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ORIGINAL ARTICLE

Toward the Development of a Hybrid Active and Measuring Exoskeleton for Upper Limbs of Heavy-duty Harbor Workers

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Abstract

The paper presents the study of a novel exoskeleton designed for the upper limbs of heavy-duty port operators responsible for lashing containers. This exoskeleton is designed to measure initially its configuration and operational times, once positioned on the workers, to pass to a partial activeness introducing motors for the shoulder, the intra-extra rotation of the forearm, and the elbow. The key concept revolves around the shoulder joint, with particular emphasis on the scapula and its motion. The scapula plays a fundamental role in moving the center of rotation of the humerus, contributing to its exceptional mobility. The fundamental objective is to develop a system that provides support for the vertical motion of the operator's arms, with a specific focus on allowing initially the vertical motion of the scapula to remain unrestricted. This approach aims to collect essential data, which, in a subsequent phase, will likely enable the addition of vertical support to the scapula, possibly with the assistance of AI. Meanwhile, the horizontal motion will consistently be left unrestricted. This exoskeleton design is inspired by previous work that conceptualized a fully measuring exoskeleton, and a corresponding patent application has been presented.

Key Words: *Exoskeleton for heavy-duty workers; Exoskeleton to support actively the scapula motion; Hybrid active and measuring exoskeleton*

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Introduction

This study was commissioned by two shipping companies operating in the Gioia Tauro harbor to address a specific issue. Upon investigation, we found that while various exoskeletons have been proposed over time, most are designed for rehabilitation purposes or to assist individuals with motor deficits. However, there is a noticeable lack of exoskeletons specifically tailored to support workers engaged in demanding tasks, such as port operators responsible for securing containers onto ships.

Recent articles [1,2] highlight the limited availability of industrial exoskeletons designed for heavy-duty work. For example, the Hardiman exoskeleton [3], initially developed for military applications to enhance the wearer's strength and performance, remains in the prototype stage due to its significant weight and complexity, including a control system based on the master-slave model.

Following this initial development, there was a shift towards studying the biomechanics of the upper limb [4-7], but it took some time before more attention was given to the issue of physical human-robot interaction (pHRI), which is crucial for the effective utilization of exoskeletons [8,9].

Subsequently, numerous projects have been initiated, primarily focusing on rehabilitating and assisting individuals with various arm impairments. However, there are limited initiatives aimed at supporting workers in strenuous occupations, such as port operators responsible for securing containers on ships. Currently, the literature leans towards assessing the effectiveness of these exoskeletons [10-19], which is an aspect our research team will also consider in the final evaluation of our results. It is important to note that most systems investigated in these studies are geared towards rehabilitation purposes.

In line with the previously mentioned articles [1,2], it is evident that there are only a few active industrial exoskeletons, with practically only six dedicated to heavy-duty work. One of these [20] supports the lower limb, making it less relevant for the present analysis. Of the remaining two developed in Germany in collaboration with Fraunhofer, the Stuttgart Exo-Jacket [21] is a modular exoskeleton designed to actively support the upper limbs during manual handling activities like lifting, holding, and carrying heavy loads. While it considers the movement of the shoulder to some extent, it appears to lack mechanical support, relying on a self-adjusting passive system. This is clearly shown in the images present on the web, which shows the system utilized more to support the worker to keep rather uncomfortable positions then to lift heavy weights.

The second system mentioned in [1], the RoboMate Exoskeleton [22], is a complex modular system available in both passive (using springs) and active editions. It addresses the shoulder movement issue by offering support from the lumbar area to grasp the forearm, but its structure is entirely independent of the body, featuring large appendices that may hinder maneuverability in confined spaces such as aisles between rows of containers. A video on www.robo-mate.eu illustrates a gardener wearing a RoboMate, corroborating the points mentioned above.

Among the other three active exoskeletons mentioned by [2], the first one, the ExIF project upper limb exoskeleton [23], offers a compelling study on the impact of wearing an exoskeleton on various physical parameters of the user. While the exoskeleton discussed in their study shares several similarities with the model presented in this article, two key differences stand out. First, the ExIF project exoskeleton employs two separate motors for shoulder flexion/extension and abduction/adduction, whereas our system utilizes a single motor, facilitated by a posterior linkage composed of three bars with parallel axes, as will be explained later. The second distinction lies in the fact that our system aims to support vertical loads on the scapula, a feature not addressed by others.

Moving on to the second active exoskeleton mentioned in [2], it pertains to the exoskeleton Carry [24], which is a clever pneumatic system designed to maintain the elbows inclined for a specific duration but does not offer assistance to other joints. Additionally, Lucy [25] does not seem well-suited for heavy-duty tasks, being even less indicated for these than the Stuttgart Exo-Jacket previously mentioned. This becomes crucial for harbor workers involved in container lashing and unlashing, where swift application of significant forces is required. For instance, during the lashing phase, one worker must securely hold a rod, typically positioned with one arm up and the other down, while another operator rapidly screws in a tensioner, known as a swivel, to fix the container's position relative to the ship. In another scenario, a lengthy vertical rod must be held to release containers from the second row upwards, necessitating one hand at the bottom to bear the weight while the other at the top maneuvers the rod to disengage container attachments. Particularly in the first case, to keep the arm raised under load, the humerus head naturally moves up from the scapula. This observation led us to initiate a study on an exoskeleton tailored for these operators.

Furthermore, there is another characteristic of the motion between the scapula and humerus, wherein the center of rotation of the humerus head is not fixed at the center of a sphere. It may migrate, especially when the arm is raised entirely. In such situations, the distance between the humerus' center of rotation and the elbow axis may increase. A solution to this issue has been identified, as will be detailed later on.

Considering the examples provided earlier, it became apparent that nobody had previously addressed the specific problem at hand. The initial approach to understanding the appropriate geometry for a potential exoskeleton for port operators involved a focus on studying the actual operations. To facilitate this, the development of a measuring exoskeleton was deemed necessary—a wearable device capable of directly capturing both the movements and the speeds at which these movements occur. This approach aimed to enable the calculation of instantaneous power required for each joint, considering the loads and dynamics, with particular emphasis on measuring the vertical movement of the humeral head. While a recent article [26] has delved into this issue by simulating worker motion using suitable software, it's noteworthy that the software simplifies the shoulder as a fixed spherical joint, highlighting the importance of studying the actual motion of the humeral head.

Building on the insights gained from the patent application [27] and considering it as the foundation for subsequent project developments, a decision was made to explore a hybrid exoskeleton that would be both active and measuring. The ultimate goal of this design was to develop a device, through multiple tests on workers during its development, capable of compensating for vertical loads by supporting the natural movement of the scapula, aligning with its motion. However, this represented a comprehensive revision of the initially conceived system presented in patent form. It was observed that the presence of two perpendicular hinges with axes passing through the center of rotation of the humerus would hinder the fluidity of movement. Consequently, the two hinges were replaced by a single one capable of rotating around the shoulder, allowing for greater fluidity in operations.

We then proceeded to study the actuation system, which senses the operator's motion intentions and activates the motors in the desired direction. Concerning the movement of raising and lowering the scapula, a motorized system for tracking this movement and the inclusion of a relative force sensor were planned from the outset. However, initially, we opted not to implement the compensation algorithm. Instead, we focused on ensuring that the system could follow the scapula's movement, recording its vertical movements. This was achieved by measuring, albeit not with high precision, the position of various components and the force applied to the structure in the vertical direction. This was accomplished through resistors or other devices positioned on three hinges.

Our goal was to understand whether it was necessary to activate the electric jack supporting the scapula. We sought to determine whether the variation in vertical forces was linked to a change in the scapula's vertical position, necessitating the intervention of the vertical jack, or if it was instead related to arm movements. The new system allows the natural movement of the scapula in all directions, with measurements limited to stresses in the vertical direction.

The exoskeleton kinematic structure design

Building upon what was previously presented in the earlier patent, we note that the studied system, initially conceptualized as a measuring system, held the distinct advantage of pinpointing the instantaneous center of rotation of the humerus. This identification was accomplished by determining the intersection point of three hinges: one aligned with the diaphysis of the humerus due to the construction of its support, and two mechanical hinges (1) and (2) perpendicular to it. These are illustrated in the left portion of Figure 1, where 1 and 2 represent the hinges whose axes converge with the diaphysis of the humerus. Additionally, a slider was incorporated to ascertain the distance between the head of the humerus and the elbow axis.

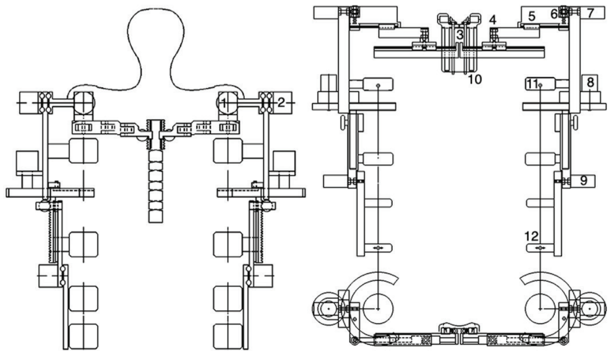

Figure 1) *The starting scheme and its first evolution.*

However, this system encountered challenges in facilitating a transition from a position of maximum lateral abduction (horizontal arm) to one of maximum arm verticalization. Additionally, while it could track the movements of the humeral head resulting from the scapula's motion, it lacked support for this movement. This absence of support was not addressed in a subsequent motorized version.

To enable a smooth transition between the maximum arm positions mentioned earlier, the only viable solution was to forego the third constraint (the hinge identified as (1) in Figure 1 on the left). This hinge, with an axis passing through the center of the instantaneous rotation of the humerus, restricted the system. By doing so, the motor responsible for lifting the arm could rotate substantially around the head of the humerus. This solution is illustrated in the right portion of Figure 1, where the numbers are illustrated in the following. The resulting linkage essentially allows the motor acting on the humerus to move freely on a plane, rotating about the center of the humerus head, while vertical motion is tracked by a measuring device. This measuring device is crucial for understanding when and to what extent this vertical motion needs assistance from a motor in subsequent stages.

After extensive studies and simulations, the revised system was achieved by initially employing a two-rail configuration placed in series on a plane perpendicular to the wearer's spinal axis. This configuration was articulated with a hinge having an axis perpendicular to both rails, allowing free movement on slides. The first rail, parallel to the frontal plane, originated at a certain distance from the spine, commencing in a backpack just a few millimeters from the sagittal plane. At the terminus of the second slide, a second hinge with a vertical axis was situated, and from this hinge, a bar extended to support another hinge, placed at a specific distance, with an axis perpendicular to the previous one. This second hinge served as the departure point for the humerus support bar, and it housed the motor responsible for rotating the humerus.

From this juncture, the new system closely resembled the previous one, designed solely for measuring the geometry and movements of the operator. In this design, (3) denotes the motorized joint with a vertical axis, exhibiting limited mobility relative to the support secured to the operator's trunk. Meanwhile, (4) and (5) represent the two non-motorized prismatic joints with horizontal axes. Joint (4) is a double joint, encompassing both a prismatic and hinge element with an overlapping vertical axis to the prismatic joint. It is followed by a horizontal bar culminating in the vertical hinge (6) in the drawing, which supports a member parallel to the humerus. This member is equipped with a horizontal axis hinge operated by the second motor (7). The primary distinction lies in the humeral bar, divided into two adjustable portions that can rotate while maintaining alignment with the humerus diaphysis. The adjustability in length allows it to adapt to the size of the operator.

The motors (8) and (9) are responsible for managing the intra-extra rotation of the forearm and the movement of the elbow, respectively. Concerning points (10), (11), and (12), they correspond in this model to the positioning of the sensors. These sensors play a crucial role in making the exoskeleton responsive to the wearer, aligning with their intentions. However, a detailed discussion of this aspect will follow later.

Nevertheless, this scheme soon proved to be practically unfeasible, primarily due to the substantial stresses that the sleds would have encountered. To bear these stresses, the sleds required dimensions that were too large to be accommodated in the available space. It's important to note that the available space between the sagittal plane passing through the center of the column and the center of rotation of the humerus head should vary between 16 and 22 cm, all while accommodating a load that can reach and exceed 50 kg. Consequently, the two horizontal prismatic joints were replaced with two bars of equal length featuring vertical hinges at the ends. This modification was deemed more suitable for transmitting the anticipated torques, as illustrated in Figure 2.

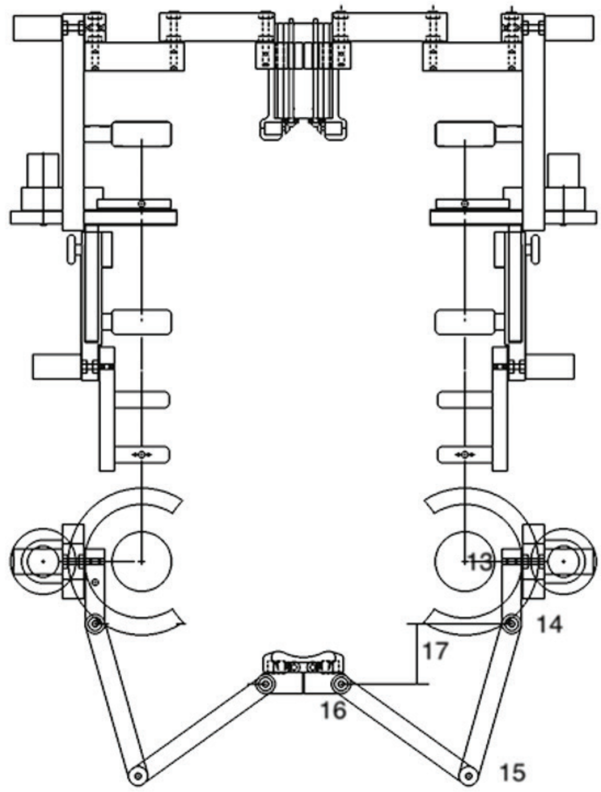

Figure 2) *The second evolution of the scheme.*

However, this solution, aimed at supporting the vertical load on the shoulder, introduces a significant torque, particularly on the vertical slide, leading to substantial dimensions. Despite the challenge posed by these dimensions, the load can be more easily supported since there is only one slide in the vertical direction. Simulations were conducted to visualize potential movements of both the arm and the scapula on the horizontal plane, including the rotation center of the humerus. The objective was to establish the lengths of various bars that allow for self-adaptation to the physical dimensions of the operator.

In the subsequent design phase of the mechanism, it was observed that the third rod placed between the hinges (13) and (14), facilitating full movement of the extendable humerus support, needed to be at least 120 mm long, considering the distance between the axes. This was necessary to allow the regulation of the length of the external support parallel to the humerus. This discovery led to the realization that if bar 2 is straight, it becomes essential that, when the motor is positioned posterior to the shoulder, the distance along the y-direction (i.e., in the direction of the sagittal plane) between the center of the first hinge (16) and the center of rotation of the humerus (17) is significantly greater than the distance between the hinges (13) and (14).

The following Figure 3 illustrates how, in the initial phase of the movement, bars 1 and 2 (the first placed between the hinges (15) and (16), the second between the hinges (15) and (14)) transition from the initial position with the arm extended in the frontal plane (red line, corresponding to an angle of -93°) before turning towards the axis of the sagittal plane (purple line, at -87°). Subsequently, they nearly touch the sagittal plane at -70° (blue line) before continuously widening until reaching 45° (green

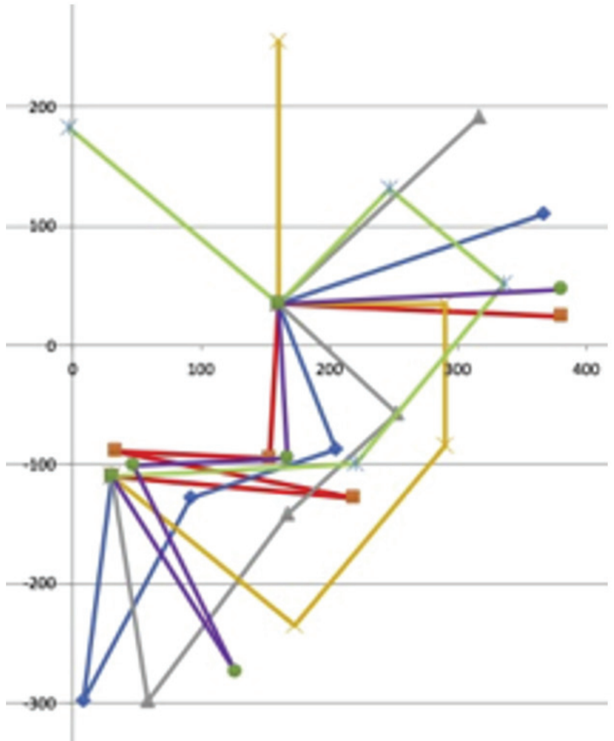

Figure 3) *Schematic representation of the bar motion during the arm movement, transitioning from maximum arm extension on the horizontal plane to a rotation of approximately 135° in the anticlockwise direction. The points with coordinates 160 and 35 indicate the position of the center of rotation of the humerus.*

humerus support length (18) became adjustable by inserting two parallel bars between the portion articulating the shoulder and the part allowing forearm rotation with respect to the humerus bar. Considering the variability in the center of rotation of the humerus head, a decision was made to use a locking screw within an element capable of small vertical movements in a suitable slot. With the capability to adjust the humerus bar length, it became evident to relocate the elbow articulation close to the open ring. Simultaneously, the open ring was extended vertically under the denture (19) to increase its rigidity. A non-symmetric configuration of the semiring was chosen to facilitate elbow flexion when the motor axis lies in the horizontal plane. The motor (20) responsible for forearm motion was fixed on this element. A possible fifth motor (21) is noted, with details to be discussed later. Figure 4 shows the latest configuration of the system.

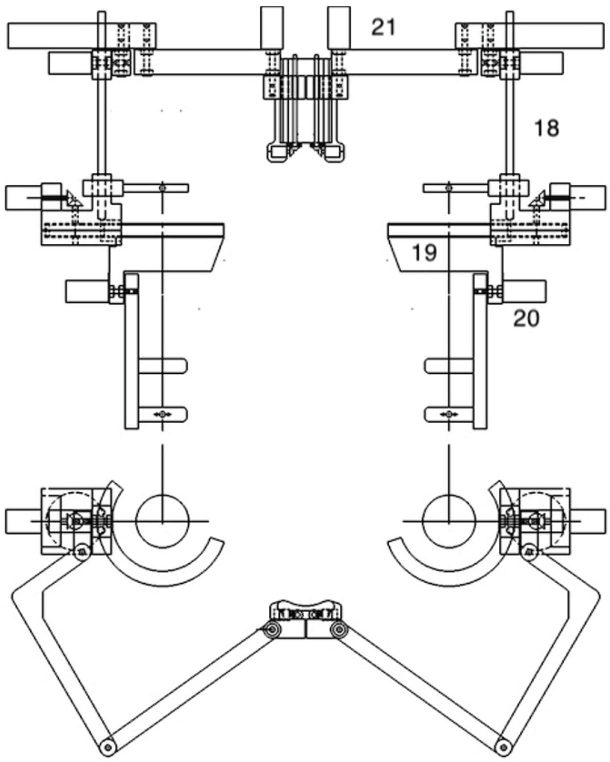

Figure 4) *The last scheme of the exoskeleton as seen on the frontal and horizontal plane. From this, the final CAD model was developed.*

Figure 5, seen from the top with a side section, depicts the articulation on the humerus support allowing forearm rotation with respect to the humerus bar. Notably, (22) is the toothed ring supporting the joint for forearm flexion and extension. (23) represents the upper component of this joint on the humerus bar, while (24) is the lower component. There are 10 small ball bearings (25)–5 on the upper component with axes parallel to the bar and 5 on the lower component. Additionally, there are 4 bearings (26) with axes perpendicular to the bar – 2 on the upper and 2 on the lower – supporting the load in the direction of the bar. These elements were missing in the first semi-exoskeleton, as shown in the final pictures. This design choice of guiding the intra-extra forearm rotation with a gear, rather uncommon, was caused to help the tensioning phase of the bar connecting the container to the ship's structure, requiring substantial power for quick and efficient operation of the swivels.

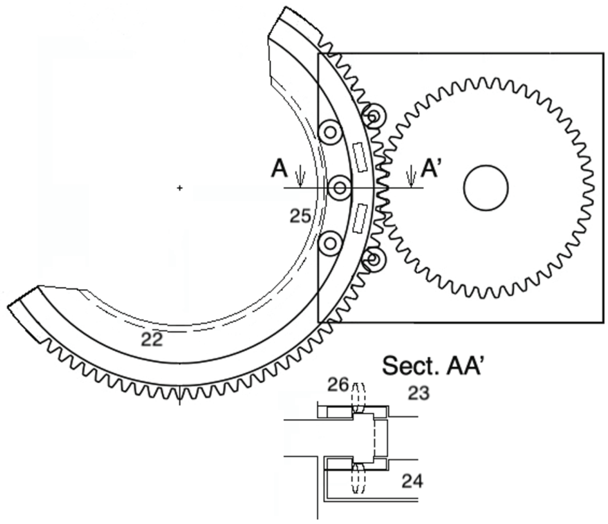

Figure 5) *The scheme of the joint allows the turning of the forearm with respect to the humerus bar.*

In the system simulation within the horizontal plane, it was observed that the system rotates smoothly around the humerus head without making contact. Subsequently, further testing was conducted in the horizontal plane projection, exploring the system's behavior as the position of the humerus varied based on both the physical dimensions of the operator and the movement of the scapula.

The results of these simulations are presented in the four images of Figure 6, each containing data related to the length between the hinges of the first two horizontal bars (bars 1 and 2), the third bar between the vertical and horizontal hinges supporting the motor that moves the arm, the Motor-Center of the humerus identified by four closely spaced dots, and the length of the humerus. The Motor Center is influenced by the dimensions of the ring controlling the intra-extra rotation of the humerus, designed to accommodate arms of varying sizes. The images illustrate the positions assumed by various components in the x, y plane, with x positioned at the intersection between the horizontal and frontal planes originating at the center of the vertebrae and y perpendicular to this in the horizontal plane. The coordinates of the first vertical hinge were assumed to be fixed. The center of the humerus was allowed to vary by 60 mm, from y coordinate 30 to 90, and for x, from 160 to 220. The latter range accounts for different chest dimensions among operators, including a small variation in the horizontal position. Notably, the strong inverse motion during the initial phase of transitioning from a fully extended arm on the frontal plane to an arm leaning forward was significantly reduced, contributing to the smoothness of the system's motion.

In any case, for even larger chests, it suffices to adjust the dimensions of bars 1 and 2, which are of equal length between the end hinges. The four images in Figure 6 depict the axes of the structure, the approximate position of the motor, and the arm's positions in the horizontal plane: out (orange), forward right tilted 45° (gray), forward (blue), and leaning left at 135° (yellow). As observed before, the motor circulates around the shoulder, and the two bars never touch it. In conclusion, it seems that the system can self-adapt to the different sizes of various operators, but this aspect needs verification.

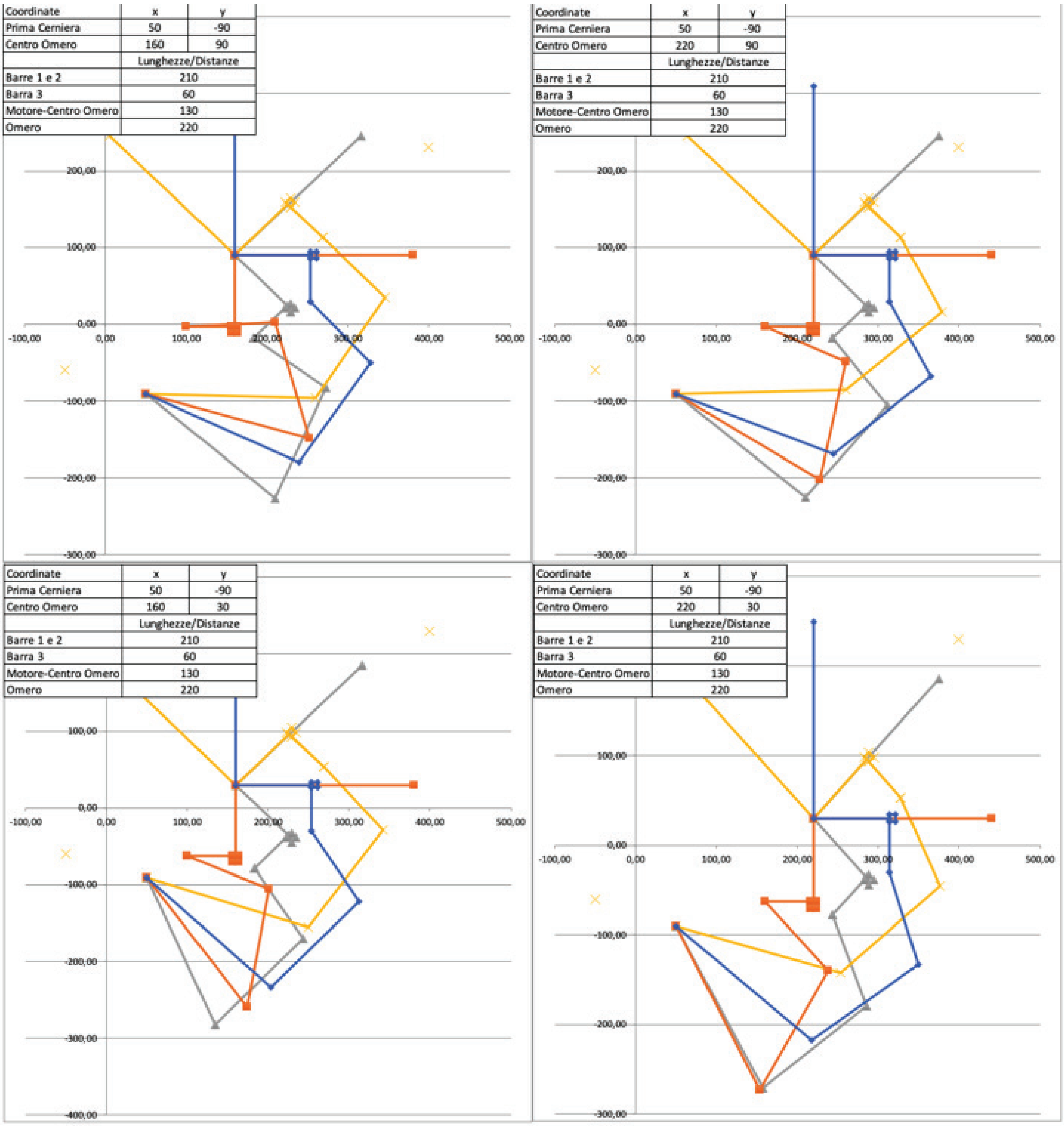

Figure 6) *The last scheme of the exoskeleton motion on the horizontal plane. From this the final kinematic and CAD models have been developed.*

Two additional considerations were made. Firstly, in the diagram of Figure 2, the first horizontal rod rested on the vertical slide, while the second was suspended from it. This arrangement posed two problems: it offered greater safety when the rods were placed one above the other, and when the rods needed to approach due to outward arm movement, overlapping was smoother. However, as seen in Figure 4, the third bar was suspended with respect to the second. In the final system, the configuration returned to that of Figure 2. The second consideration is that, for them to overlap under load, they must allow limited deformation, resulting in unique shapes of these elements, which will be highlighted below.

To conclude this discussion, Figure 7 presents the kinematic model of the system, where q1 to q5 represent passive joints, while q6, q7, and q8 are the active joints controlled by the sensors. The concept is that, over time, joints q1 and possibly q2 could become active, potentially incorporating additional yet-to-be-defined sensors. This will be clarified once data from the wearer are obtained, establishing the correlation between arm positions and scapula motion to provide support when needed.

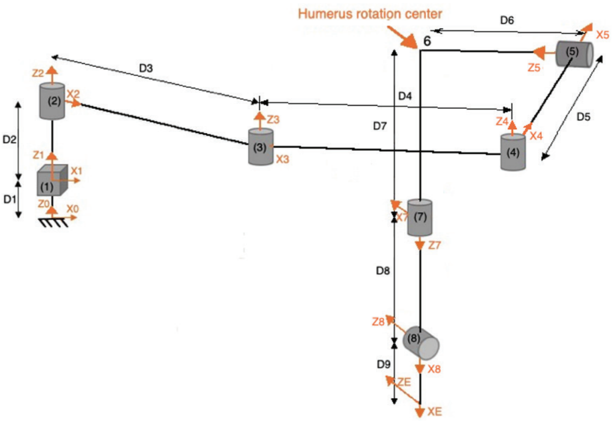

Figure 7) *Kinematic model of the exoskeleton.*

The Denavit-Hartemberg [28] data of the model are provided in Table 1.

Table 2 presents the motors and encoders as well as control boards associated with each motor and encoder.

Human Machine Interface

Now, let's delve into how the system interprets the operator's movement intentions. Primarily, absolute angular encoders will be employed, to be later substituted by cost-effective angular resistors. Figure 1, (3), represents the vertical slide that will be motorized to support the load acting on the scapula. This motor should be activated in the presence of a load variation, as lifting the scapula reduces the load on the surface sensor which measures the force acting on bar 1. But if one should leave the vertical slide to move freely, the sensor would always measure nothing but friction due to the motion of the vertical bar. Placing instead a vertical spring positioned between the vertical slide and the backpack allows the force measurement, knowing the spring constant and the displacement measured in the meantime by another absolute encoder.

In the initial assembly of the system, the motor and the worm screw will be absent. Instead, a high-resolution encoder fixed to a gear meshing with a rack will be utilized, as identified in a subsequent image. These encoders will monitor vertical movements and rotations between the first three vertical hinges. Absolute encoders will be placed on each hinge connecting them. The arm movements produced by motor (7), equipped with an angular encoder, will also be recorded. The sensor controlling the arm movement is placed on the external support of the arm itself. This hybrid system collects data to optimize the overall functionality.

This consideration also led to the idea that a motor could be placed on the first of the three vertical hinges (21 in Figure 4). Its movement could be controlled by an additional sensor on the arm, sensing any intention to abduct the arm in a horizontal position. This can be easily achieved with the current system by slightly flexing the arm and initiating the rotation to bring it into the position of maximum abduction. The inclusion of motor (21) will be decided based on the experimental results obtained.

TABLE 1

Kinematic model of the exoskeleton

Joint	Type	Rz	Dz	Dx	Rx	Dy	Dn	Articulation	Length
T00	origine	0	0	25	0	-50	D1		
T01	prismatic	0	q1	0	0	0	q1		0-100
T12	aux1	0	100	0	0	0	D2	shoulder	100
T23	hinge	q2	0	210	0	0	D3	shoulder	210
T34	hinge	q3	0	210	0	0	D4	shoulder	210
T44′	hinge	q4+π/2	0	80	0	0	D5	shoulder	80
T4′5	aux2	0	0	0	- π/2	0	-		-
T56	hinge	q5	140	0	0	0	D6	shoulder	140
T66′	aux3	0	0	0	π/2	0	-		-
T6′6″	aux4	0	170	0	π/2	0	D7		170
T6″6‴	aux5	π/2	0	0	0	0	-		
T6‴7	hinge	q6	50	0	0	0	D8	humerus	50
T78	aux6	0	0	0	π/2	0	-		
T8E	hinge	q7	0	250	0	0	D9	elbow	250

TABLE 2

List of hardware initially acquired in this prototype

Joint	Type	Measure	Hardware	Articulation
1	prismatic	Encoder 12+ 4 bit	Posital Fraba UCD-CAB1B-0012 + 0004	scapula
2	hinge	Encoder 16 bit	Posital Fraba UCD-CAB1B-0016	shoulder
3	hinge	Encoder 16 bit	Posital Fraba UCD-CAB1B-0016	shoulder
4	hinge	Encoder 16 bit	Posital Fraba UCD-CAB1B-0016	shoulder
5	hinge	Motor + reducer	Maxon Motor RE40+ENC HEDL 5540+GP52C + mmc Epos2	shoulder
6	hinge	Motor + reducer	Maxon Motor RE40+ENC HEDL 5540+GP52C + mmc Epos2	humerus
7	aux6	Motor + reducer	Maxon Motor RE40+ENC HEDL 5540+GP52C + mmc Epos2	elbow

The idea is then that the movements of the scapula are connected to the movement of the arm, and that by monitoring these parameters, vertical force sensor (10), vertical movement assisted in parallel by a spring of suitable rigidity, and rotation of all components of the system, we will be able to establish if the force sensor, coupled to the movement of the arm, is giving us the right indication of the required scapula vertical movement. We believe this to be true, but we believe this intermediate step is essential before motorizing scapula motion support. Figure 8 shows a sketch of the element surrounding the forearm, which must be sensitive to the intention of elbow flexion and intra-extra rotation of the humerus. In particular, the numbers from (27) to (30) are four sensors (resistors) whose output cables are placed in series, while the power supply is connected to the first pin of (27) and to the last of (30), while the signal which causes the elbow motor to operate is taken at the junction (28)-(29). Indeed, the mechanical support is on the lower part of the arm. When you press in one direction, the resistances of the side receiving the push decrease, while that of the opposite side increase until they become infinite, and vice versa. Hence, this system is extremely sensitive. Of course, a predetermined variation will be required to initiate the motor drive to avoid inducing vibration in the system. Obviously, then the sensors (31) and (32) instead control the intra-extra rotation of the humerus, and therefore of the forearm. The circle (33) then represents the forearm in section, held in the center of the ring by a 25 mm high belt (34) which connects to two diametrically opposite points, while (35) and (36) are rubber elements with a thickness variable that keep the limb in the middle, and this pattern is repeated at least eight times on each side. It should also be noted that the sensors are placed on fixed elements and not on rotating elements, such as the open ring gear which controls the intra-extra rotation of the humerus, because otherwise the signal would become difficult to interpret.

Results

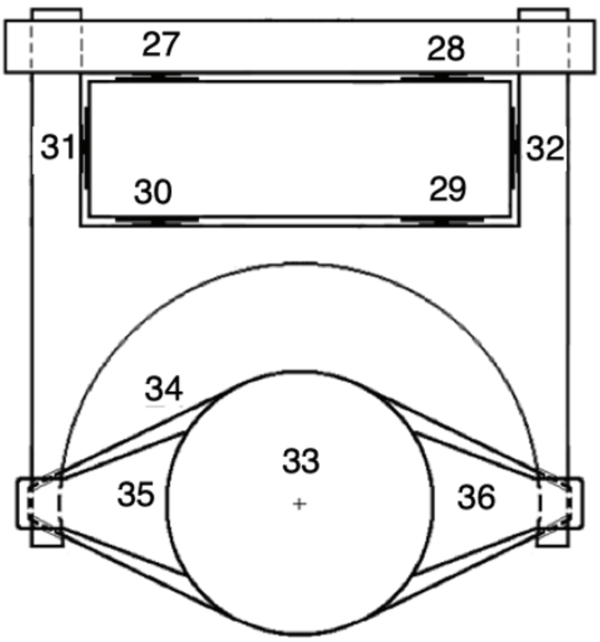

Figure 8) *Scheme of the position of surface resistors to work as motion intention detection.*

The system has been theoretically verified (Figure 6) to work, allowing the motor to rotate around the humerus head, and it is less cumbersome than the previous one. The new exoskeleton was designed and, for the moment, only the right portion was built to discover errors in the initial design. Figure 9 shows the semi-exoskeleton resting on the floor without engines or encoders, while the following Figure 10 is related to the system of measuring the vertical movements of the scapula.

Figure 9) *The hemi-exoskeleton assembled.*

Figure 10) *The system to measure scapula motion (in the previous image is the member on the right.*

Images of the system worn by the corresponding author are presented in Figure 11. However, these initial trials were conducted without permission from the Ethical Committee, and for this reason, the trials are limited to very informed persons. Naturally, before going further ahead, we will present our request to the local Ethical Committee.

Figure 11) *The initial images of the half exoskeleton provided valuable insights. Two important lessons were learned: firstly, the straps must be very tense, and secondly, the first strap on the forearm must be positioned very close to the elbow. Additionally, it was observed that the position of the fourth encoder must be above the third bar that holds the motor on the shoulder. In both cases, the hinge that should bear the motor is aligned with the clavicle. These observations highlight the importance of precise adjustments and alignments for optimal functionality.*

The main problem encountered was the size and weight of the chosen motors, which were deemed too large and heavy for an exoskeleton, already weighing a considerable amount (7 kg for only half the exoskeleton without motors, each motor weighing more than 1 kg). Consequently, the structure needs to be redesigned to be lighter and much stronger. The improper hinge allowing intra-extra rotation of the humerus in this first edition did not work correctly, lacking the ball bearing for vertical load, as previously discussed in Figure 5. However, the system can follow any motion, as shown in Figure 12, which displays two additional positions. Many components need to be redesigned, necessitating the rebuilding of the entire exoskeleton.

Figure 12) *Two more images of the half exoskeleton show two more positions.*

Particularly noteworthy is the fact that, in this case, the hinge allowing articulation of the humerus is rotated by 90° thanks to the articulated system composed of bars 1, 2, and 3 as mentioned in the kinematic model description. This rotation occurred effortlessly. Additionally, the significant size of the forearm support is evident in Figure 9b. The system for wearing the exoskeleton needs to be reconsidered, and it's mentioned that a four-point safety belt was initially purchased but unfortunately got lost in the process. Adjustments and refinements in the design and wearability are crucial aspects of the ongoing development process.

For instance, Figure 13 shows the new model of the forearm and of the mating element that holds the sensors. These are located on the flattened portions, clearly visible in the picture. Note also that in order to allow fixing the forearm with the first belt very close to the elbow to maximize the sensitivity of the system, the first slots for fastening the strap are positioned asymmetrically, centering in any event the forearm, while the final ones are positioned to be parallel to the axis of the elbow, in order to supply the correct info to the control system.

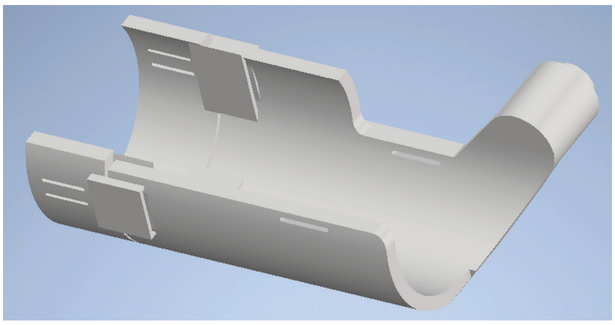

Figure 13) *The new forearm model is much lighter and anatomically correct.*

Another important observation looking at Figure 9, is that it should be rather important that the first point of embracement of the arm should be as close as possible to the armpits, again to ensure that the external support axis is really parallel to the humerus diaphysis, and for this reason the upper part of the element connected to the sensors of motion required of the arm, indicated by an arrow in Figure. 9 should be cut and transferred to the element directly commanded by the motor. Figure 14 shows the new element directly commanded by the motor bearing the two lateral arms bearing the first centering belt.

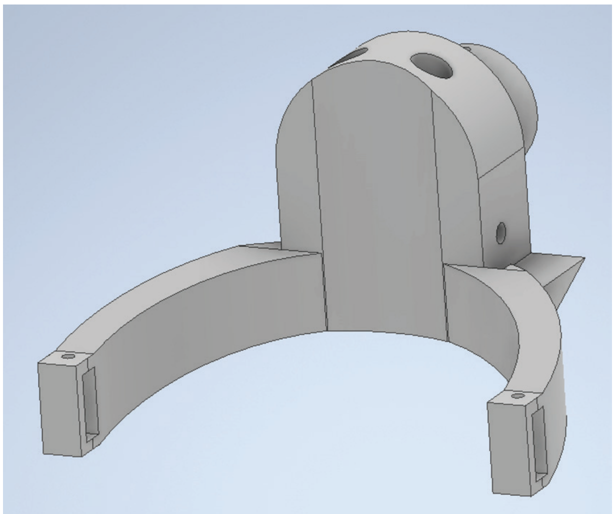

Figure 14) *The new top portion of the humerus exoskeleton, bearing two arms to hold the first centering belt.*

Discussion

The project has advanced to a stage where, after completing the redesign and construction of the modified structure and addressing the issues observed in the initial half exoskeleton, the next steps involve the installation of all encoders, substituting also the motors with encoders, in order to obtain the full picture of the movements and relative times. Very important will also be the addition of a spring in parallel to the vertical member allowing the scapula vertical motion, because, in absence of this addition, the force sensor would have registered forces only when the system reaches end scale position. For this, the use of the kinematic model will be essential, allowing to verify the possibility of establishing a relation between turning the humerus in the vertical direction and scapula movement. In fact, the shape of the acetabulum of the head of the humerus has to rotate to allow verticalization of the humerus, and this probably causes the scapula elevation.

Only after this analysis we will install the motors already purchased. These motors were chosen based on positive past experiences with their usage alongside the respective control boards.

While this initial version may not be suitable for practical usage in a harbor or heavy-duty environment, it serves the purpose of studying the control system dedicated to supporting the vertical movements of the scapula. This phase will enable the collection of data in a controlled laboratory setting, simulating the actions of workers, and probably also some on harbor trials after obtaining permission from the local Ethical Committee.

Subsequent plans include the acquisition of new, lighter, and smaller motors with harmonic drives, such as the Zeroerr eRob 70 or 80, along with their respective control boards. As the entire exoskeleton will need to be rebuilt to accommodate these new components, the use of filament containing carbon fibers is considered to enhance the strength of the exoskeleton structure. Additionally, the integration of batteries and a portable PC will be necessary to facilitate data collection in real harbor conditions.

Conclusion

The project's next steps involve first printing and assembly of the full new version of the exoskeleton which must start from a better backpack, including positioning of the encoders and relative control electronics, while obtaining permission from the local Ethical Committee. Only then a first session of field testing to assess the exoskeleton's functionality in a real-world environment will start, allowing for the collection of authentic data. Once the data is obtained, the motors will be installed a new test will allow to explore the integration of motorized support to follow the scapula motion, potentially with the assistance of artificial intelligence (A.I.).

A potential future development is the addition of another motor on hinge 2, coupled with new sensors on the arm to command the rotation of the motor responsible for the arm's motion around the humerus center of rotation. However, it's noted that this additional movement might be unnecessary as it is essentially load-free. The ongoing evolution of the project will depend on the results obtained from field testing and the specific requirements identified during the data collection phase, besides the non-negligible problem of funding.

Patents

From this work, an Italian patent application is quoted as [29] in the references.

Author Contributions

Conceptualization, DG, and CG methodology, LF software, GL, and PM validation, DG, GPF, and GL formal analysis, DG, GPF, and PM investigation, CR, LF, and OA resources, CR, LF, and OA data curation, DG writing—original draft preparation, DG writing—review and editing, DG visualization, DG supervision, DG project administration, DG funding acquisition, CR, LF, and OA. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Essentially no new data were created, beside what is shown in the article, beside the model in CAD, plus Excel and MATLAB simulations and pictures of the system built.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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