
Designing a Wearable Soft-Robotic Orthosis: A Body-Centered Approach

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ABSTRACT

Given an extension of the working life and the large number of musculoskeletal disorders associated with occupational activities, wearable assistive technology could help to enable workers to carry out their profession as long as possible and necessary. In this pictorial we describe our design process towards a wearable soft robotic orthosis and illustrate a "body-centered" design approach that involves the human body throughout the different stages of the project and takes advantage of its abilities to specifically address the challenges in the development of wearable technology.

Authors Keywords

Soft Robotics; Body-Centered Design; Bodystorming;
Participatory Design; Orthotics; Human Machine Interaction

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INTRODUCTION

Demographic change and changes in the employment behavior of older people led to a shift in the age structure of employees in Germany in recent years [3]. An increasing working life up to old age makes it necessary to think about new concepts in the context of work to enable workers to carry out their professions as long as possible. Despite the modernisation of work processes and the use of new technologies, a large number of musculoskeletal disorders can be traced back to occupational activities [1].

The aim of the project PowerGrasp is to reduce the physical strain of assembly workers by means of strength assistance, thus preventing possible consequential damage and preserve the workers' physical health. For this purpose, the interdisciplinary project team developed a body-worn soft robotic support system for arm, shoulder and hand support that provides active force assistance as needed by compensating muscle fatigue. While other partners focussed on control technology and technical implementation [7], our specific focus in the project was on the user-experience and acceptance. In this paper we illustrate our development process from a design and user perspective.

The development of wearable technology is a topic that requires special consideration in the design process. When investigating user requirements, very personal and sensitive topics may be discussed in workshops or interviews. The requirements to such a system are often very individual. Ergonomics and wearing comfort play a central role and anatomical and physiological characteristics of the human body have to be carefully considered to avoid injuries. To address these challenges, we followed a what we called 'body-centered' design approach in which we took advantage of the human body and its capabilities in a variety of ways.

Reflecting this process, this paper focuses on the following question: *How can the involvement of the human body and its abilities support the design process of a wearable assistive system?*

In this context, we have identified five key roles of the body in our design process, which we will discuss below: The body as a means of communication, thinking through the body, evaluating through the body, the body as research object and the body as working area.

THE BODY AS MEANS OF COMMUNICATION

While traditional design research methods primarily focus on what people say (e.g. interviews), do or use (observational research), a growing number of approaches aim to understand people's thoughts, feelings and dreams by accessing tacit knowledge and latent dreams that people cannot readily express in words [6]. So called "Make-Tools" facilitate exchange and communication between possible users of a product or service and the people that design and develop it. By providing toolkits people can use to express their thoughts, feelings or dreams with by creating an artefact and/ or model, as-yet unknown and/or unanticipated needs are meant to be discovered [6].

Within our design process, we conducted participatory workshops with potential users and experts to learn about their thoughts, needs and visions regarding an assistive system. Therefore, we developed a "body-storming toolkit" (fig. 1) for the design of a wearable support system for arm, hand and shoulder. In bodystorming [16], situations and/or motion sequences within a specific use case are simulated together with users in order to work out possible problems, ideas or needs in dialogue. We combined this method with a toolkit consisting of a set of materials and tools, with which the participants could visualise their ideas and suggestions prototypically on their own bodies.



Fig. 1

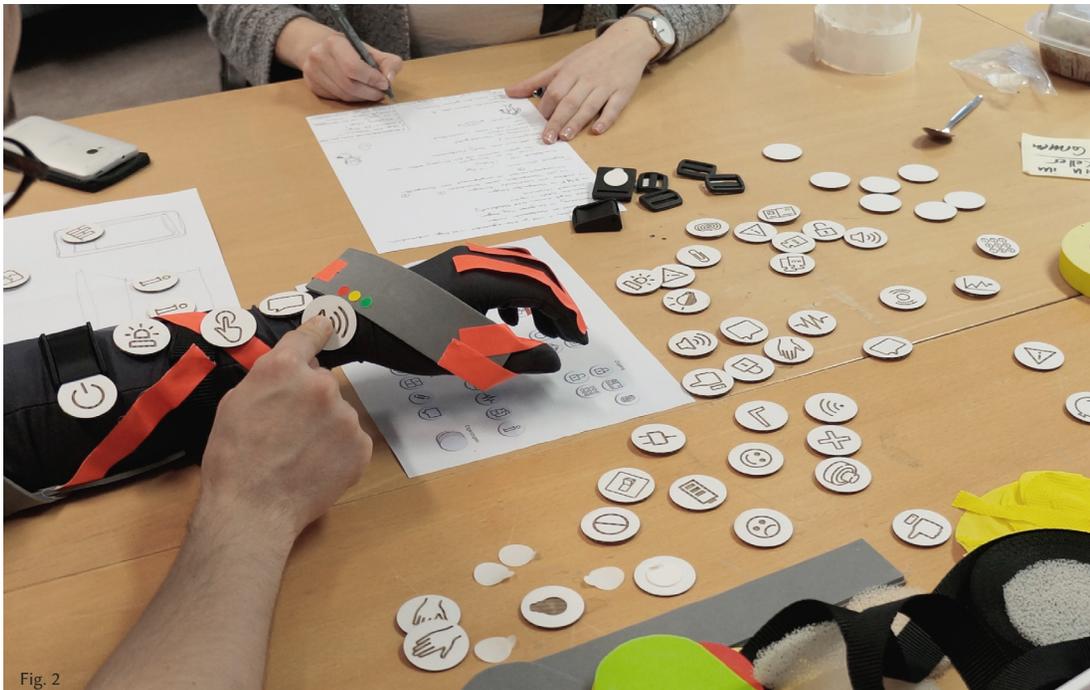


Fig. 2

Fig. 2: A participant using the bodystorming toolkit to express his needs and ideas for a wearable support system.

Fig. 3: A participant performing workplace-related movements within the creation process.



Fig. 3

Fig. 2 and 3 provide some insights into the participatory workshops that lasted about one hour and were conducted as individual sessions to make sure that the participants feel comfortable to freely talk about their personal considerations without having any inhibitions towards colleagues or superiors.

At the beginning of the bodystorming session, the participants were asked about their workplace related activities and potential physical complaints. On a glove that reached up to their shoulders they were then invited to mark areas where they felt a particularly strong physical strain. In a second step, they were asked to metaphorically “build” a support system for their individual needs directly on their bodies and equip it with the desired functions and features. Therefore, various materials and chips with a series of symbols were provided. The different materials represented different material properties and volumes while the symbols were meant to stimulate reflection on different aspects of interaction with the system. Later in the text, we give a detailed insight into the materials and the functionalities indicated on the icons.

Within the creation process, the participants were asked to perform workplace-related movements in order to consider possible constraints, to think about how they would like to interact with the system and how the device could support them in specific situations. Throughout the process, they expressed their thoughts and ideas by “thinking aloud”[18]. At the end of the session, they presented their results to the researchers by explaining and demonstrating how they would use the device.

The workshops were conducted with two groups of people: 1) with four people working at the assembly line of an automotive company and 2) with three therapists: two physiotherapists and one ergotherapist. While the first group focused on use case and task related requirements, the results of the second group was especially interesting in means of physiological aspects. Insights into these workshops will be given in the next section “The body as research object”.

All workshops were documented by video and audio recordings. The artifacts created by the participants complemented the analysis. In combination with the transcripts they provided numerous design approaches and ideas that formed the basis for deriving user requirements and further concept development.

A challenge in the choice of materials was to offer the participants a purposeful and manageable range of functions and materials, without influencing them too much by our selection. For this reason we tried to keep both the materials (fig. 5) and the functionalities illustrated by icons (fig. 4) abstract to leave room for interpretation. The selection of the functionalities represented on the chips (fig. 4) was made on the basis of experience from earlier projects.



Fig. 4

In the “Feedback” section, different channels of perception are addressed: visual, auditory and haptic feedback, the latter represented by a vibration icon. The smileys represent a positive-negative pair of opposites, leaving much space for interpretation. The speech bubble represents feedback in the form of a speech output and the siren icon was intended as an abstract warning function.

The “Access and Authentication” area should encourage participants to consider certain aspects of accessibility and data protection. The importance of the individual icons was not necessarily a priority. Rather, our goal was to make the participants reflect on the topic through the functions presented (i.a. locked/unlocked, pin input, a personal profile).

The same applies to “Data and Statistics”: With these symbols we wanted the participants to reflect on whether and which data could be collected by the system (e.g. vital data, degree of strength support) and what they would like to know about these data in which form (e.g. changes over time, rewards).

We also choose some abstract “status messages” such as warning or information, that should be specifically defined or filled with content by the participants when used. To do so, we asked specific questions in the workshop when necessary.

The icon in the category “Interaction” stands for a user input. Empty chips could be labelled by the participants themselves.

In the workshops we had a few more icons, which turned out to be redundant (e.g. thumbs up/down, different On/Off switch icons, an “out of order” icon) or not understood (e.g. a balloon as pneumatic function). We have therefore removed these icons and not shown them here.

When using the toolkit, we noticed that many of the icons and materials were interpreted or used very freely (light, intended as feedback, was used as a flashlight on the finger, coloured adhesive dots as different status LEDs, foam as a display, tape as an actuator). This led to very creative applications and interesting findings.

Conclusions from our work with the materials:

- It has proved positive to prepare the materials by cutting them to different sizes and shapes (fig. 5). At this point an abstract level is important so that materials can be used for different purposes than originally planned.
- In case of the chips (fig. 4), abstract representations of (basic) functions have turned out to be very valuable, as these could be interpreted broadly by the participants. Overly technical approaches (e.g. different switches, technical features such as pneumatics, ...) were not useful and made the chip set unnecessarily complex.
- The “Access and Authentication” and “Data and Evaluation” chips have in fact helped participants to address the issues involved. However, it was helpful here to specifically address the participants’ opinions on the topic in order to give an impulse for reflection.
- It is important to let the participants explain each of their design decisions, as the materials used may mean something quite different from what the researchers assumed.



Fig. 5

- 1 The employee wants an orthosis into which he can “slip in” “like a glove”. It should be fastened with buckles
- 2 Volume should be placed on the outside of the body e.g. shoulder area or elbow joint.
- 3 Switching on at the inside of the forearm.
- 4 Status LED on the inside of the forearm indicates erating or not.



Fig. 6

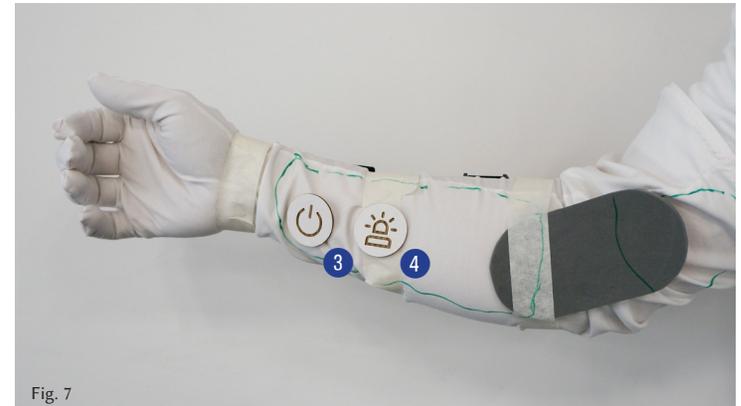


Fig. 7

- 1 Freedom of movement is very important to the second employee. Volume should be placed in the upper arm area, no volume on the fingers.
- 2 The orthosis is on as soon as the zipper is closed.
- 3 It creates a profile for each employee and gives recommendations. Identification is done via pin pad.
- 4 In case of critical movements, a vibration signal is given.



Fig. 8



Fig. 9

- 1 The third employee wants a system to prevent physical health problems. She would like to put it on like a jacket and close it with velcro.
- 2 It is switched on at the inside of the forearm.
- 3 The status of the system (on/off/battery status) is represented by LEDs.
- 4 A red LED gives a warning in case of wrong movements.



Fig. 10

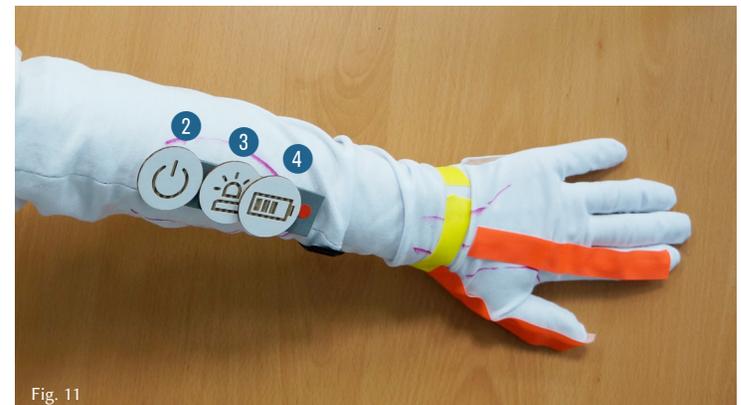


Fig. 11

One of the main results of the workshop analysis was a concise collection of requirements for a body-worn support system in the following topics: Design and construction, usage, interaction and feedback.

Design & Construction: The orthosis must under no circumstances be able to injure a person and must inform the user of this fact through its formal design. The system should be soft and flexible, like a garment, rather than rigid like a “classic” exo skeleton. Solid elements should at least be well padded or embedded to prevent the orthosis from scratching and denting workpieces or getting stuck while working in narrow spaces. It must be easily removable in the event of a malfunction. Technical components and volume in general should be placed on the outside of the body, preferably on the upper arm or back. Volume on the finger should be avoided as far as possible, as fine activities such as gripping through metal sheets may have to be carried out. The wrist should also remain flexible, but should be supported as needed.

Design considerations: The system is designed like a garment and, if possible, should completely avoid rigid components. Volumes for technical components are placed on the back.

Usage: The support system is more likely workplace-related than assigned to a specific employee. That means it is located on the respective workplace and can be worn by anyone who works

there. Therefore, it must be wearable over regular work clothes and adaptable to different body shapes. The subject of hygiene must also be considered thoroughly in this case. Due to the risk of injury, the device must not be connected to a stationary system by cables or tubes.

Design considerations: The system is designed as a vest with adjustable straps so that it is flexible in shape and can be combined with work clothing. The system must be completely mobile and the entire energy supply must be wearable on the body.

Interaction & Feedback: The orthosis should be quick and easy to put on and take off, for example for (toilet) breaks. Some participants would rather have the orthosis switched on explicitly by a kind of switch, while others preferred a more casual switch-on, for example by putting on the orthosis or by starting a workflow. Two of the participants wished for an individual setting of the level of assistance. The others simply wanted automatic support without the need for further adjustments. In each case, the user must always have full control over the system. The orthosis should indicate its respective status, such as whether it is ready for use, possible malfunctions, and the battery status. Light and haptic feedback were often mentioned as feedback types. At least two participants were critical about audio feedback, as additional sounds could be lost or even be disturbing in an already noisy working environment.

Design considerations: To ensure that the user always retains control over the system, it mainly compensates muscle fatigue. The user can thus overcome the system at any time and does not run the risk of being controlled or injured. Buckles and Velcro fasteners allow for quick putting on and taking off. Different switch-on and switch-off solutions as well as feedback possibilities have to be explored.

The workshop results provide a solid set of requirements that such a system must meet in order to go beyond the technical demonstrator to an application-oriented device that is accepted and used by its potential users. For organisational reasons, we were unable to hold the workshops at the real workplace. As a result, the movements performed by the participants remained relatively abstract. At this point, core elements of the workplace could have been simulated, either by a physical construction, or by a sketch on the wall, in order to put the participants more into the situation. This might have led to some more specific workplace related insights.

Fig. 12: Synthesis of the key ideas and insights provided by each artifact in the analysis process.

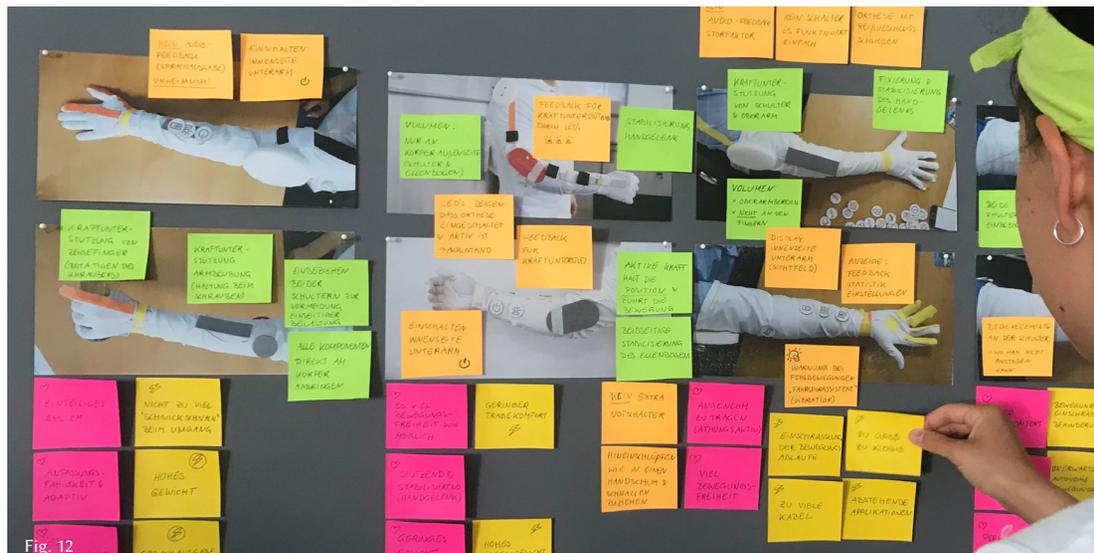


Fig. 12



Fig. 13

Fig. 13: The first therapist wants to put on the orthosis by slipping into it like a glove. It must not be too tight or too compressive - she wants to have the feeling that the orthosis belongs to her. Moreover, she wants to be able to manually adjust the degree and region of power assistance.



Fig. 14

Fig. 14: The second therapist wants to slip into the orthosis like a sock, without further buckles or fasteners. Her orthosis is designed to support the rotational movements of the arm by traction. The orthosis should recognize her and know which tasks she is going to perform in order to “simply work” and support her.

THE BODY AS RESEARCH OBJECT

As the human body is a highly complex anatomical and physiological system, it entails a series of specific abilities and constraints [8]. Developing a system that is meant to be worn on and support the body, a very important part of the research was dedicated to the understanding of these given parameters. Therefore, we conducted workshops with two physiotherapists and one ergotherapist using the toolkit described before. Whereas in the first workshop the toolkit served to address and communicate tacit knowledge, it now supported the therapists to structure and express thoughts and knowledge by visualizing anatomical concepts. Furthermore, it facilitated the communication between therapists and designers and developers. In these workshops, we were able to identify a set of physiological requirements to be considered in the design process:

Physiological requirements:

In order to protect the joints, it is essential to carefully study and consider the respective degrees of freedom. Places where many nerves and vessels are located should be left free. This includes in particular the crook of the elbow and the armpit. Solid components should not be located on muscles, as they may squeeze the arm when the muscle is actuated. In terms of power assistance, the entire body must be considered: when a force is dispersed in one part of the body, it can cause problems in another part. For one-sided power support, this means that the other shoulder must be included in order to distribute forces evenly.

Design considerations: As few technical components as possible are placed on the arm. They are placed on the back, with volume and weight evenly distributed over the body. The system is designed in the form of a vest that distributes the force evenly over both shoulders.

THINKING THROUGH THE BODY

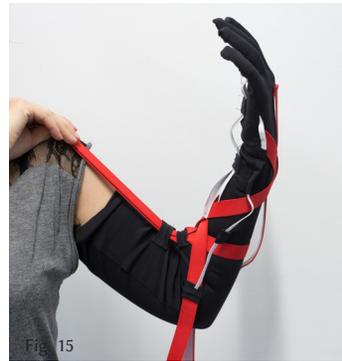
Our mind and body are strongly connected when it comes to learning and reasoning. Research on embodied cognition states that bodily activity plays an essential role in human cognition [13]. Prototyping processes in design practice vividly illustrate this interconnection of action and cognition: Klemmer et al. [6] describe this process aptly as a “conversation with materials” in which the feedback of every built object helps to uncover problems or generate suggestions for new designs.

Since the findings of our workshops suggested the development of a soft orthosis, we focused on techniques that do not require rigid structures. On the basis of existing research in the field of softrobotics and softrobotic orthoses [2,4,5,11,14,17,19], we aimed to adapt certain functional principles to our specific use case: Overhead work during assembly jobs. In this early stage of the design process we started to experiment with different techniques and materials to find opportunities to move shoulder, arm, hand or fingers according to the movements we identified in the workshops for the given use case. As a reflection and adaptation of our research results, we created what we called “functional samples” (fig. 15-20).

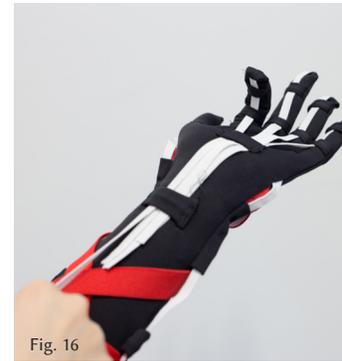
We used low budget materials to build early prototypes that allowed us to experience certain working principles on our own body. In this way, we were able to roughly examine the following aspects, among others, for each sample: How could it feel to be moved by such a system? How much force could be exerted on the body?

The samples not only helped us to understand certain functional approaches and to transfer them to our specific use case, they also made them visually, haptically and to a certain extent acoustically experienceable. This made them an important tool for communicating ideas to team members and project partners. It certainly could have been well suited for an evaluation and discussion of subfunctions with potential users. Due to organisational difficulties, we were unable to do so, but we consider this to be an important question for further research as to whether and to what extent such feedback could have provided valuable insights at that early stage.

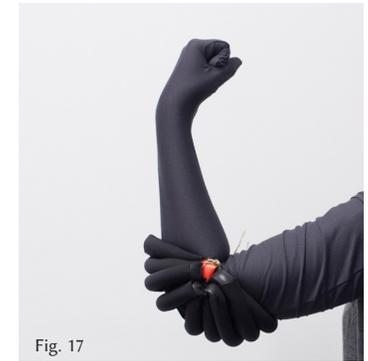
Since the two pneumatic samples fig. 17 and 20 provided very inspiring and well-functioning results, we decided to continue working on these principles.



This functional model was used to reproduce movements of the upper extremity by means of traction ropes: Elbow flexion, pronation, supination, flexion and extension of the wrist (fig. 15), as well as gripping movements of the fingers (fig. 16).



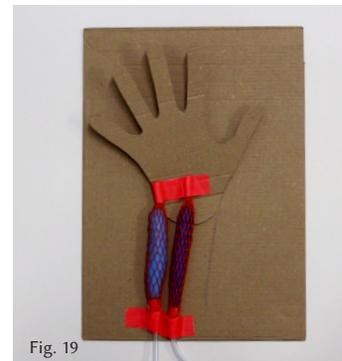
Reproducing finger movements: This technique could be well suited for the actuation of the fingers, as it has little volume.



Pneumatic sample based on the principle of bellows, made of a bicycle tube incorporated into a two-layer textile (rigid bottom layer, stretchable top layer). It bends the arm with high power when inflated. Sample served as basis for the final elbow concept.



The principle of fig. 17 was extended by additional air chambers as levers for better force transmission. Our sample withstood little pressure due to limited manufacturing possibilities and was therefore not very effective. Better manufacturing processes could have led to very interesting results.



Functional sample of an artificial muscle, pneumatically operated. Exploration of how pneumatic elements could be placed to realise different hand movements (dorsal extension, ulnar abduction). Size and position of the pneumatic element correlate with the range of motion.



Pneumatic sample made of two bicycle tubes and a two-layer textile shell (rigid bottom layer, stretchable top layer): One tube serves as dynamic air chamber and is inflated to lift the arm. The other one is constantly filled with air and serves as static air chamber to ensure firm positioning on the body.

In the case of the elbow support, we started experimenting with different materials following the functional principle of the sample shown in fig. 17. An example with foil (fig. 18) led to poor results due to the limited manufacturing possibilities. A second approach with silicone provided very promising results.

We derived the following findings from sample fig. 17 and fig. 18:

- In addition to the shape of the construction, the two-layer principle contributes significantly to the functionality. The different elastic layers increase the bending of the actuator.
- Support elements on the upper and lower arm increase leverage.

In order to combine the two-layer principle with the silicone body, a inelastic textile was embedded into the bottom layer of the silicone actuator during the process. We experimented with different shore hardnesses and wall thicknesses as well as exterior shapes of the actuator and shapes for air chambers (fig. 21-22). The actuator shown in fig 23. was finally able to bend the arm.

In case of the shoulder support, the challenge was to design a system that adapts well to the body, allows as much freedom of movement as possible, supports upward and forward movements of the arm and distributes the forces well over the whole body. In a first step we developed a mockup directly on a dummy (fig. 24), to get an idea of the dimensions and possible positions of technical components and of the fastening possibilities on the body.

From the sample fig. 20 we derived the following findings:

- A combination of static and dynamic air chambers improves the mechanism of action and supports stable attachment to the body.
- Two dynamic chambers (instead of one continuous one) allow more freedom of movement for the arm.
- The two-layer principle is essential for the performance of the actuator.
- The positioning and attachment of the actuator to the upper arm and upper body are crucial to achieve optimum leverage.
- Fastening to the arm is a challenge due to volume changes when inflated and deflated. Flexible fastening is important.

Based on these findings and the mock-up (fig. 24), we started developing and designing a first prototype for shoulder support made of a two-layer textile and bicycle tubes. Several iterations finally led to a working prototype which was at this stage operated manually with an air pump (fig. 25).



Silicone actuators: Different shapes, air chamber parameters and wall thicknesses were tested.



Result: Wearable elbow actuator consisting of a silicone body and solid support elements, capable of flexing an arm when inflated.



Mock-up of a wearable pneumatic support system.



Result: Wearable prototype of pneumatic shoulder support, at this stage operated manually with an air pump, capable of lifting up an arm when inflated.

THE BODY AS WORKING AREA

Based on the design considerations derived from the workshops, the project team agreed on the construction of an entirely mobile system with compressed air supply. After the development of the actuators, the next step was to integrate the necessary technology for an adaptive control system. As a basis, we got a technical construction plan from our technical partner. In several iterations we developed a concept for the placement of the technical components on the body, the so-called “back module”.

The human body with its anatomical attributes offers a fairly strict defined working area. Especially for the design of the back module, this aspect played an important role: All technical components (i.a. control unit, valves, power supply, compressed air storage, sensors) had to be placed in a very limited space without restricting the user or creating an unpleasant wearing sensation. For that purpose we set up a wearable mock-up with all components either in the original or as volume models with realistic weight. In cooperation with other project partners, the components were attached to the body in various constellations to find the most suitable solution. Some steps are illustrated in the pictures (fig. 26-31).



Fig. 26

Placement of the valves and control unit in the waist area: Too little space left for the battery pack.



Fig. 27

Placement of valves on the back. Compressed air bottle (and battery) placed in the middle of the body to prevent one-sided loads. Compressed air bottle collides with valves.



Fig. 28

Separation of valves and compressed air cylinder into two layers: Technical level underneath and easily accessible compressed air bottle in pocket above.



Fig. 29

Conception of the compressed air supply at the back. Tubes run from the back of the shoulder to the arm.



Fig. 30

Layout of power and data cables, elaborated together with project partners. All components are later sewn invisibly into the textile.



Fig. 31

Final concept of the back module: Technology is compactly packaged and the compressed air bottle stowed in second, easily accessible layer.

The Demonstrator

As one result of the research project and in cooperation with the involved partners, a working demonstrator of the assistive soft robotic system was built (fig. 32). Due to workplace-related requirements, the mobility and wearability of the system on the body played a particularly important role in the development process. As a result, the developed system does not require any external power or air supply.

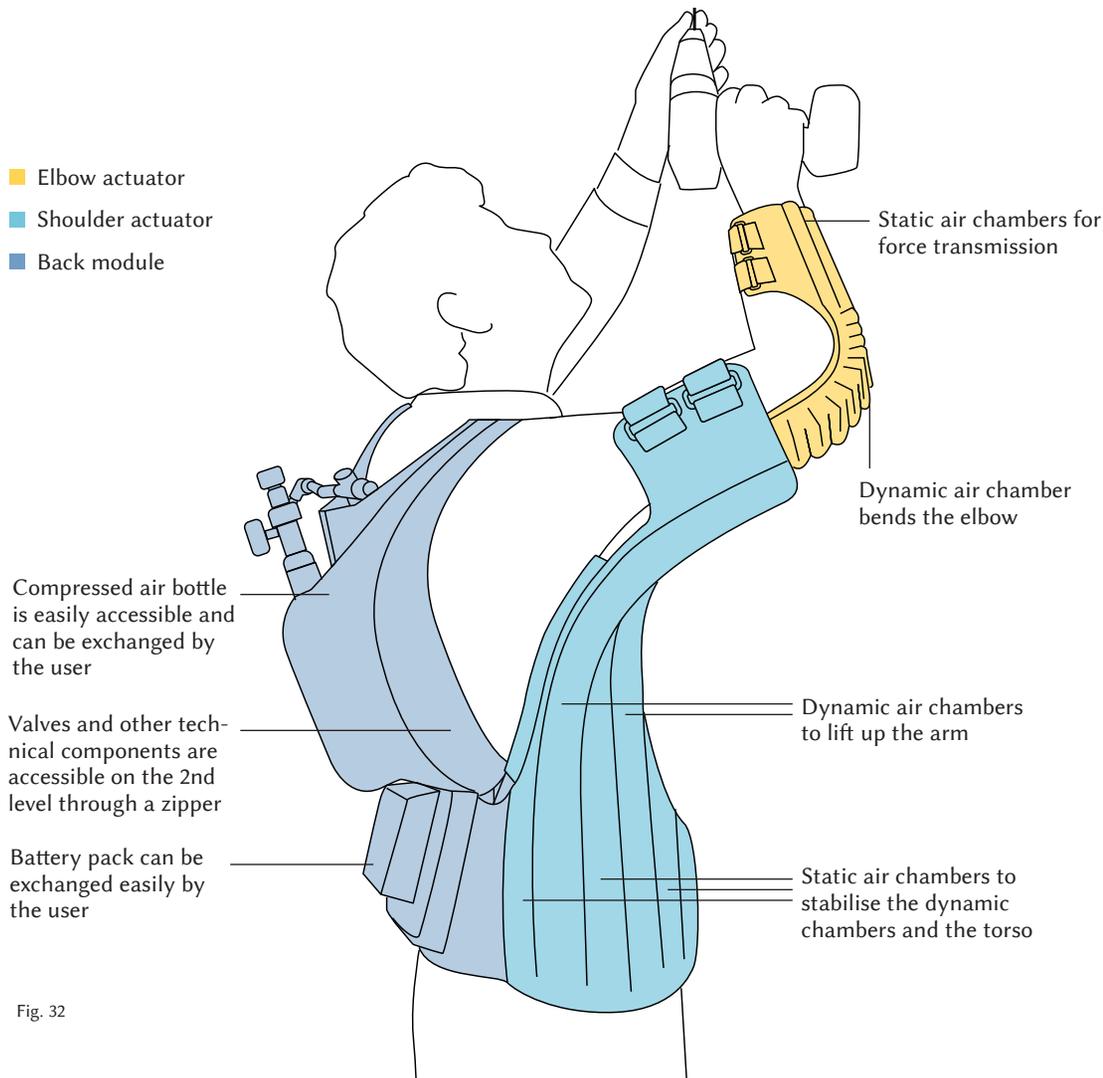


Fig. 32

EXPERIENCING AND EVALUATING THROUGH THE BODY

The human body is a highly complex instrument of perception [10]. Body perception played an important role in the evaluation of the Power Grasp system with potential users: External perception of physical origin (e.g. how does the system feel, is it comfortable to wear, does it allow enough freedom to move?) as well as inner perception (e.g. how do I feel about wearing it? Do I feel strong, does it stigmatize me, do I perhaps even feel inferior because I need support?). To evaluate the system, we conducted workshops with five people, three of whom were working at the assembly line of a large automobile manufacturer. The participants first had time to try out the working system and “think aloud”. They were then asked to express their feelings about the system. To facilitate this, the participants got a coloured scale from positive to negative and a set of cards with keywords derived from the workshop results (fig. 34). The keywords refer to dimensions of usability and acceptance (e.g. wearing comfort, freedom of movement, security or everyday suitability). By arranging the terms on the scale according to their perception, the participants evaluated different attributes of the system. The scale was primarily intended to promote reflection on the subject and to encourage participants to relate and compare terms rather than to serve as a quantitative evaluation. Most insights were gained from the conversation and the “thinking aloud” during the sorting process. The evaluation revealed a strong need for power assistance during assembly work. All participants could imagine to wear the system at their workplace. Nevertheless, the evaluation revealed a number of points which still need to be optimised in order to allow adequate use of the system.



Fig. 33

Fig. 33: Workshop pre-test with team members to improve study concept.

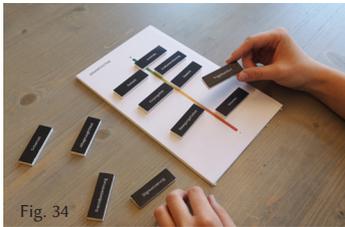


Fig. 34: A participant evaluating different attributes of the system by arranging UX-related terms on a scale while “thinking aloud”.

Nevertheless, the evaluation revealed a number of points which still need to be optimised in order to allow adequate use of the system. Especially in case of wearing comfort and freedom of movement the participants expressed concerns regarding adaptability to different sizes and body shapes, pressure on the arm and freedom of movement above head level.

Design consideration: The system is separated into a hip belt and a shoulder actuator that can be moved and secured on the belt to achieve a more flexible adaptation to different body shapes.

Unfortunately, we could not conduct the evaluation at the workplace and instead did so in an office environment. A test in the real environment would certainly have led to further interesting insights.

DISCUSSION

We used the body in various ways within different stages of the project. Especially in communication, whether with workshop participants to communicate ideas and thoughts, or to communicate with project partners, this approach proved to be very valuable. With the bodystorming toolkit we proposed a tool to enable participants to reflect on the topic and to express their needs, feelings and ideas freely. In the literature, different approaches to bodystorming can be found. Oulasvirta et al. [12] describe bodystorming as a roleplay to represent the situation or action for which is being designed. Schleicher et al. [16] describe a bodystorming method in which an idea is tested in a replicated environment, and the method of “embodied sketching” as a group activity for collaborative thinking and envisioning by enacting a scenario. Segura et. al. [9] propose “embodied sketching” as a bodystorming method that supports idea generation when designing for bodily experiences. They describe a co-design session with users, mainly focused on non-technical aspects such as socio-spatial arrangements. We see our approach somewhere in between the aforementioned methods: Unlike the above, our workshops focused more on the individual and were conducted as individual sessions to ensure that participants feel comfortable talking freely about their personal considerations. The participants did not perform a “role”, but were supposed to reenact their own workflow in order to become aware of their movements and bodies. At the same time, they were asked to actively express their needs and visions with the toolkit. Besides aspects such as acceptance and user experience, our approach also specifically addresses technical aspects.

The use case in automotive manufacturing made it difficult to carry out the workshops at the respective workplace, as this is not possible for organisational reasons during ongoing production. However, in order to achieve specific use case related results, it might have been useful to roughly replicate the workplace, as suggested in [12], in order to help participants put themselves in the situation. This applies to both the bodystorming and the evaluation workshops.

The creation of early mock-ups was a helpful tool to quickly understand functional principles and to test initial ideas. It would have been interesting to test these samples with potential users to see how they are perceived.

CONCLUSION

In the development of wearable systems, a strong focus on the human body and its diverse abilities can make an enriching contribution to the design process. Summarising our findings, we would like to point out the following possibilities and advantages of involving the body and its abilities in the different project phases:

- **User Research:** Enabling participants to express and communicate thoughts, feelings and visions through bodystorming. Accessing knowledge of participants.
- **Ideation:** Understanding functionalities and quickly developing and testing ideas by creating functional samples. Communicating ideas to team members and project partners.
- **Creation:** Receiving direct feedback about physical characteristics (e.g. functionality, dimensions or placement) through one’s own body perception when prototyping on the body.
- **Evaluation:** Evaluating through external body perceptions (e.g. wearing comfort, appearance) as well as internal perceptions (e.g. how do I feel about wearing it?)

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REFERENCES

- [1] Aptel, M., Aublet-Cuvelier, A., & Cnockaert, J. C. (2002). Work-related musculoskeletal disorders of the upper limb. *Joint bone spine*, 69(6), 546-555.
- [2] Asbeck, A. T., Dyer, R. J., Larusson, A. F., & Walsh, C. J. (2013). Biologically-inspired soft exosuit. In 2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR) (pp. 1-8). IEEE.
- [3] Brenke, Karl (2013): Immer mehr Menschen im Rentenalter sind berufstätig. DIW-Wochenbericht, ISSN 1860-8787, Deutsches Institut für Wirtschaftsforschung (DIW), Berlin, Vol. 80, Iss. 6, S. 3-12.
- [4] Kang, B. B., Lee, H., In, H., Jeong, U., Chung, J., & Cho, K. J. (2016). Development of a polymer-based tendon-driven wearable robotic hand. In 2016 IEEE International Conference on Robotics and Automation (ICRA) (pp. 3750-3755). IEEE.
- [5] Kesner, S. B., Jentoft, L., Hammond, F. L., Howe, R. D., & Popovic, M. (2011). Design considerations for an active soft orthotic system for shoulder rehabilitation. In 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) (pp. 8130-8134). IEEE.
- [6] Klemmer, S. R., Hartmann, B., & Takayama, L. (2006). How bodies matter: five themes for interaction design. In Proceedings of the 6th conference on Designing Interactive systems (DIS) (pp. 140-149). ACM.
- [7] Kusch, J., Goppold, J. P., Schmidt, H., & Krueger, J. (2018). PowerGrasp: Concept for a novel Soft-Robotic Arm Support System. In 2018 50th International Symposium on Robotics (ISR) (pp. 1-6). VDE.
- [8] Loke, L. & Robertson, T. (2011). The lived body in design: mapping the terrain. In Proceedings of the 23rd Australian Computer-Human Interaction Conference (OzCHI) (pp. 181-184). ACM.
- [9] Márquez Segura, E., Turmo Vidal, L., Rostami, A., & Waern, A. (2016). Embodied sketching. In Proceedings of the 2016 Conference on Human Factors in Computing Systems (CHI) (pp. 6014-6027). ACM.
- [10] Merleau-Ponty, M. (1962). *Phenomenology of Perception* Routledge & Kegan Paul. London, UK
- [11] Otherlabs Exoskeletons. <https://www.otherlab.com/blog-posts/exoskeletons> [last access: 27.11.2019].
- [12] Oulasvirta, A., Kurvinen, E., & Kankainen, T. (2003). Understanding contexts by being there: case studies in bodystorming. *Personal and ubiquitous computing*, 7(2), 125-134.
- [13] Pecher, D., & Zwaan, R. A. (Eds.). (2005). *Grounding cognition: The role of perception and action in memory, language, and thinking*. Cambridge University Press.
- [14] Polygerinos, P., Lyne, S., Wang, Z., Nicolini, L. F., Mosadegh, B., Whitesides, G. M., & Walsh, C. J. (2013). Towards a soft pneumatic glove for hand rehabilitation. In 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 1512-1517). IEEE.
- [15] Sanders, E. B. N. (2002). From user-centered to participatory design approaches. In *Design and the social sciences* (pp. 18-25). CRC Press.
- [16] Schleicher, D., Jones, P., & Kachur, O. (2010). Bodystorming as embodied designing. *Interactions*, 17(6).
- [17] She, Y., Li, C., Cleary, J., & Su, H. J. (2015). Design and fabrication of a soft robotic hand with embedded actuators and sensors. *Journal of Mechanisms and Robotics*, 7(2), 021007.
- [18] van Someren, M. W., Barnard, Y. F., & Sandberg, J. A. C. (1994). *The think aloud method: a practical approach to modelling cognitive*. London: Academic Press.
- [19] Wehner, M., Quinlivan, B., Aubin, P. M., Martinez-Villalpando, E., Baumann, M., Stirling, L., Holt, K., Wood, R. & Walsh, C. (2013). A lightweight soft exosuit for gait assistance. In 2013 IEEE international conference on robotics and automation (ICRA) (pp. 3362-3369). IEEE.