Too Close to Comfort? A New Approach of Designing a Soft Cable-driven Exoskeleton for Lifting Tasks under Ergonomic Aspects

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***Abstract*— At this point of their development, available exoskeletons for industrial applications still lack broad acceptance by users on the shop floor; this is allegedly due to discomfort and restriction of movements. Exoskeletons are in close physical interaction with the user. For everyday use at work, the kinematic chain of the human and the exoskeleton must satisfy the needs of every possible user in terms of high usability and positive user experience. Focusing on aspects like the users' wearing comfort, reduction of interaction forces and easy setup, a new concept for an exoskeleton that supports the elbow movement during lifting tasks was developed. To avoid misalignments between the exoskeleton and the human, and to allow a full range of movement, a soft cable-driven structure was chosen. In an iterative design process, a basic structure made of a rather stiff fabric with elastic inlays was developed. The cut is meant to suit a wide range of anthropometric measures while ensuring a tight fit for good transfer of forces. Using soft materials and cables poses a challenge for calculating, simulating and measuring force distributions not only in the exoskeleton, but also in the human tissue and bones. A suitable model of the kinematic human-machine-chain and a method for testing the new concept were therefore developed. Since ergonomic design and the users' needs were of high priority in the design process, the robustness and the maximum load capacity of the system are initially left out of this concept.**

This paper will present the design of the soft fabric-based structure as well as the kinematic design of the cable train and the implementation.

***Index Terms*—exoskeleton, ergonomic, kinematics, exosuit**

I. Introduction

The implementation of exoskeletons in the working environment have not succeeded yet, since the systems are still lacking acceptance by end users. From an ergonomic perspective, exoskeletons have the potential to have long term health benefits for industrial workers.

The target group for exoskeletons for industrial applications are usually everyday people without any specific training, who sometimes have very low technical affinity. The design of an exoskeleton therefore needs to be realized accordingly. It can be assumed that this target group has high requirements for a positive user experience, usability and value comfort and an easy setup, more than potential health benefits. To tackle this challenge, a new approach to designing exoskeletons needs to be established, since ergonomic requirements must be integrated into the development process at a very early stage.

Taking the ergonomic needs of the potential end user into consideration, the requirements for a new exoskeleton project can be summarized as follows:

- Good comfort
- Low interaction forces
- Full range of movement
- Lightweight
- Easy setup
- Easy use

These requirements are built on the ideas presented in [1].

The requirement "good comfort" describes the absence of unwanted forces, like lateral, and shearing forces, but also the use of skin-compatible materials. In contrary, the requirement "low interaction forces" refers to compression forces in those places, where the exoskeleton is attached to the human body and the assisting forces are applied. High interaction forces might not only cause discomfort but even lead to bruising or reduced blood flow. A good exoskeleton does not only assist the user in the intended direction, it also facilitates the execution of tasks outside the supported movements. A "full range of movement" is to make the system usable in modern workplaces with flexible production processes, where not only one repetitive task needs to be executed, but also a lot of additional work needs to be done. Those additional work tasks may not need the same kind of assistance, but the exoskeleton should not constrain the execution of those tasks. The aim of exoskeletons for industrial applications is to reduce the strain on the human during their daily working tasks. If the exoskeleton is too heavy, the stress of carrying the system around cancels out the potential benefits, there for "lightweight" is a necessary requirement for a good usability of the system.

An "easy setup" and therefore a short daily setup time makes the exoskeleton easier to integrate into a workflow. As a result, it is more attractive to use, if the workers only need to slip on the system, instead of spending a lot of

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time and effort into putting it on. In addendum, they also do not want to be bothered during their work tasks, so an “easy use” is also a mandatory requirement. Furthermore, the cognitive load should not be increased by the exoskeleton, so the users do net get distracted during their primary work tasks. This is also important regarding work safety, since it reduces the chances of mistakes in the execution of the work task as well as in the operation of the exoskeleton.

For the sake of fulfilling these requirements, the following exoskeleton properties will be set to the lowest priority in this early stage of development. The Prototype does not have to support loads over 10kg. It does not have be very robust either, which means it does not have to run many load cycles.

In the presented project, a soft exoskeleton design, also called “exosuit”, is pursued to ensure the requirement of “high comfort”. Since comfort is hard to measure objectively [2], this design is chosen under the assumption that a soft design can potentially offer more comfort than a design with rigid elements. These rigid elements can cause pressure points or even collisions with the human body. Since pneumatic and elastomeric actuators, which are common in soft robotics, tend to have a complex or heavy actuation system, a cable-driven actuation system was therefore chosen for this approach. Thus, the “lightweight” and “easy setup” requirements are fulfilled.

In the initial considerations, the supported movement was limited to supporting the elbow joint during the lifting and lowering of loads below 10 kg to keep the complexity in the low range.

II. Fundamental Principles

A. Biomechcanics of the Human Elbow

The main actor of the elbow flexion is the biceps brachii, a biarticular muscle extending from the scapula through the shoulder to the elbow joint and the forearm [3]. The two distal tendons of the biceps brachii are attached to the radius with a distance of roughly one to five centimeters to the center of rotation of the elbow, and therefore form leverage for flexion of the elbow joint [4].

The elbow joint is usually modeled as a hinge joint with a fixed center of rotation in the design of exoskeletons, but this does not match reality. Since the joint is composed of two unevenly shaped bone structures, they rotate around various instantaneous centers of rotation that wander along a screw displacement pattern [5]. Misalignments between these centers of rotation and joint axes of the exoskeleton are presumed to be a reason for discomfort and are a potential health risk.

B. Exosuits

In literature, soft, cable-driven exoskeletons for upper body movements are mostly designed for rehabilitation or living assistance purposes. There are many exosuits for walking assistance such as the myosuit [6], but since the targeted use case is the lifting of loads, these exoskeletons are not elaborated any further. Soft exoskeletons for hands are also not taken into consideration.

Most projects focus on technical development and control of the actuators of soft cable-driven exoskeletons [7–10], with the tendons attached to the body using pads on the upper and lower arm with buckles and Velcro straps [11] or a boa lacing system [7]. Most of the soft exoskeletons are made for rehabilitation purposes; where exoskeletons need to support every possible movement in all directions. This directly translates into more complex actuation systems with six [8] or even up to ten [9] motors.

Another use case of soft exoskeletons for rehabilitation purposes, is the support of movement in only one direction, either for very specific training, or for assisted living purposes. Examples are the soft exoskeleton in [12] or the “ExoFlex” [13], which both assist the flexion of the elbow. The first one is a Polyester vest with an upper arm and a wrist cuff made from PLA, which are connected with two Bowden cables on each lateral side of the arm [12]. The “ExoFlex” uses rigid 3D printed parts as well as velcro straps to attach the Bowden cables to a fabric structure, whereby one cable actuates one degree of freedom [13].

A novel twisted string actuation system was developed in [10] that does not need a winch but needs a very high rotational speed of the motors instead. The “soft elbow exosuit” [7] was developed for industrial applications, which uses a rigid hinge joint parallel to the elbow joint. But this hinge joint might lead to misalignments between the rotational axes, as described in II.A.

The question on how to attach the exoskeleton correctly to the human limb is shown in detailed elaboration by [14] and a few more authors e.g. [15, 16] for the application of upper body exoskeletons. These projects consider the problems of misalignments or high interaction forces between the human body and the exoskeletons. However, they mainly focus on exoskeletons containing rigid elements and are not applicable to soft systems. To the authors’ knowledge, there are no publications describing the development process of the soft structure of an upper body exosuit for supporting healthy adults with lifting loads.

III. Exosuit Design

In this paper, the main focus is on the design and the materials of the soft structure of the exosuit, which was developed in an iterative process and inspired by human anatomy.

A. Textile Structure

Loads up to 10 kg, meaning 5 kg per arm, are intended to be supported by the exoskeleton. Therefore, the main material needs to be able to withstand these forces without ripping or uncontrollable lengthening. The fabric of choice was the “Cordura® ripstop”, which is a commonly used material for outdoor clothing and has very low elasticity and high robustness against ripping.

In accordance with the “easy setup” requirement, the exoskeleton was designed like a normal piece of clothing. Without elastic properties in the fabric, the shape of a short “bolero” jacket seemed to be the most suitable. To reduce unwanted movement between the skin and the fabric, the long arms of the jacket were tailored in a tight fit. Since the Cordura® fabric does not stretch, it does not allow any movement in the elbow or shoulder on its own and the hand cannot fit through the sleeve. It was therefore paired with a material with a very high elasticity in specific places. The elastic material was chosen to have very high elasticity, so that it is able to lengthen significantly in relation to taking up only a very small space in the exosuit. The main property of the Cordura® fabric and the exosuit for transporting forces away from the human body is therefore maintained despite the added elasticity. The chosen elastic material is a “functional bike jersey” commonly used in the design of bike sportswear. In an iterative process, the correct placement and shape of the elastic inlets as well as a reinforcement of non-elastic structures was developed. The final design is shown in Fig. 1.

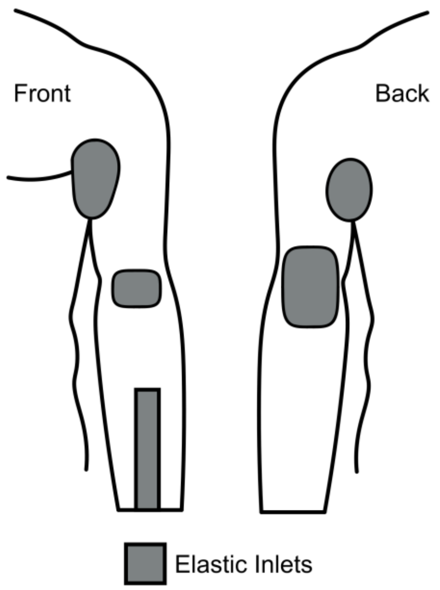

Figure 1. Placement of the elastic inlets

Elastic inlets that allow a full range of movement are used on the inside of the shoulder and elbow joints to prevent fabric from uncomfortably piling and throwing folds. The skin around the outer part of the elbow stretches during flexion and an elastic inlet is included in the exosuit at this point to accommodate that movement.

Since the circumference of the wrist is significantly smaller than that of the hand, an elastic inlet along the forearm is needed for the user to be able to put the exosuit on. This flexibility causes the exosuit to ride up the arm, when forces are applied in proximal direction, so that an adjustable wrist band is added to reinforce the structure after putting on the garment. Another reinforcing band is added just in front of the elbow, where the cables will later be led in the project.

B. Cable Design

The design of the cables is inspired by human anatomy, the myosuit [6] and the soft elbow exosuit [7]. Since this part has the smallest circumference, the cable is attached at the wrist and follows the medial line of the forearm muscles on one side and the lateral line on the other side. It detaches just in front of the elbow joint on both sides to form a leverage similar to the biceps brachii (see II.A). Likewise, the cable reattaches in the medial and lateral area of the middle upper arm and is guided across the shoulder as far as the actuation unit that is attached to the back. The course of the medial half of the cable is shown in Fig. 2.

The cable forms a closed loop with two motors to ensure even distribution of loads between both sides of the arm during lifting movements. The cables are made of Dyneema® and guided within low friction PTFE (Teflon) tubes so they can slide with negligibly low friction.

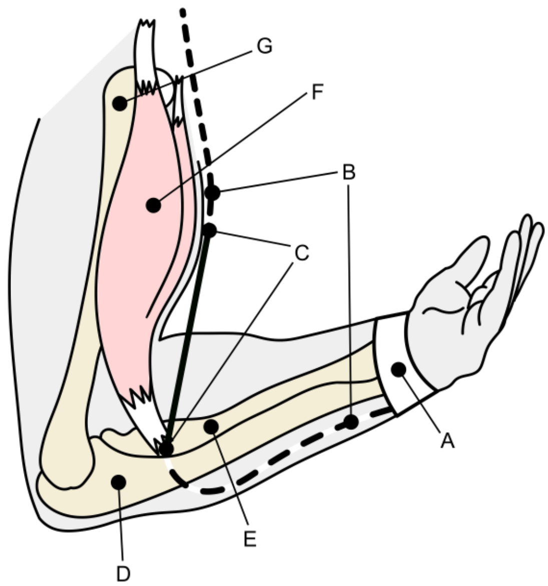

Figure 2. Representation of the Dyneema® cables following the arms’ muscles and tendons respectively in accordance with the human anatomy. A: wristband B: cables in PTFE tubes C: entry points of cables into the guidance tubes D: Ulna E: Radius F: Biceps brachii G: Humerus

A tube attachment and tube guide are required to attach the tubing to the jacket. Those define the course of the tubes and keep them fixated during movement. The soft guiding system can either consist of a rigid housing that can be sewn to the textile, or a textile guide that is made by sewing on a fabric tunnel. For this prototype, textile tubes for guiding the Dyneema® cable are sewn between two layers of Cordura® fabric that form a textile housing. The housing itself consist of another ground layer of fabric to prevent the jacket from distorting. A second layer sewn over the tube keeps the tube itself in place.

The textile housing is then attached to the jacket with two seams on both sides of the tube, as seen in Fig. 3. Those are needed to give the tube guiding system more rigidity when forces are applied. The Dyneema® cable is then passed through the tubing. Through the double layer under the tube a greater robustness is achieved.

On each end of the tubes a grommet is attached to protect the tubes from wearing out and keep the cable from kinking. The latter is achieved by rounding the grommet with a three-millimeter Radius.

The whole tube and cable system is attached to the jacket at the wrist in a loop. That way slight offsets between the motors and the rotation of the upper arm can be compensated. Further, an even distribution of forces can be realized between both sides of the arm (see Fig. 4). The tube loop is placed on the ulnar side of the wrist. The placement is chosen because this side faces the floor when the hand is in its neutral posture and the elbow is bent at 90°. In addition, during the lifting of boxes or crates, this side of the hand usually points downwards.

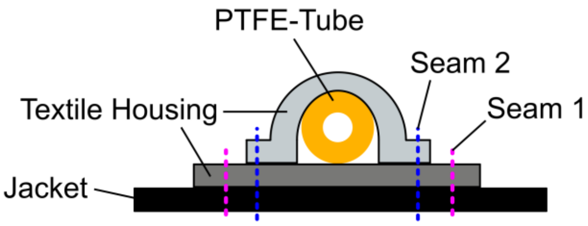

Figure 3. Textile housing of the cable bearing tubes

So, with the attachment of the cable on that side, the supporting forces, which are pointed upward, are directly transferred into the human body, where they are wanted. Attaching the cable on any other side of the wrist would result in an upwards pulling of the fabric, which causes shearing and tearing movements and forces at the wristband. These result in discomfort or even scraping at the skin.

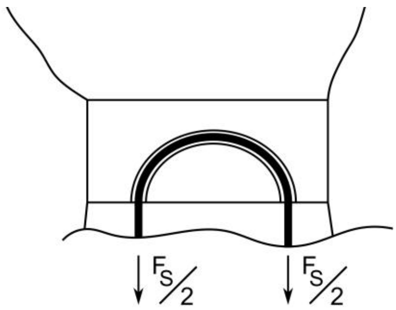

Figure 4. Integration of the tube into the wrist attachment to allow free movement of the cable and an even distribution of forces along the forearm

C. Fastening

The exosuit is fastened at the wrist with a velcro and at the lower arm with a lacing cuff. The wrist band is used to prevent proximal displacement. The tube loop is held between the two velcro strips and can be removed, when the velcro is opened.

Due to the high forces that are applied at the cable detachment point, the housing system described in Fig. 3. is not stiff enough to keep everything in place. Therefore, more layers of fabric are added for further reinforcement of the tube guidance at that point. This is implemented with an additional textile cuff around this part of the lower arm, which consists of four more layers of Cordura® fabric. That cuff is fastened with a lacing system, which results in a better adaptability in comparison to velcro regarding the uneven surface of the lower arm. It also makes the system adaptable to different anthropometries. The fastening is equipped with a fast-lacing system to facilitate a one-handed setup.

IV. Calculations of the Kinematic Chain

A. Modeling the Human-machine-kinematic Chain

After the basic structure design was completed, the kinematics of the human-machine-chain were modeled to calculate the necessary motor power and identify any unwanted forces. Unwanted forces can either be interaction forces between the human skin and the fabric in lateral directions or an additional load in the elbow joint, which can potentially harm the joint tissue.

To calculate these forces, flexion of the elbow was abstracted in a two-dimensional space of the sagittal plane. While the cable runs parallel to the forearm, the rope force does not influence the momentum around the elbow joint. Thus, the point of interest is where the cable detaches from the forearm and forms a leverage around the elbow. Together with the point where it reattaches at the upper arm, a triangle is formed that can be used to perform a vector analysis of the cable force. The schematic model of the kinematic chain is shown in Fig. 5. A coordinate system that is fixed to the forearm and has its origin at the center of the rotation of the elbow is used for the calculations. Since the movement of the upper arm is not relevant for the rope force, the elbow is simplified to be a fixed bearing. In addition, the two-dimensional approach allows the two sides of the cable, pulling equally on the lateral and medial side of the arm, to be subsumed into one strand.

The most important variable is the cable force Fs. The length l_m is the distance between the elbow and the center of the mass m, which is the combined mass of the limb itself and any manipulated object. The measurement l_0 represents the distance between the elbow and the point where the cable reattaches to the upper arm. Both parameters can be calculated with different datasets from anthropometric databases to represent a variety of different individual's sizes. The angle α represents the elbow flexion and ranges from being fully flexed at 20° to being fully stretched at 180°, and the rope angle β measures changes from the forearm proportionally. The length l_s is the distance from the rope outlet to the elbow joint and has a major influence on angle β.

Using a static approach, the cable force Fs can be calculated in a moment equilibrium around the elbow with (1).

$$F_S = \frac{m g l_m \sin\alpha}{l_S \sin\beta} \tag{1}$$

Since β is dependent on α and l_s, it can be represented by these two parameters using the law of cosines and the law of sines, thus resulting in (2).

$$\beta = \operatorname{acos}\left(\frac{-l_S + l_0\cos\alpha}{-\sqrt{l_S^2 + l_0^2 - 2 l_S l_0 \cos\alpha}}\right) \tag{2}$$

Plugging (2) into (1) offers the formula to calculate the cable force for discrete values of l_s, l_0, and in dependence on the flexion angle of the elbow.

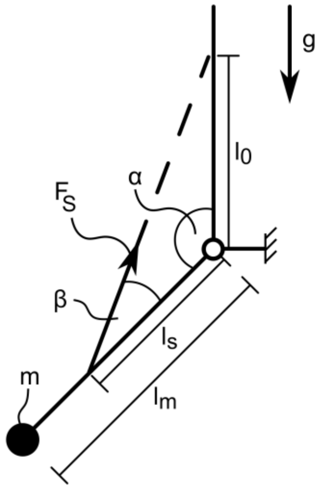

Figure 5. Schematic model of the exosuit kinematic

B. *Influence of β and l_s on Tendon Force*

Considering Fig. 5, it can be assumed that longer leverage around the elbow equals lower cable force according to the lever principle. However, β changes as well, becoming proportionally smaller for angles of α greater than 90°. Hence, the amount of the rope force acting orthogonally on the forearm and generating the supporting force for lifting loads gets smaller with an increasing distance to the elbow.

To estimate the relation between these two effects, F_s was calculated for different l_s and put into the relation. In Fig. 6, a representative curve is shown for α = 90° and m = 1 kg, with the center of mass defined in the middle of the forearm. The dimensions of a 50th percentile person from Germany were used for this representative calculation.

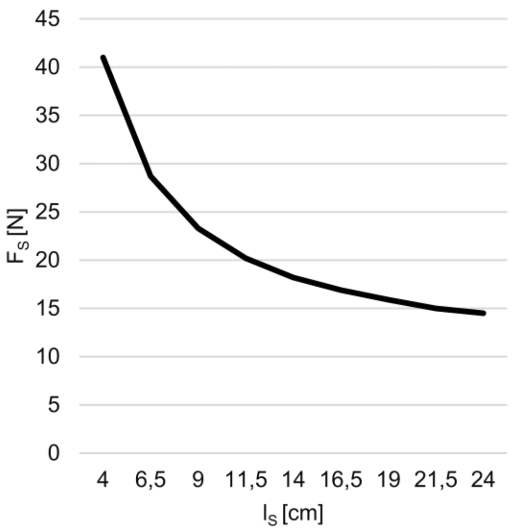

Figure 6. Rope force for different distances between the cable outlet and the center of rotation of the elbow (α = 90°, 50th percentile person, m = 1 kg)

The flattening curve for higher values of l_s shows tangential behavior and reveals that the positive influence of a larger lever gets negated by a small angle β. There is therefore no need to move too far away from the elbow to produce small rope forces, and so the proximal amount of the force can be kept relatively small. This is important so that no high forces are induced into the elbow joint. Complementary measurements also showed a similar course of the force along l_s.

Interpreting these values for the presented prototype of the exosuit, parameter l_s was chosen to be 10 cm. The resulting prototype without actuation is shown in Fig. 7.

When both ends of the cable are pulled, a supporting force can be sensed by the wearer and an actual movement can be produced, so that the basic functionality of the concept can be proven.

Figure 7. Prototype of the exosuit: structure and cable design

V. DISCUSSION

This paper presents a prototype of a soft exoskeleton for supporting healthy adults while lifting loads. In the development process, the focus was on the design of a suitable fabric structure, where the cable ducts can be built on top of the fabric. Since it has a cable that is guided on both sides of the arm and is potentially being pulled by two motors, it differs from other soft upper body exoskeleton designs like [7]. The independence from the upper arm rotation is advantageous, since it allows the two-dimensional approach in IV.A to be correct even for a holistic view of the whole arm.

There is still a lot of potential for optimization, e.g. the proximal vector of the rope force pointing in direction of the elbow joint, since this vector is potentially inducing shear forces into the joint. In the next iteration, this proportion of the force needs to be compensated or absorbed by the exosuit structure.

The following chapters discuss the optimization potential of the prototype and present concepts that are planned for further improvement of the exosuit.

A. *Concept for Compensation of Proximal Forces*

As mentioned above, due to the design of the cable, there are going to be proximal forces that can possibly damage the elbow. Furthermore, it can be observed that the textile structure is pulled towards the elbow and ruffles up as soon as the cable is pulled. This happens because it is not possible to attach the wrist band tight enough and the human tissue also succumbs to the applied forces. The stretching of the skin at the wrist will also result in discomfort for the wearer.

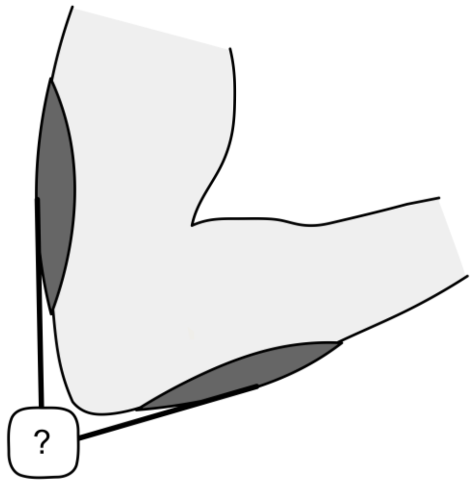

Figure 8. The connection between the upper and lower arms must be designed in a compatible way

The next iteration of the prototype should therefore feature reinforced structures that compensate the proximal forces and keep the fabric from being pulled back. These rigid structures need to be attached in such a way that the flexibility of the textile structure is sustained while it is still lightweight. The forces need to be taken away from the joint and led through the exoskeleton structure instead. Ideally this should be from one bone to the other, from the ulna and the radius to the humerus as pictured in Fig. 8.

The challenging part is to design the rigid structures in a way around the elbow, so that no misalignments as described in II.A occur.

Technologies with a fixed center of rotation such as a hinge joint, cannot be used. Rather, non-anthropomorphic joint structures need to be used, for example like the one developed in [17].

A possible approach might be going through a bionic design process and implementing solutions inspired by insects, fish or even plants.

B. Optimization of the Physical Human Machine Interface

Attaching the exoskeleton to the human wrist poses disadvantages, since it is not feasible to strap it tight enough. This is especially true when future users are taken into consideration, who might feel uncomfortable when using it and might be prone to misuse. Due to the large displacements of the wrist during pronation and supination, attaching the exosuit there is prone to induce shearing forces.

As discussed in V.A, having the cable attached to the wristband also results in it being pulled back and tearing the skin underneath.

Both issues might be fixed by attaching the exoskeleton to the whole hand with a glove. Looking at the fact that the forces are applied at the hands during most handling tasks, it makes sense to also attach the cables at the same point. The strain induced onto the wrist and the hand, especially the metacarpus, might be reduced by doing so.

In the next iteration, a detachable glove will therefore be designed that the cables are fixed to and where the induced forces are distributed equally across the whole hand to reduce places with peaking pressure. While doing so, the possible twisting of the cable between the forearm structure in V.A and the glove needs to be taken into consideration.

C. Sensoric Concept for Intention Recognition

To achieve the “easy use” requirement, it is important that the exoskeleton’s user needs to enter as few commands as possible. In addition to active support in the lifting task through the powered exoskeleton, the system needs to know when the user wants to lift something.

The principle of “intention recognition” by the soft exoskeleton may relieve the user of cognitive load. If the users do not need to give active commands to activate the power assistance, they are able to focus on the work task. Therefore, the probability that the exoskeleton is perceived as useful and not a burden increases.

To detect the intention of the exoskeleton user, there needs to be a sensor-based detection of biological signals that can be interpreted accordingly. Systems like the HAL (Cyberdyne) use electromyographic (EMG) signals at the skin surface to measure muscle activity. In medical applications, like robotic orthoses and prostheses, EMG and EEG signals are commonly used [18] to enable natural movement with the system. But these sensory applications are rather complicated to attach, since the skin needs to be prepared and the sensors need very precise placements. EMG signals especially tend to have very high inter- and intra-individual variations; correct calibration and processing of the data is therefore crucial for correct interpretation, and therefore also rather complex and prone to error. A sensory system is needed for the concept of an easy to use exoskeleton with intention recognition that is not difficult to attach or to calibrate, and is robust against influences of different body types and clothing worn underneath the exoskeleton. To measure muscle stiffness and thus detect intention of movement, Force Sensing Resistors (FSR) can be used [19].

Under these aspects, a prototype was developed using FSRs on top of the two main active muscles. the *biceps brachii* and the *triceps brachii*. An array of FSRs with force applicators at the biceps and at the triceps measures muscle stiffness, which indicates when a contraction of the muscle is planned to be implemented. The force applicators should be calibrated to a pressure of 0.1 kg/m^2 when the muscles are relaxed and with the arms hanging down to keep the pressure at or below the level of low discomfort [20]. Furthermore, two inertial measurement units (IMU) need to be integrated to track the position of the upper and lower arms as well as a binary push button in the palm of the hand to detect loads applied at the hands. The sensor placements are shown in Fig. 9.

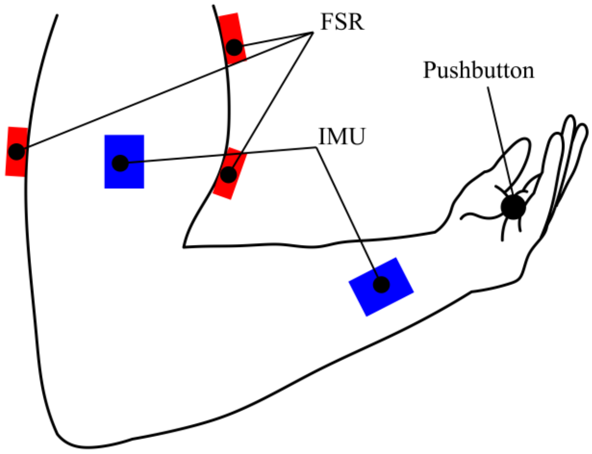

Figure 9. Placement of FSRs on the muscles, IMUs on the upper and lower arms and the binary pushbutton in the palm of the hand.

The combination of the measured sensory inputs is used to interpret the intention in discrete states. The defined states are:

- lifting
- static holding with 90 ° angled elbows
- lowering
- static holding with 180 ° angled elbows

While *lifting* and *lowering* are dynamic movements, *holding* requires a static posture of the arms. Dynamic movements are defined to always end in a static posture, while a static posture can remain indefinitely or change into a dynamic movement again.

These constraints are formulated into a state machine and the different states are triggered by different combinations of the sensory inputs from measured biological parameters.

The state machine is visualized in Table I. The initial condition for the intention recognition process to start is the binary signal of the push button in the palm, meaning that the user grabbed an item with his hand. The position of the upper arm is defined to be always in a vertical position.

TABLE I. INTERPRETED SIGNALS OF THE POSITION OF THE LOWER ARM AND MUSCLE STIFFNESS RESULTING IN FOUR DIFFERENT INTENTIONS

position of lower arm	muscle stiffness	interpreted intention
vertical	< lower threshold	static holding
	> lower threshold	lifting
horizontal	< upper threshold	lowering
	> upper threshold	static holding

The sensory system needs to be evaluated in regard to sensitivity and specificity for the correct recognition of intentions of lifting and carrying objects. The system needs to show robustness against influences by anthropometry, supination of the forearm and clothing.

VI. CONCLUSION

Are exoskeletons “too close to comfort”? - The challenge of putting mechanical structures, actors and other technology very close to the body was approached by choosing a soft design and a cable-driven actuation. Compared to the mainly rigid exoskeletons, uncomfortable or harmful misalignments can be avoided. A slim and lightweight prototype was set up that differs from existing exosuits in its easy to put on, jacket-like design.

New challenges arise when no rigid structures are used. The forces cannot be transferred away from the body completely, only local redistributions are possible, e.g. around joints. Also, the attachment of actuators, in this case cables, becomes more difficult. On the other hand, flexibility makes anthropometric adjustments easier.

In future iterations of the prototype those solutions and ideas will be tested. The design will be improved over time with fast and short development cycles.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Christina M. Harbauer and Martin Fleischer are the lead researchers, wrote the paper and supervised the research of Thao Nguyen, Fabian Bos and Stefan Kopfinger. Thao Nguyen is responsible for the design of the prototype. Fabian Bos revised the mechanical calculations. Stefan Kopfinger presented the concept for intention recognition. Klaus Bengler is the head of the chair and coordinated the project.

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