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A Novel Concept for Wearable, Modular and Soft Support Systems Used in Industrial Environments

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Abstract

This paper presents a novel concept for wearable support systems based on the approach of the Human Hybrid Robot (HHR), which can be adapted easily to the user and the activity. The concept focuses on modularity and makes intensive use of new manufacturing technologies like 3D-printing as well as flexible kinematics and textile components, in order to fit the system to different individuals and tasks as well as to increase human safety.

The main idea can be applied to various applications. In this paper we are focusing on a functional exoskeleton prototype for the upper extremities. It comprises a Human-Machine-Interface (HMI) using a glove equipped with haptic sensors to measure grip force as well as force sensors in a coupling to the user at the forearm. This functional prototype was then successfully evaluated in a blind study with 20 test subjects

1. Introduction

Even though automation has helped raising quality and productivity in many industries, human work will continue to play an important role in manufacturing, consignment and many other applications. In the producing industry decreasing lot sizes and an increase in variants for a single product makes it difficult to establish a return on investment from automation. Packet weight as well as size vary tremendously in logistic and consignment, which makes automation merely impossible in this fields.

Work-related load manipulation has been linked to degenerative deformation of the spine [1] and musculoskeletal problems in general [2]. As the average age of the workforce is rising and qualified workers are turning scarce, it is necessary to provide proper support in order to reduce musculoskeletal problems. In the end this will be beneficial for the company as well as for the individual.

In principle there are many ways to ease physically demanding work. In the past a lot of this work has been automated. This however requires large quantities of a certain product to be practical. Besides, the worker, who has been doing the work, possibly loses his job and in the end is not supported at all. Therefore, systems for individual support without replacing the human by a machine are required. Moreover, such systems must especially be applicable in environments, which require the flexibility only a human worker offers. In order to be universally applicable, those solutions have to be user-orientated instead of being task-orientated. In the end, this leads to a modular architecture for exoskeleton systems.

Various research has been done for exoskeletons in the last decades. While there has been a huge progress from the first concepts developed in the 1960s [3], many challenges, that have been identified back then, still remain. Among those is the proper identification of user intention [4], which will be discussed here.

Surface Electromyography (sEMG) is a well-known approach in literature to detect user intention [5-8]. sEMG measures the action potential in the muscle generated by the Central Nervous System [9]. As the action potential can be measured before muscle contraction begins, this approach will offer a low delay. However, the signal obtained from sEMG highly depends on the user's physiology and requires preparation of the skin prior to every use, which is not practical in consignment, logistic and production. Therefore EMG is not considered here as a means of detecting user intention.

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Besides, most systems documented in literature are monolithic systems that have been built to fulfill a certain predefined purpose and are usually built a single time. Therefore, they need to be adjustable to different individuals, leading to high bulkiness and thereby reduced acceptability.

2. Concept description

In consideration of the approach of the Human Hybrid Robot (HHR) [10], a modular concept is developed here in order to adapt the system ad hoc to different tasks as well as different users. Easy-to-use interfaces between modules give the user the ability to customize the system without the need for additional tools or extensive engineering knowledge.

3D-printing plays an important role as an enabling technology. On the one hand, it gives the system designer the possibility to create complex structures, which cannot be manufactured using traditional technologies. With the increased structural complexity it is possible to create novel, much more anthropomorphic system structures as well as a higher degree of functional integration (e.g. flexure bearings). On the other side, such technologies allow for user individual manufacturing or as an intermediate step a higher number of variants, making a better fit for the user possible. This reduces the perceived bulkiness as well as the structural weight, since the structural volume can be reduced and mechanisms to adjust the structure can be omitted. In the end, this will help to reduce the perceived dominance of the system and thus facilitates the acceptability.

Another key part of this concept is the combination of soft and rigid components in a single system. Soft components shall be used wherever contact with the operator is desired or possible. However, to reduce bulkiness, high strength materials (carbon fiber, high strength steel and aluminum) shall be used for structural parts.

A key challenge within this concept will be the integration of sensors in soft components. Especially when using flexible structures, which are difficult to map into a dynamic model, sensors close to the mechanical interfaces to the user will be of most value.

3. Application of the concept

3.1 Development of a design prototype

A modular support system for lifting tasks will be developed here and showcase some features of the previously outlined concept. The wearable support system will be used to help workers in consignment and logistics to lift crates and other heavy objects (see Figure 1). Individual modules created for this support system are a drive unit, an upper arm module and a module for the forearm. These modules are interconnected by easy-to-use mechanical interfaces (see Figure 2).

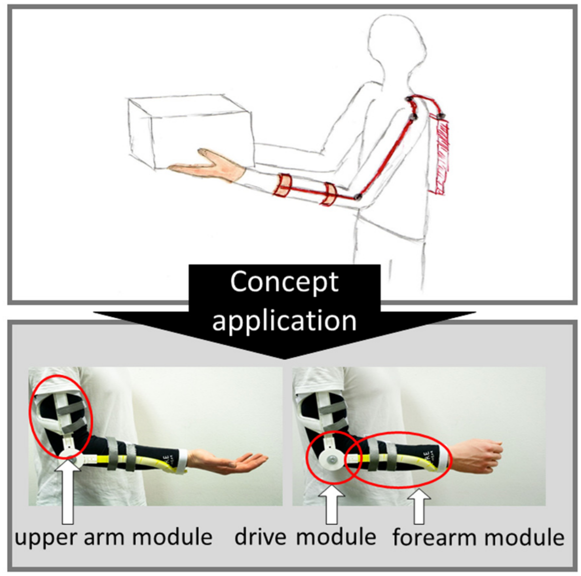

Figure 1. Application of the concept to a modular support system for the elbow

The concept tries to mimic the human degrees of freedom closely, thus resulting in an almost anthropomorphic system design [11], which incorporates flexible elements to adjust for differences between the human and the exoskeletons kinematics.

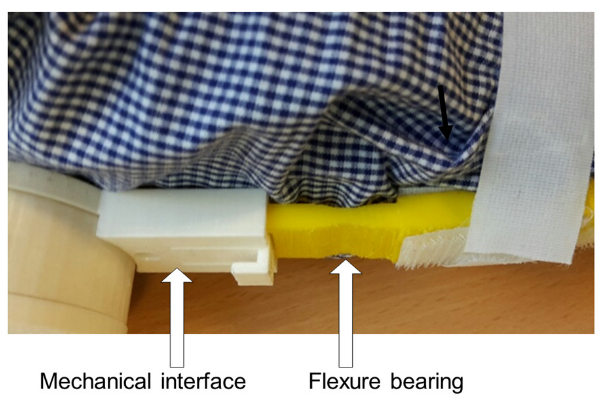

Figure 2. Forearm link with integrated flexure bearing to ensure a compliant behavior

In comparison to the degrees of freedom of a “real” elbow, a simplified model for the elbow is used in our approach. The elbow is simplified to a purely rotational joint with a flexure bearing in the forearm link (see Figure 2), which adjusts for the carrying angle of the forearm (angle between forearm axis and upper arm axis, when forearm is extended to 180°). The forearm link is attached tightly to the proximal end of the forearm and only loosely with a strap at the distal end, in order to restrict the pronation/supination movement of the forearm as little as possible (see Figure 1). The forearm link is constructed such that force is introduced from below the wrist (see Figure 1). On this way, no tight fit is necessary at the wrist to enable functional support.

A drive mounted at the elbow will support the flexion of the elbow joint, while another drive mounted at the shoulder will support the user during the anteversion of the forearm. Additionally support for the extension movement of the spine will be integrated, but not discussed here.

Since EMG is not applicable in the industrial environments targeted by the project, a glove equipped with thin and flexible force sensors similar to [12, 13] will be used to estimate the users intention from the measured grip force.

Experiments with the design prototype have shown, that while the flexure bearing is necessary to account for the carrying angle, it needs to be placed at the distal end of the upper arm and not at the proximal end of the forearm.

3.2. Realization of a functional prototype

A wall-mounted prototype with only a single active degree of freedom at the elbow was developed as an intermediate step to a body-mounted exoskeleton (see Figure 3). Different from the previous design prototype it provides a high mechanical stiffness to ensure good control performance, high torque (up to 40 Nm) and zero backlash. This allows an evaluation of the sensors with less influence from the systems structural behavior. The effects of a low stiffness structural configuration can then be simulated in the control software and design parameters for the mechanical structure can be derived subsequently.

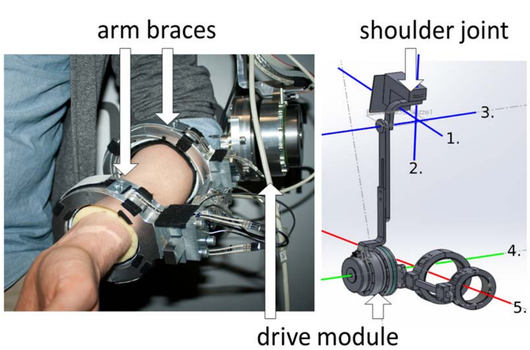

Figure 3. Kinematic concept of the functional prototype for a lifting-aid

The kinematic structure can be seen in Figure 3. The prototype comprises two rotational degrees of freedom allowing for adduction/abduction of the shoulder (axis 1 in Figure 3) as well as rotation of the upper arm (axis 2 in Figure 3).

The anteversion/retroversion movement of the shoulder is locked since the corresponding axis 3 is parallel to the drive axis (axis 4 in Figure 3) and therefore a torque applied here will result in a reaction torque in axis 3. However in the final support system a drive will be placed here, which transfers the reaction torque to the shoulder and supports the user's anteversion/retroversion movement.

The elbows complex flexion/extension movement is replicated by a simple rotational degree of freedom. The pronation/supination of the forearm is accounted for by a rotational degree of freedom in the two arm braces coupling the system to the user (axis 5 in Figure 3). The user keeps his shoulder in the point of intersection of the three orthogonal rotational degrees of freedom (axis 1-3 in Figure 3) and the forearm along axis 5 with the elbow intersecting axis 4.

3.3. Interaction force measurement in coupling to the forearm

It is crucial for every actuated system, which works in collaboration with the human, to measure or estimate the interaction forces between system and user to ensure safe operation as well as the desired functionality. For a serial kinematic, such as the proposed exoskeleton, this can be accomplished by either directly measuring the forces at all contact points with the user or indirectly by measuring all joint forces and using a model of the system dynamics to calculate the contact forces.

While measuring the interaction forces at all contact points between the user and the exoskeleton directly returns the desired control variable, interaction forces at contact points other than those designed for and equipped with sensors cannot be measured. In contrast, when using joint torques, interaction forces are measured regardless of the contact point. To compare both methods, the prototype of the lifting aid is equipped with a torque sensor in the elbow drive unit as well as force sensors in the arm braces.

While the torque sensor is a standard spoke wheel sensor based on strain gauges, the sensors used in the exoskeletons coupling to the forearm are built from flat piezoresistive force sensors (Tekscan FlexiForce A201, see Figure 4). In comparison to well established force sensing solutions based on strain gauges, these sensors are easier to integrate and less sensitive to overload. Even though these offer less precision than strain gauges, it has been shown, that they are applicable in force-control [14].

Two of those sensors are integrated in each of the two arm braces coupling the user to the forearm (see Figure 3 and Figure 4). To protect the sensor and to ensure that all the force is transferred through the sensors, they are applied between an outer ring connected to the elbow joint via a bar and an inner ring holding the sliding mechanism (see Figure 4).

In order to read the sensor signal a current-to-voltage-converter, as depicted in the datasheet [15], is used. The sensors supply voltage is set to -1 V and the gain resistor is chosen to 29 kOhm.

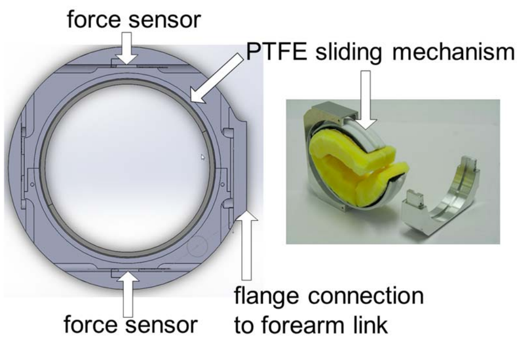

Figure 4. Force sensors and sliding mechanism in the arm braces coupling the exoskeleton to the forearm

3.4. Design of a haptic glove

The grip force, which will be used by the control algorithm to estimate user intention, is measured by flexible and thin piezoresistive force sensors (Tekscan FlexiForce A201, same as in forearm rings) as proposed by [16].

It is known, that the transfer characteristic of these sensors depends on the surface area in contact with the sensors [16]. To reduce this influence, textile strap (Polyamid, Hilco Textil) is used on both sides as protection and a round elastic actuator is placed on top of the sensor area to increase the share of grip force transferred through the sensors (see Figure 5).

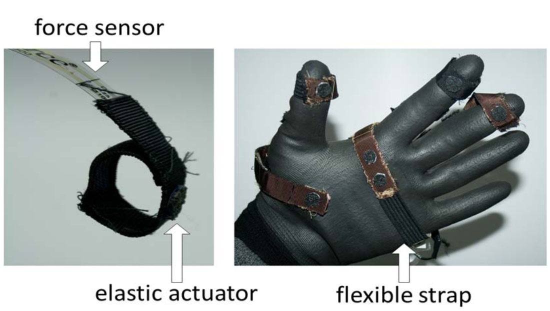

Figure 5. Force sensor protected by textile for the index finger (left), full glove (Nitras Nylontex 3520, right)

To read the sensor signal a current-to-voltage-converter, as used for the sensors in the arm braces, was used. However, the gain resistor is chosen as 293 kOhm, resulting in a higher sensitivity than in the arm braces.

Three sensors have been placed in the palm, one onto the tip of the thumb and two on the tips of index and middle finger (see Figure 5).

3.5. Control strategy

Admittance control is used as a control scheme to generate the reference velocity for the elbow $\dot{q}_{ref}$ (see figure 6), which is fed to the PI-velocity controller of the motor controller (EPOS 70/10, Maxon Motor AG), which controls a brushless DC Motor (EC90 flat, Maxon Motor AG). The motor drives a Harmonic Drive gear unit (HFUC-2UH, i=100, Harmonic Drive AG), which is mounted to the elbow joint and connected to the forearm link (see Figure 3).

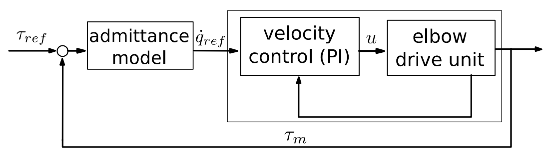

Figure 6. Control scheme

3.5.1. Interaction torque The signal $\tau_{torque\ sensor}$ measured by the torque sensor not only contains the torque applied by the engine to the user, but is influenced by the inertia and gravitation of the forearm link. For the relatively slow movements performed here, inertia does not play an important role. However the gravitational component of the link to the users forearm may not be neglected and therefore is compensated by

$$\tau_{m,elbow} = \tau_{torque\ sensor} - 1.6 \cdot \sin(\varphi_{forearm})$$

using the angle $\varphi_{forearm}$ between forearm link and upper arm link as well as the measured maximum offset torque (1.6 Nm) for $\varphi_{forearm} = 90°$.

The force signals F_1 and F_2 (see Figure 7) calculated from the two forces sensors in each ring are converted to the effective torque around the elbow

$$\tau_{m,forearm} = F_1 \cdot r_1 + F_2 \cdot r_2$$

allowing for an easy comparison with the signal $\tau_{torque\ sensor}$ generated by a torque sensor integrated in the elbow drive unit.

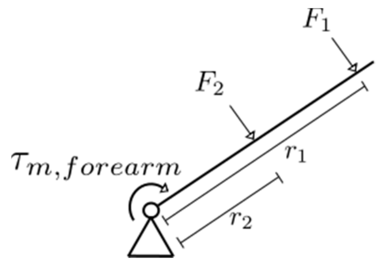

Figure 7: calculation of elbow torque from force sensors in forearm rings

3.5.2. Calculation of reference velocity. The reference angular acceleration

$$\ddot{q}_{ref} = \frac{\tau - d \cdot \dot{q}}{J}$$

for the elbow drive unit is generated using a simplified admittance model with the torque input $\tau = \tau_m + \tau_{ref}$, the damping parameter d and the inertia J. The reference velocity

$$\dot{q}_{ref} = \int \ddot{q}_{ref}\, dt.$$

used by the motor controller is then obtained by numeric integration over time. The support torque reference

$$\tau_{ref} = k \cdot \sin(\varphi_{forearm}) \cdot \sum_{i=1}^{6} F_i$$

is calculated as the scaled sum of the forces measured by the sensors in the glove.

Using the angle $\varphi_{forearm}$ between the upper arm and the forearm to scale the torque reference and assuming a vertically positioned upper arm results in a support that increases when flexing the forearm to a 90° angle, where the user feels the maximum gravitational effect of the weight and decreases with further flexion. With this influence of the angle and by also choosing the value k low enough, the user can always override the system, while giving support when it is needed. Further research will have to include a muscle model, which accounts for the fact, that available muscle force is not constant over the full range of motion.

The control algorithm was implemented using the dSPACE DS1103 rapid control prototyping hardware and executed at 1000Hz. The admittance models inertia J was heuristically chosen to 0.1 $kg \cdot m^2$ and the damping was set to 1 $\frac{Nm}{rad/s}$. Lower values did not improve the systems dynamical performances greatly, but resulted in occasional instability and undesired resonance. The gain factor k, which couples the support torque to the measured grip force has great influence on proper functionality. It was set here to 0.5 $\frac{Nm}{N}$. Using larger values was beneficial for some test subjects, giving them more support, while other test subjects failed to extend the elbow from the most flexed position.

4. Evaluation of the functional prototype

The trials scope is to answer the following questions regarding the sensory concept:

- Do trials with active glove sensors result in a higher support than reference measurements with inactive glove support?
- Where shall the sensors be placed on the gloves surface? On the palm or on the fingertips?
- Does the way of holding the test piece (vertically vs. horizontally) influence the support torque and the support rating by the user?
- Does the torque sensor in the elbow drive unit perform better than the force sensors in the coupling to the users forearm?

Those questions are considered to be the most interesting ones in this paper. However, one can think of other open issues, which are not discussed here.

4.2. Test subjects

20 test subjects have been recruited among students and researchers from the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) in Stuttgart, Germany resulting in a sample with 18 male and 2 female subjects with an age from 23 to 29 years (median: 25,5 years) and a height between 1.60 m and 1.98 m (median 1.74 m).

4.3. Testing Procedure

First, the prototype is adjusted to the test subjects shoulder height, followed by adjusting the length of the upper arm link and by an individual positioning of the forearm links. After the adjustment, the test subject is standing straight in the support system with the shoulder joint positioned in the intersection of the exoskeletons axis one to three (see Figure 3) and the elbow is intersecting axis 4. The exoskeleton is coupled to the users left forearm. The user puts on the glove at last.

Prior to the measurement trial, the user is given a learning weight (see Figure 8) in order to learn how to operate the system. As soon as the user is proficient with the system´s behavior the measurements are started. All measurements are performed in a vertical and a horizontal orientation of the testing weight (see Figure 9) in order to estimate how the type of grip influences the system performance.

Figure 8. Learning weight (2 kg, left) and measurement weight (4.2 kg, right)

During a single experiment run, the user flexes and extents the forearm five times using the full range of motion (30° to 170° angle between upper arm and forearm).

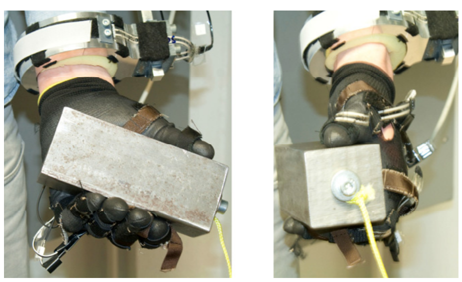

Figure 9. Weight orientation vertical (right) and horizontal (left)

To assess the performance of the glove, individual measurements are performed while activating the sensors in the fingertip and in the palm respectively and compared to the reference condition with all sensors in the glove deactivated.

Finally all measurements are performed with the forearm force sensors signal $\tau_{m,forearm}$ as a means of measuring the interaction torque and a second time with the torque sensors signal $\tau_{m,elbow}$, thus resulting in a 3x2x2 repeated measures factorial experiment design (see Table 1).

After each measurement run the user was asked to rate the support by the system on a scale from 1 to 10 (1="Did not feel supported at all", 10="System supported me a lot"). This data was used as a second dependent variable for the systems evaluation besides the measured and gravitation compensated torque $\tau_{m,elbow}$.

The user was not informed about which glove setting was active and what type of interaction force sensor was used. The order, in which experiments were tested, was randomized to reduce the influence of learning effects and muscle fatigue.

Table 1. Factorial repeated measures experiment design with three independent variables

Exp.-type	Glove setting	Weight orientation	Interaction sensor
1	Fingertips active	Vertical	Forearm
2	Fingertips active	Vertical	Elbow
3	Fingertips active	Horizontal	Forearm
4	Fingertips active	Horizontal	Elbow
5	Palm active	Vertical	Forearm
6	Palm active	Vertical	Elbow
7	Palm active	Horizontal	Forearm
8	Palm active	Horizontal	Elbow
9	Glove deactivated	Vertical	Forearm
10	Glove deactivated	Vertical	Elbow
11	Glove deactivated	Horizontal	Forearm
12	Glove deactivated	Horizontal	Elbow

4.4 Data processing

All data is measured at 1000Hz using the previously described equipment, based on the dSPACE DS1103 Realtime Control Prototyping Hardware. All data is processed in MATLAB and statistical analysis is being performed using the R statistics framework.

The user´s support rating is fixed by the type of setting tested first. However, only the difference between the settings is important here. Therefore for every user an adjustment term is calculated and added to every measurement of the corresponding user, resulting in the adjusted user rating $rating_{adj}$. The mean adjusted rating for a single test subject thus equals the global mean. The support torque $\tau_{m,elbow}$ is measured for 10 seconds during task execution and averaged over this period for evaluation.

5 Results

5.1 Effectiveness of the haptic glove

Support torque $\tau_{m,elbow}$ as well as support rating from the user $rating_{adj}$ is higher when the glove sensors are active (see Table 2 and Figure 10). Analysis of variances $(F_{\tau_{m,elbow}} = 9.26\,, F_{rating_{adj}} = 7.60 \cdot 11^{11},\ df = 19)$ has shown, that this effect is significant (p < .05).

Both dependent variables indicate significantly higher support when using the fingertip sensors, than when using the palm sensors, $(F_{\tau_{m,elbow}} = 4.85\,, F_{rating_{adj}} = 3.53,\ df = 38)$. When fingertip

Table 2. Results for different glove settings

Glove setting	Median user rating $rating_{adj}$	Std. Dev. $rating_{adj}$
Fingertip	6.438	1.997
Palm	4.604	1.875
Deactivated	3.688	
	Median support torque $\tau_{m,elbow}$	**Std. Dev. $\tau_{m,elbow}$**
Fingertip	1.969 Nm	2.227
Palm	0.244 Nm	2.127
Deactivated	-0.141 Nm	1.700

sensors were active, test subjects also reported a better controllability of the system than they did with sensors in the palm activated. Especially when the weight was orientated horizontally, resulting in form-fit with the hand, users reported that they were able to control the support particularly well.

Only a small difference between measurements with horizontal and vertical orientation of testing weight was recognized in the trial (see Table 3). The difference is not significant for the support rating, but for the support

Table 3. Results for different orientations of the test piece

Test piece orientation	Median user rating $rating_{adj}$	Std. Dev. user rating
Horizontal	5.063	1.997
Vertical	4.729	1.875
	Median support torque $\tau_{m,elbow}$	**Std. Dev. support torque**
Horizontal	0.322 Nm	2.012
Vertical	0.725 Nm	2.479

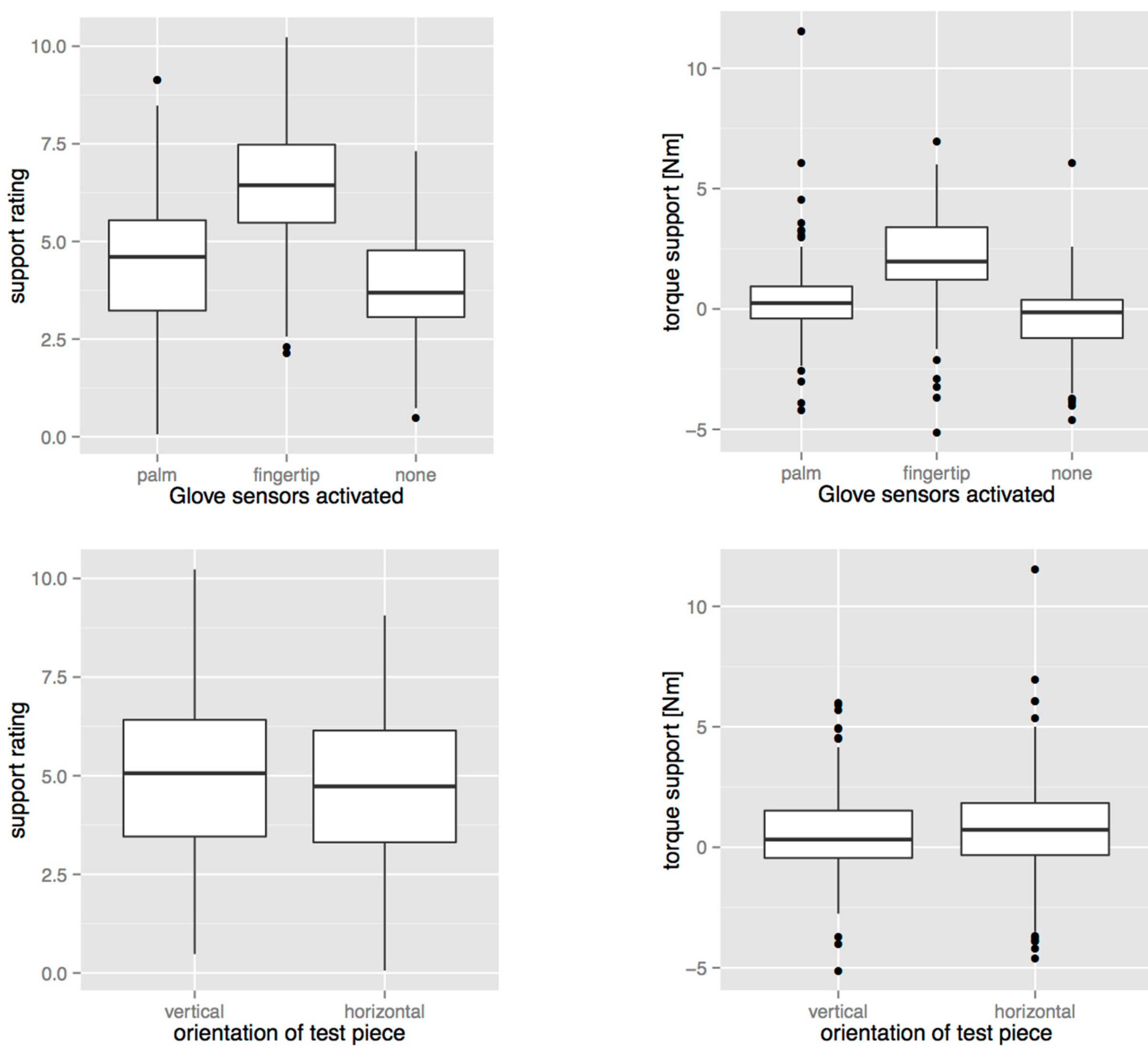

Figure 10. Support depending on the test piece orientation and the glove setting

torque it is ($F_{\tau_{m,elbow}} = 4.88$, $F_{rating_{adj}} = 1.44$, $df = 19$). Further research with a two arm support system will have to show, how the glove performs with rectangular shaped objects such as crates and boxes.

5.2 Evaluation of the interaction torque sensors

A disagreement between the signals of the two sensor types was found in the trial with test subjects (see Table 4). Results have shown, that the torque sensor performs significantly better than the force sensor in the forearm, ($F_{\tau_{m,elbow}} = 23.85$, $F_{rating_{adj}} = 6.19$, $df = 19$).

Table 4. Results for the two methods to measure interaction torque

Interaction torque sens.	**Median user rating $rating_{adj}$**	**Std. Dev. user rating**
Elbow	5.063	1.997
Forearm	4.729	1.875
	Median support torque $\tau_{m,elbow}$	**Std. Dev. support torque**
Elbow	0.322	2.012
Forearm	0.725	2.479

Also Standard Deviation for torque support and torque rating is higher, when using the forearm sensor. However a high agreement between the elbow torque measurements using the torque sensor and the forearm sensors was found in a trial measuring $\tau_{m,elbow}$ and $\tau_{m,forearm}$ simultaneously for a single test subject (see Figure 12).

The Root Mean Square Error in this experiment was calculated by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\tau_{m,elbow,i} - \tau_{m,forearm,i})^2}{2}} = 0.9583\ Nm$$

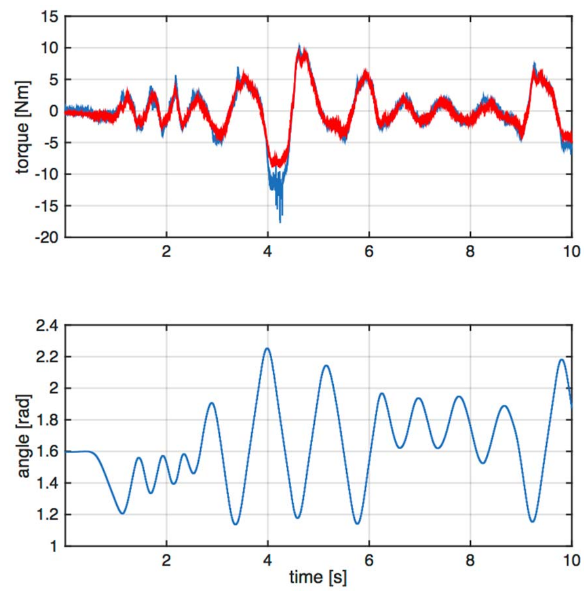

Figure 12. Comparison between interaction torque measurement $\tau_{m,elbow}$ (blue, up) using the elbow torque sensor and the signal $\tau_{m,forearm}$ (red, up) from the forearm force sensors, movement performed (blue, below)

Further analysis has shown, that the disagreement in the trial might be due to the mechanical design of the structure. Some test subjects in the trial had contact to the exoskeleton outside the two rings, thus bypassing the sensors and deteriorating the performance. This is a matter that can be improved for in future design, but is

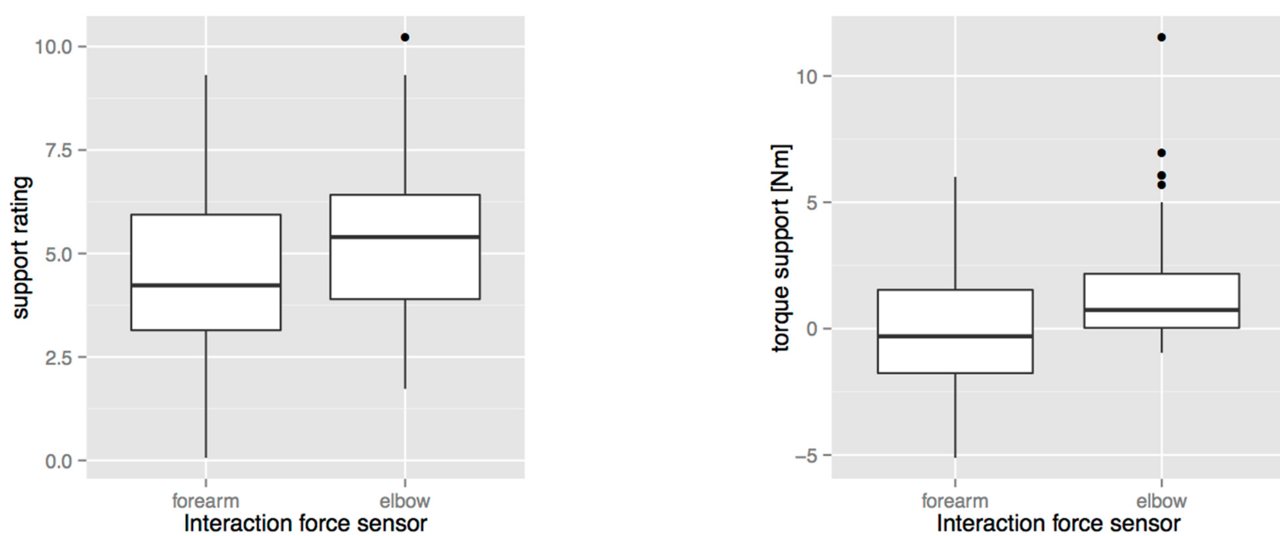

Figure 11. Support depending on the interaction torque measurement

to a certain degree a problem inherent to end-effector based force sensing.

6. Conclusions

This paper presents a novel concept for exoskeleton support systems for upper extremities, based on flexible structures, soft control and textile components. A modular design prototype as well as a functional prototype for a support system, especially designed for lifting activities, have been built and evaluated.

A trial with 20 test subjects has shown that the haptic-glove developed as part of the human-machine-interface is a useful way for detecting user intention. The mean support torque as well as the support rating from test subjects was significantly higher, when activating the sensors in the glove. Especially the sensors in the fingertips proved to be very effective. Also the way of holding the object (vertical vs. horizontal) did not influence the performance greatly.

The evaluation of two methods to measure interaction torque between the user and the exoskeleton has resulted in a high agreement between both signals. However in the trial some test subject bypassed the force sensors and thereby deteriorated the systems performance, resulting in a lower support rating.

Further research will need to unify the developed design prototype and the functional prototype into a single working concept, which incorporates all features of the overall concept.

7. Acknowledgement

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The sole responsibility for the manuscript contents lies with the authors.

8. References

[1] U. Bolm-Audorff, A. Bergmann, D. Ditchen, R. Ellegast, G. Elsner, J. Grifka, ... A. Seidler, "Zusammenhang zwischen manueller Lastenhandhabung und lumbaler Chondrose – Ergebnisse der deutschen Wirbelsäulenstudie", Zentralblatt für Arbeitsmedizin, Arbeitsschutz und Ergonomie, vol. 57(10), pp. 304-316

[2] E. Schneider, X. Irastorza, "OSH in figures: Work-related musculoskeletal disorders in the EU - Facts and figures", European Agency for Safety and Health at Work, 2010

[3] B. R. Fick and J. B. Makinson, "Hardiman I prototype for machine augmentation of human strength and endurance: Final report," General Electric Company, Schenectady, NY, GE Tech. Rep., 1971, pp. 1056

[4] J. Perry, J. Rosen, S. Burns, Upper-Limb Powered Exoskeleton Design, IEEE/ASME Transactions on mechatronics, volume 12(4), pp. 408-417

[5] R.A. Gopura, K. Kiguchi, Y. Li, "SUEFUL-7: A 7DOF Upper-Limb Exoskeleton Robot with Muscle-Model-Oriented EMG-Based Control", 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, USA, pp. 1126-1131

[6] T. Lenzi, N. Vitiello, S.M. Rossi, S Roccella, F. Vecchi, M. C. Carozza, "NEUROExos. A variable impedance powered elbow exosekelton", Proceedings - 2011 IEEE International Conference on Robotics and Automation, Shanghai, China, pp. 1419-1426

[7] J. Rosen, M. Brand, M.B. Fuchs, M. Arcan, "A Myosignal-Based Powered Exoskelton System", IEEE Transactions On Systems, Man and Cybernetics – Part A: Systems and Humans, vol. 31(3), pp. 210-222

[8] C. Zhu, S. Shimazu, M. Yoshioka, T. Nishikawa, "Power Assistance for Human Elbow Motion Support Using Minimal EMG Signals with Admittance Control", Proceedings of the 2011 International Conference on Mechatronics and Automation, Beijing, China, pp. 276-281

[9] J.L. Pons, "Wearable robots: Biomechatronic exoskeletons", Wiley & Sons Ltd., New York

[10] R. Weidner, N. Kong, J.P. Wulfsberg, "Human Hybrid Robot: a new concept for supporting manual assembly tasks", Production Engineering Research and Development, 2013, vol. 7, pp. 675-684

[11] A. Zoss, H. Kazerooni, A. Chu, "On the Mechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)", Proceedings of the 2005 IEEE International Conference on Robotics and Automation, pp. 4345-4352

[12] A. Pedrocchi, S. Ferrante, E. Ambrosini, M. Gandolla, C. Casellato, ..., G. Ferrigno, „Mundus project: MULtimodal Neuroprosthesis for daily Upper limb Support", Journal of neuroengineering and rehabilitation, 2013, vol. 10, pp. 66

[13] K. Yonezawa, N. Mizutani, N. Kato, K. Yano, T. Aoki, Y. Kobayashi, Y. Nishimoto, "Extension Force Control Considering Contact with an Object Using a Wearable Robot for an Upper Limb", Proceedings - 2013 IEEE International Conference on Systems, Man and Cybernetics, SMC 2013, pp. 3555-3560

[14] C. Lebosse, P. Renaud, B. Bayle, M. de Mathelin, "Modeling and Evaluation of Low-Cost Force Sensors", IEEE Transactions on Robotics, vol. 27(4), pp. 815-822

[15] FlexiForce A201, Tekscan Inc:, South Boston USA, https://www.tekscan.com/sites/default/files/resources/FLX-A201-A.pdf, downloaded: 15.06.2015

[16] L. Paredes-Madrid, L. Emmi, E. Garcia, P.G. de Santos, "Detailed Study of Amplitude Nonlinearity in Piezoresistive Force Sensors", Sensors, Basel, Switzerland, 2011, vol. 11(9), pp. 8836-8854