solutions for workers who need to perform physically demanding actions, especially for long time periods, such as lifting and carrying heavy objects, to enhance their performance and reduce stress on workers' bodies. Exoskeleton types can be divided in many ways as seen in Table 1 [3].

TABLE I. CLASSIFICATION OF EXOSKELETON TYPES

Classification	Exoskeleton types
Power consumption	Passive, Powered, Pseudo-passive, Hybrid
Mobility	Mobile, Fixed, Supported
Control method	Sensors, Panels, Not controlled, etc.
Materials used	Flexible, Rigid, Hybrid
Origins	Labs, Governments, Companies, Home built
Body part	Full body, Upper body, Lower body

The application fields are mainly focusing on medical, industrial, and military with numerous products of successful exoskeleton companies. There are well-known exoskeleton companies that work on industrial applications and some of their products' information is publicly available. For this scope, most relevant ones are the upper-body exoskeleton products of companies Exhauss [4] and Innophys [5]. However, even they have shortcomings such as requiring air supply or cost.

It is important to consider the acceptance of the device by the intended users. Main points to consider are facilitating conditions (the trainings given by the organization), ease of use (required effort or practice to use the system), performance improvement (advantages during work), social influence (thoughts of colleagues), user reaction (given feedbacks), and international standards (appropriate certification). There are many sources that is worth learning about to improve the theoretical and practical understanding on exoskeletons such as European Space Agency (ESA), MovAiD, AXO-SUIT, Wearable Robotics Association, and Exoskeleton Report. Also, there are many related research in universities all around the world like Nakamura Lab (Biomechatronics Laboratory of Chuo University) and Aalborg University (developed the AnyBody software). These are projects identifying and fixing existing problems, or simply experimenting [1].

After the academic research, current research interests and related benchmark are investigated. According to Scopus, there are more than 25000 documents that has the concept of exoskeletons in them, mostly articles and conference papers in engineering areas. There are many theoretical research and practical development done for various applications using exoskeletons. However, they are still not commonly used in any field, and they need much more improvements.

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A. *Related Standards*

International standards regarding exoskeletons are still a very young concept. Currently, they are mainly considered as service (i.e. household, personal care, and medical) robots and most of them are studied under personal care (i.e. mobile servant, physical assistant, and person carrier) robots. Physical assistance robots can be restraint (exoskeleton) and restraint-free (humanoid) types. Exoskeletons are getting to the industrial levels they deserve with the standardization reforms of organizations like IEEE, ISO and ASTM. The main standards used in this study is [6]. Besides to the ISO standards, there is a separate set of standards regulating Exoskeletons and Exosuits in industrial applications by ASTM within Committee F48 [7].

The standards regarding the power of the device are divided in three parts as storage, failure/shutdown, and start-restart to have a safer look on each part individually. In addition, contact with the hazardous energy parts is also a major safety issue to consider on the design. However, hazards due to the design is not limited to the energy scope but electromechanical too. It includes robot shape, insufficient durability, contact with moving components, and electrostatic potential. Other than these, hazards due to emissions such as noise, vibrations, and extreme temperatures (both cold and hot) must be considered for safety as well as comfort of the user. It is also possible to have stress or hazards due to the usage of the robotic device. This can be physical stress and posture hazards or mental stress and usage hazards depending on the situation. Ergonomics and maintenance needs of the device must be developed accordingly. Another point to consider is instability due to robot motion which includes mechanical instability, instability while carrying loads, instability in case of collisions, and instability while attaching/removing the robot. Lastly, it is important to protect the wearer from autonomous decisions and actions of the exoskeleton. Extra validation and verification steps can be added to the exoskeleton control and monitoring algorithm in case of faulty or dangerous circumstances.

III. HUMAN-ROBOT INTERACTION

The interaction study between human and device includes information about kinematics and gives an idea about the work process. The baseline analysis of a human body without the exoskeleton should be known for further comparison including the motion of parts and angles of joints. Then, the actual interaction between the musculoskeletal human and exoskeleton systems can be evaluated and optimized [8].

There have been studies to create proper human kinematics and dynamics knowledge on upper-body for exoskeleton development by studying the manipulability and isotropy of genuine devices. It was discussed that the daily life of a human requires tasks using a combination of joints and velocities. Three most common combinations are high velocity in the shoulder and elbow joints with low velocity in the wrist joint, high velocity in the wrist joint with low velocity in the shoulder and elbow joints, or high velocity in all three joints [9]. It is worth noticing that most studies have assumptions as well as focus points on the body. Many relevant research is worried about the arm structure (with the shoulder) but not the waist.

The interaction of human and exoskeleton systems is dependent on the kinematics of both. Mutual effects should be considered for a better performance on both cognitive and physical aspects. Analysis of the interaction must achieve minimal discomfort (good ergonomics) with a cost-effective approach. Ergonomics essential on every wearable robotics application that must be addressed by analysing all phases such as put on/off, standing/sitting, and working. For this, the design must include the environment/workplace as well.

A. *Work Process*

There have been many reports and studies examining the work process and the worker disorders in recent years. The European Risk Observatory Report of European Agency for Safety and Health at Work (EU-OSHA) has detailed surveys related to musculoskeletal disorders (MSDs) as well as health, safety, and risk factors due to daily work processes [10].

Other than optimizing the exoskeleton design for the job description, the work area can also be adjusted to be more suitable for working with one. For a specific environment, a simulation with the variables and the scenery can be created. Figure 1 shows an example of such a process where the worker picks up a box and places it on a lift as a part of the job [18].

Figure 1. Process simulation to show work process without exoskeleton [18]

B. *Physical Interaction*

Focus of this study is on physical interaction rather than cognitive because of the nature of the desired task. The mechanical process must have better results and the user shall not require extreme knowledge or training to use the device.

Inadequate force application can cause fatigue, which means temporary loss of strength or energy due to hard work. More specifically, continuous mechanical loads to limbs can cause the loss of endurance. The main concerns here are the human tolerance of pressure and mechanical character of soft tissues [11]. Depending on the application, the variable impedance can be selected by different control approaches such as telemanipulation, functional compensation, rehabilitation, or empowering. The scope of this study is interested in the empowering approach which has a goal of amplifying the physical capacities of the wearer. Here, the user gives control signals while the device provides mechanical power. The target impedance is determined to minimize the interaction force, which can be achieved with a zero-interaction force controller. 1 DOF controller of such kind can be seen in Figure 2 [11].

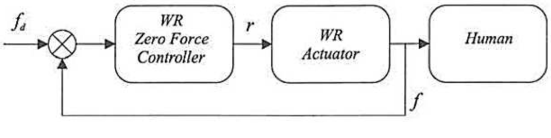

Figure 2. Example for 1 DOF zero-interaction force controller [11]

IV. POWER REQUIREMENTS

Every mobile robotic device requires a portable energy storage element to provide power for the desired operation. In any wearable robot, the chosen technology for this must supply the needed power and energy. For an exoskeleton application, the storage system can include fuel cells, batteries, or a hybrid source. However, there is a trade-off between required parameters and cost as well as weight of the storage device. Optimal choice shall be decided with the appropriate actuators within the planned control strategy. Also, the design of the exoskeleton must ensure that the energy storage component and human body remains separate as described in the standards section previously. Most popular energy storage systems include lithium-ion, sodium-sulphur, and sodium-nickel chloride as they are the high energy (W·h/kg) batteries [11].

Since the scope of this study is focused on a mobile electromechanical exoskeleton, the required power must be supplied from a battery attached to the device. Most commonly used batteries for augmentation focused devices, including several projects mentioned before (i.e. AXO-SUIT), are rechargeable lithium-ion batteries (LIB).

V. COMMUNICATION PLANS

The communication plans include a general overview of network terminology and communication technologies. In network technologies, the terminology is usually defined by the engineers working on such protocols. Various protocols are already established for wired and wireless communication by many agencies. However, for the basic understanding of the topic, understanding terms Quality of service or QoS (high QoS means good control of the network), Latency (time between the occurrence of an event and its effects), and Network topology (the way physical interconnections between the nodes of the system is implemented) are enough without the details of protocols [11]. Different network topologies (star, bus, mesh, ring) can be used for different applications according to the needs of the system. For this exoskeleton, even though all topologies have their own benefits, bus topology is the most decent choice. There are many more less crucial terms used in communication such as network throughput (amount of information transmitted on a period of time), data fusion (clustering process of combining the acquired information), and ambient intelligence (create local interaction by short-range networks) [11].

Choosing the proper technology for the communication is the main step after defining the network requirements. In industrial applications, high QoS with the wired networks such as fieldbus is preferred. In wireless systems, it is possible to improve QoS by transmission mechanisms, dynamic routing algorithms, and acknowledgement schemes. Yet, the low latency is only guaranteed by the wired control [11].

Components of a network can be gathered in various combinations. One common component in all networks is the controller. Other than that, various sensors and actuators can be used. The sensors will be used in several ways such as describing the nodes, calibration, adjusting frequency, filtering results, and checking problems. In addition, it is beneficial to have data loggers to save the generated data during the process. Information can be stored by memory cards with different writing speed and protocols. With every new component, the network traffic will increase, and controller must optimize the process (e.g. treating data logger as actuator) [11].

The control and monitoring of the exoskeleton can be done by using various methodologies. In fact, according to needs of the exoskeleton system presented, it may be more practical to use different technologies on control and monitoring. Control of the exoskeleton is more efficient in several aspects with the wired communication technology while the monitoring of the working process of the exoskeleton is much easier with wireless technologies.

VI. DESIGN OF THE DEVICE

The design of a new upper-body exoskeleton requires several levels of work. In addition to the background studies done for the existing products and research, there was a need to have a preliminary design to support the initial work to evaluate the conducted research [8]. Getting inspiration from AXO-SUIT and MovAid designs, a preliminary design was prepared to enrich the initial research. To have an idea on the motion of the exoskeleton, a certain motion simulation was conducted with the preliminary design. For the safety of the user, the shoulder and elbow joints must be mechanically limited between 90° - 180° degrees. The aim is to make a 90° motion for each joint and make them move from first position to the second position as shown in Figure 3 [8]. Even though these maximum positions may not be required in real-life, it must be addressed in simulation for accuracy.

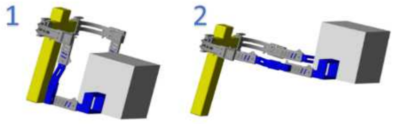

Figure 3. Simulated motion positions of preliminary design with a load [8]

Comparison of mechanical behaviour shows the least deformed results when the parts are subjected to same load. Tension, compression, bending, and torsion simulations with circle, rectangle, and ellipse shapes (cross-sections with almost constant total area) for the cross-sections of four parts of the exoskeleton (back, lower arm, upper arm, and shoulder) are used to choose the optimum shapes as well as the alternatives. Below, Figure 4 shows the generic form and position of these main parts as rigid sticks [12].

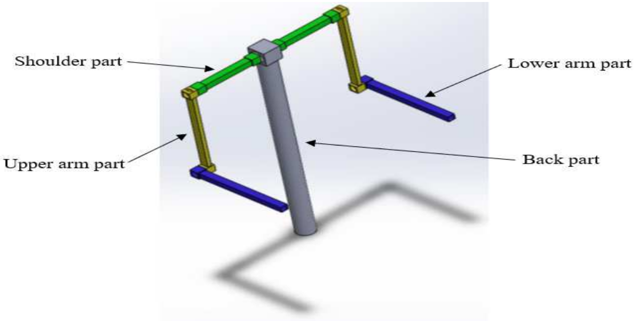

Figure 4. Generic draft of the rigid parts of the exoskeleton [12]

Simulations are resulted with the best shape for lower arm part as Circular Inner Shape and Rectangular Outer Shape (CISROS), upper arm part as Ellipse Inner Shape and Rectangular Outer Shape (EISROS), shoulder part as Circular Inner Shape and Rectangular Outer Shape (CISROS), and back part as Circular Inner Shape and Circular Outer Shape (CISCOS) cross-sections [12].

Braces are important connection points with the human and exoskeleton. The simplest choice for the limbs is the bands to attach to the wearer. They will be basic Velcro straps, adjustable to the waist and arms of the user. Of course, the straps should be as thick as necessary but not uncomfortable. The hand part of the exoskeleton, after the wrist joint, is decided to be a rigid part without a glove-like structure. It will remain as a piece to put the hand in like the preliminary design.

A. Joints

The joints of the exoskeleton can have various DOFs and they can either be passive or active. In this particular device, the only active joints will be on shoulders and elbows. Each arm shall have three powered components (two on shoulder and one on elbow joint) to allow the user all motions such as flexion, extension, abduction, and adduction. It is impossible to have the exoskeleton match the human perfectly on joints. But it is suggested that direct installation of the drives on the active joints minimizes the problems. A novel device called Stuttgart Exo-Jacket reaches up to 12 DOFs on arm kinematics with a similar design [13].

Main challenge on upper-body exoskeletons is shoulder. There are several studies that aims to have the optimum joint design (e.g. AXO-SUIT). A good example is the hybrid mechanism with two revolute joints connected via a double parallelogram linkage (DPL) rotating around a center of motion seen in Figure 5 [14].

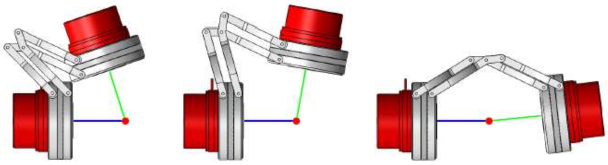

Figure 5. DPL joint for shoulder complex [14]

The rotational motions are protraction (extension) or retraction (flexion) and elevation (rising) or depression (recession). DPL mechanism is chosen as the ideal shoulder complex joint here as well. It will consist of two motors on each side and connect them passively allowing a movement around the imagined center of motion.

The mechanically restricted (between 90° - 180°) active joint on the elbow does not have to be very complex, it can be a simple 1 DOF joint with extension ignored. In addition, the joint on the wrist is chosen to be a passive one since it will be neither useful nor necessary for any lifting operation. The passive joints on upper arm and lower arm as well as the wrist shall allow a turn of 180° (±90° from the initial position) for comfort and flexibility. Figure 6 shows the joint positions and information on whether they must be active or passive [1].

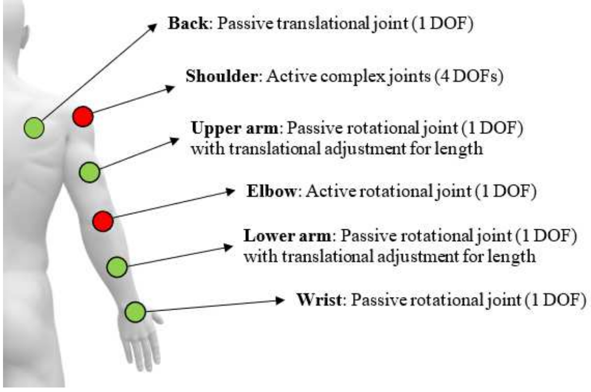

Figure 6. Information of joints [1]

Topology optimization is the most beneficial design method for devices with weight and cost limitations. To have a more efficient design, it can be used to minimize the used material while keeping the mechanical strength intact [15]. This is how the ideal weight shall be reached for the device.

B. Torso

Regarding the design of the torso piece, it is observed that users prefer a crossed X shaped vest on the chest rather than a regular rucksack and straps. In addition, the belt on the waist is preferred to be wider since it unloads the assistive forces on a larger body area [16]. Figure 7 shows the less preferred version among workers on left and the more preferred version on the right [16]. The exoskeleton shall have locks under the arm and in the middle of the belt with hook and loop fasteners.

Figure 7. Less (left) and more preferred (right) designs [16]

C. Mechanical Draft

The electronics required for the control such as main processor is lightweight enough to store them at the upper back position. They will not give a considerable amount of load to the spine. The mechanical design of the exoskeleton should satisfy all the aspects discussed earlier and be as simple as possible. According to the completed research, a mechanical draft was developed, only including the rigid parts and joints, excluding the soft interaction parts and electrical components. This can be considered as the skeleton of the exoskeleton.

The controller will be on the back, and the rigid parts will not interact with the user directly without any soft plastic or textile part in between. Even though the main concern is human augmentation here, comfort should be considered, and interaction forces must be minimized. Therefore, an elastic piece between the rigid back part and the belt is added to ease the stiffness. The active joints are including LEDs on them to indicate the activation of each one. Since the users will be considering the exoskeleton as not a robot but like a jacket, the ease of use including the time and effort to wear it is essential.

Static analysis showed that the design is more than capable of carrying 30 kg load without any stress or strain. There were several issues due to primitive design but eventually mesh was possible to create and, including the rotational joints, it acted as expected. Analysis of fatigue was harder to achieve with imperfections of the design. The data used in here (load, material, etc.) were implemented from the static simulation. Total damage information with these was minimal as expected. However, total life simulation showed a fine detail that would affect the maintenance work needed for the device. Especially the elastic piece used between the rigid back part and the belt connection on the waist will have much shorter life than the other parts. Therefore, it shall be replaced within certain periods of usage. Figure 8 shows the simulation results for static strain and fatigue life cycle analysis [1]. On the strain simulation, equivalent strength on the device is calculated low enough to not stress the device. On the fatigue simulation, total life cycle of the device shows that it can endure a high number of usage for given tasks.

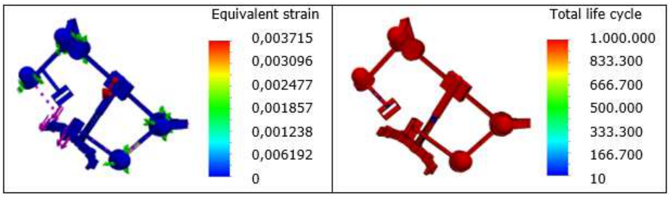

Figure 8. Static strain (left) and fatigue life (right) analysis [1]

The weight of the device when all the elements in this draft is considered as Titanium alloy (including the actuators considered as solid elements) is 34.8 kg. It is important to notice that this choice was done because it is a simulation study, if it was an experiment with a real-life prototype then this choice will be very heavy and costly. The total weight of the device should not exceed half of the maximum load capacity (30/2=15kg) no matter how ergonomic the design is. Ideal design would have no more than 10 kg total weight.

To sum up, created design of this exoskeleton will resemble a combination of previous projects with similar aims such as [13], [14], and [16]. Increasing the number of design parameters shall benefit the result but higher number of joints, or DOFs on joints, will result in a complex system.

VII. CONTROL APPROACH

Mainly, two most important components for control of the system are the actuators and sensors. Other elements mostly work with these elements to have the desired outcome.

Series elastic actuation (SEA) architecture for the control is mainly used to reduce the mechanical stiffness on the actuators. They can be controlled with position or torque modes with simple algorithms that monitor each joint for torque constraints. It is also possible to use SEAs for detecting contractions and collisions [17]. The reason electrical motors are used commonly for similar devices is that they are dynamic, precise, and controllable with motion systems [18]. Figure 9 shows the basic schematic of a SEA (a) and elements of such actuator (b) used for a lower-body exoskeleton [19].

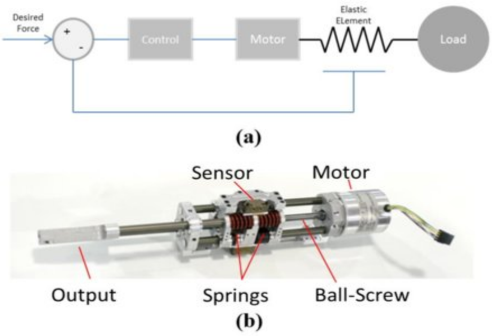

Figure 9. A series elastic actuator schematic (a) and elements (b) [19]

According to the design, the motors (6 in total) and their controllers will be located on the active joints for more optimum design. A similar exoskeleton design uses a motion controller on each motor directly installed within the joint [20]. Chosen actuators, motors, or drives can be adjusted or changed according to the specific application of the exoskeleton. Nevertheless, regarding this device, active joints shall be supported with high power density electronically commutated (EC) motors. These motors must be flat type to minimize the volume of the device.

In a measurement system of any wearable robotics system, there is a trade-off between functional accuracy and simplicity. For this case, the control and monitoring algorithm is mainly based on angular position measurements. Most important additional ones are physical kinematic measurements which includes force, torque, and pressure sensors as well as linear displacement when necessary. The chosen sensing technology for the motor position control (and even speed control when applicable) is joint position transducer, specifically encoders. Since the angle measurement is essential for the intended control algorithm, it is safe to have the information directly from the active components. Therefore, there will be direct data acquisition instead of indirect with sensors/transducers located on the joints. Having such a transducer instead of a simple sensor for measuring the angles is more efficient and reliable. One of the most efficient methods used in exoskeletons is having absolute encoders with pressure (and sometimes torque) sensors/transducers [20]. The Force Sensing Resistor (FSR) is a commonly used technology on similar applications too, especially when they are located under the feet to measure the weight of the user and load [20] [21]. In addition, to measure the speed of the motor, even though encoders shall also be used here, tachometers can be added to double check the results.

Controller will take the relevant information from the sensors/transducers such as position (encoder) or speed (tachometer) and adjust the actuator motion by giving the appropriate commands including the right current and voltage values coming from batteries. In any number of differences between these values, average value must be considered until the measurements can be repeated, which should take less than a second if a microprocessor is used. This power management process must constantly observe the current, voltage, and temperature of battery cells to calculate the required energy. Similar systems use CANOpen for communication [13].

A. *Algorithm*

The algorithm shall be coded into the microcontroller to control the whole system. It must be as simple as possible to allow further improvements and adjustments. Therefore, it is decided to accept the previously conducted motion simulation assumption and give the exact responses to both arms when the device is active. This will also encourage the workers to move their arms in parallel to each other when lifting, forcing them to carry equipment with both hands all the time.

The basic control strategy is given in Figure 10 as a block diagram. Here, square represents the main components and specific controls are shown as circles with arrows to indicate they are loops. Pressure (hands) and temperature (joints) sensors were added separately since they are not really a part of the loops. It must be addressed that the controller and battery connections to each part is not given in here to make it simpler.

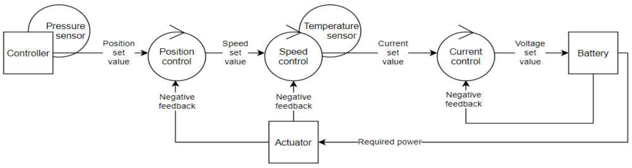

Figure 10. Basic control strategy representation for the exoskeleton

VIII. CONCLUSION

To conclude, the exoskeleton developed here shall be more optimized than the current ones with similar design and goals. The study was focused on the development of an active mobile upper-body exoskeleton for industrial workers to use during heavy lifting operations. It must obey the current and future standards related to robotics as it is considered as a wearable robot. The interaction must consider the symbiotic human-machine (physical) relationship by investigating kinematics and dynamics of both systems. The device shall be electromechanical and powered by a battery (LIB) and the communication architecture should be reliable. The design/draft suggested in this study is a result of a long research. It is the most comfortable and efficient version which can be achieved with the simplest approach. The sensors and actuators will work with a controller to ease the work process of the wearer. The goal is to ease the handled load weight by 15-25 kg depending on the situation. Also, the exoskeleton itself must be maximum 10 kg. Currently, there is no exoskeleton developed that covers all the desired criteria.

After this point, there are several steps to take. Initially, the power and communication findings must be improved, as well as control elements and strategy. Also, the research shows great promise with the CORC system as the control and monitoring network. After that, a complete version of the intended design must be prepared including all the active (actuators, sensors, controllers) and passive (braces, rigid parts, spring, belt, torso piece) elements. Experiments shall be done with the prototype to verify and validate the expectations. The optimization process will require a human-exoskeleton interaction software such as AnyBody or OpenSim.

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