Institute for Cognitive Systems
Department of Electrical and Computer Engineering
Technical University of Munich

Tendon-Driven Pinch-Grasp Exoskeleton with Vibrotactile Feedback Mapping for Sensorimotor Neurorehabilitation

Christian Ritter ✉, **Karahan Yilmazer** ✉, **Miriam Senne** ✉, and **Onur Icin** ✉

✉ christian.ritter@tum.de
✉ karahan.yilmazer@tum.de
✉ miriam.senne@tum.de
✉ onur.icin@tum.de

July 26, 2022

1 Introduction

Tactile feedback and fine motor skills are the two key-steps to perform fine hand movements. These fine movements are necessary to engage in the activities of daily life. To perform these tasks, sensory feedback evaluation combined with right muscle activation should be accomplished. In the cases of peripheral nerve damage or dysfunctions, ability to perform these skills may be lost or reduced. Especially in the case of peripheral neuropathy, patients lose both their motor performance and tactile feedback with a prevalence of 2.4% of the general population [1].

A huge inspiration for the current project was [2]. In this study, a pinch grasping exoskeleton controlled with an EEG system was designed for tetraplegic patients. It was shown that with only a pinch grasp, many activities of daily living could be performed by such patients who had residual upper arm movement.

Regardless of this system's usability, the researchers mentioned that "more intelligent systems that provide sensory feedback to the user and adapt exerted forces according to the objects that are manipulated may further improve the practicability of the system" [2]. By following this lead, this project introduces a tendon-driven pinch-grasp hand exoskeleton that incorporates vibrotactile feedback for grasp strength.

The current study aims to answer the following research questions:

- Can a tendon-driven pinch-grasp exoskeleton help with performing the activities of daily life in case of motor dysfunction or muscle weakness?

- Is remapping the sensory (tactile) information of the grasp force via vibrotactile motor an assistive technology in the absence of sensory perception?

2 Related Work: Active Hand Exoskeletons for Rehabilitation and Assistance

The applications of hand exoskeletons span various fields, like, rehabilitation, assistance, haptic devices and force augmentation [3]. This section reviews the first two in terms of design and actuation methods. A particular focus will be on tendon-driven actuation that is also used for the project implementation described in the next chapter.

2.1 Types of Hand Exoskeletons

In general, hand exoskeletons can be classified into rigid and soft structures. Rigid Exoskeletons, like [4], employ mechanical structures to generate torques at the finger joints [3]. In contrast, soft exoskeletons involve compliant or elastic structures for force transmission [3], for example, realized by tendon driven gloves made from flexible materials [5, 6] or pneumatically actuated exoskeletons [7].

Link-based rigid structures have the advantage of easy force transmission and control, however, the necessity to align the centers of rotation of the exoskeleton and the finger joints often result in bulkiness of the wearable part [5].

Soft exoskeletons are characterized by a more compact structure of the wearable part and the use of elastic materials, like, polymer or fabric, allows better customization and comfort [5]. On the other hand, the compliance and possible deformations of the material introduce control challenges [5]. Especially in tendon-driven exoskeletons the force transmission to the finger is weak compared to serial linkage mechanisms and pneumatically actuated exoskeletons can only perform flexion and are not portable [5].

2.2 Requirements

In [3] four general requirements of hand exoskeletons are stated: safety, comfort, affordability, adaptability. Since the exoskeleton is adding power to the system, safety is the most crucial aspect and injuries must be excluded. Different layers of safety mechanisms are recommended. Those can be implemented by mechanical safety stops [8] or software constraints that induce limits on force and rotation.

In [3] it is concluded that rigid link-based structures typically are characterized by better adaptability to different hand sizes while compliant and jointless designs are more customized to the user. On the other hand, soft exoskeletons are classifed as more comfortable [3].

The "primary concern" towards safety and to ensure a natural movement of the fingers is the coincidence of the centers of rotation of the robotic device and the finger joints [9]. This is a particular design consideration when it comes to rigid structures as soft exoskeletons do not face joint alignment problems [6].

A further requirement of hand exoskeletons is the provision of sufficient force to perform the intended set of tasks. The force required for the manipulation of objects of daily living does not exceed 10-15 N [10, 11], which can be considered as a reference for the mimimal graping force in terms of assistive devices.

2.3 Tendon-Driven Hand Exoskeletons

Motivated by the advantages of soft exoskeletons, like, the light-weight structure, no joint alignment issues, higher comfort and more moving freedom by the patient due to compliance, we decided for a tendon-driven approach. A further reason is the possibility to perform flexion and extension in contrast to pneumatic actuation and the "mimicking the actuation of the actual human hand" [9].

2.3.1 Design and Mechanisms

A common approach towards tendon driven hand exoskeletons are fabric gloves that are used to attach the tendon routing. Examples can be found in [12, 6]. The tendon routing consists of low-friction tubes, e.g., made from teflon, that are sewed on the glove.

An alternative approach consists of using a silicone glove that is characterized by a more robust material and allows to only partly cover the skin [5, 13]. In this way, the tactile perception of the skin can be exploited in contrast to fabric gloves. The tendon routing is embedded in the silicone.

A more sophisticated design is based on a push-pull bowden cable transmission that employs linear actuation [14]. Also, it is possible to combine cable driven actuation with a rigid linkage structure [15].

2.3.2 Tendon Actuation

The general working principle of tendon actuation is depicted in 3. Pulling on the tendon causes normal forces F_1 and F_2 at the attachment points which result in a torque at the respective joint τ_i. Examining one link of the finger, P_1 and P_2 represent the anchor points, e.g., given by each end of the routing tube that is attached to the respective link. We denote h as the distance between the connection line from P_1 to P_2 to the sagittal plane of the link. Based on this considerations, [12] choose the anchor points in a way that the sum of torque, i.e., $\tau_1 + \tau_2 + \tau_3$ is maximized. This is achieved placing the anchor points in the following way

- Place P_1 and P_2 at the most distal position on of the link such that the lever function of the joint can be exploited.
- Maximize the distance h.

The last point introduces a trade-off: Placing the tendon routing for extension at the inner side of the finger maximizes the force transmission but also blocks the grasping surface of the finger. Placing the tendon routing more towards the side, reduces the reduces the joint torque but is more comfortable for the user.

Finally, in addition to flexion, the extension movement is necessary to perform the antagonistic movement. This can be realized by two motors that act independently [15] or one motor that actuates the tendons in a antagonistic manner, i.e., the tendons are winded in opposite direction [5, 16]

3 Methods

3.1 Hand Exoskeleton Design

The goal of this work is to build a tendon-driven exoskeleton for pinch grasping. Due to its many advantages, a fishing wire was chosen as tendon. Besides the light weight, the breaking strength is also an important feature. Since the string is exposed to a lot of movement, its abrasion resistance is crucial. For precise control, a low elasticity of the tendon is required.

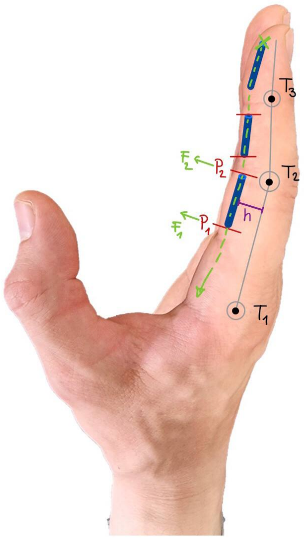


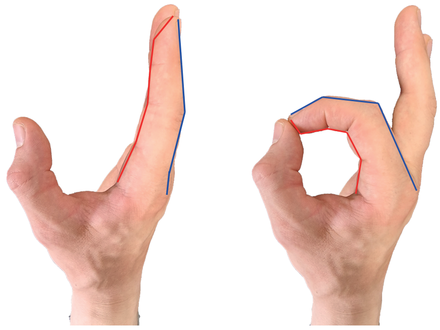
Figure 1 Anchor points of the tendon routing for the flexion of the index finger. The blue lines indicate the support structures of the tendon, e.g., realized by tubes. Pulling on the tendon that is fixed to the fingertip produces a normal force at the anchoring points P_1 and P_2 resulting in the flexion movement.

The fishing wire offers all the mentioned properties and was therefore chosen for this project.

To further reduce the friction of the wire and to avoid high abrasion of the printed parts, it was worthwhile to follow the approach of [5, 6] and use PTFE tubes as guidance system for the wire.

Since the exoskeleton supports two movements, namely flexion and extension of the finger, two separate wires are used. The conventional way of pulling a wire is to use a motor and a pulley. Even though using two motors, one for each wire, would allow an independent control, only one 12V DC motor was chosen to be implemented. Despite this aspect, the use of only one motor is not only convincing because it is the cheaper option, but also because of the lower weight, the smaller space requirement and the better controllability, which are essential arguments in the construction of an exoskeleton.

Since only one motor is used and the wires cannot be controlled independently, two pulleys have to be constructed. Due to the design, one wire always winds while the other one is unwinding during the finger movement, it is possible to use one motor and attach two pulleys to it, where the wires are winded in opposite directions. Besides that, it is obvious to see, that both the inner and outer side of the finger change their length, depending on the current position. The length that the wires would have in each position was measured for both sides of the finger, represented as the red line (inner distance) and the blue line (outer distance) in Figure 2. The difference in distance at extension and flexion was calculated for both colors and the ratio of the differences of both sides was determined, which is also the ratio that the radius of both pulleys have to each other. They define the fingers trajectory and were 3D printed, as can be seen in Figure 3. The pulley with the larger radius pulls the inner (higher distance difference) wire and the smaller pulley pulls the outer (smaller distance difference).



(a) A hand that in the extension position. **(b)** A hand that in the flexion position.

Figure 2 The two desired positions that can be achieved with the exoskeleton. The red line shows the distance at the inner side of the finger and the blue one on the outer side.

Figure 3 A 12V DC motor with encoder is used with two connected pulleys on left side. The one with the larger radius is connected to the inner side of the exoskeleton and the other pulley is connected with the outer side. The different sizes were chosen, since both sides have different differences of distance between flexion and extension.

A problem that occurred using this approach is the derailing of the wires on the pulleys. To counteract that issue, a motor box was designed and 3D printed, which covers the pulleys and prevent the wires from derailing. The design of the motor box can be seen in Figure 4. The opening is where the wires are connected to the tubes and led to the finger.

For the first prototype, tubes were glued onto a glove to derive weather a tendon driven mechanism is working in practice. Since the results were very promising, another prototype was designed, solving some issues from the previous one. To achieve more torque, the tubes were to be shortened. Another factor is the po-

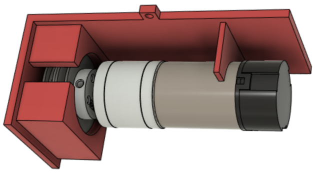


Figure 4 DC motor placed in the motor box (red), which covers the pulleys to prevent derailing of the wires during winding and unwinding.

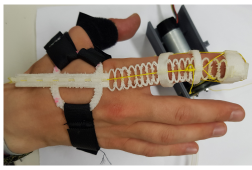
sitioning of the tubes. As discussed in 2.3.2, there is a trade-off between a better force transition when putting the tubes in the center on the inner side of the finger and the comfort and freedom of movement of the patient. Therefore the tubes were positioned on the lower side of the finger. The tubes are inserted in rings, which were glued onto a glove, as can be seen in Figure 5.

Figure 5 The second prototype, where two rings and a fingertip cover were 3D printed. They have holes, where tubes were inserted and the wires (yellow) are led through.

Test runs with this prototype were successful, but through inspiration from [5], the final prototype was designed, which was printed with flexible TPA and makes it possible to do without the glove. Flexible O-shaped parts between the previously introduced rings, allow flexible hand sizes and comfortable usage. The result can be seen in Figure 6. The printed parts, as well es the thumb, which has to be in a position, that the flexed index finger can touch it, are fixated using velco straps. This design has many advantages, like being lightweight, adjustable to different hand sizes and being slim and comfortable.

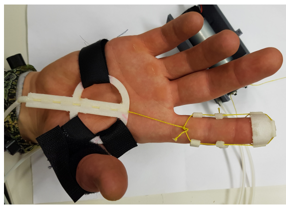
3.2 Arduino Setup

As mentioned before, the designed hand exoskeleton could give vibrotactile feedback to the participant based on the strength of the pinch grip. For this purpose, a force sensor had to be used to detect the force applied from the fingertip to the grabbed object.



(a) Back view.

(b) Side view.



(c) Front view.

Figure 6 Final exoskeleton design seen from different angles. The shell was 3D-printed with flexible TPA material for a lightweight and breathable design 3D-printed with flexible TPA material. A tendon-driven mechanism and velcro tapes were used for maximum compatibility among different users.

To do that, the raw force sensor reading was normalized to a value between [0, 1]. This value was then multiplied with a heuristically chosen dampening constant to drive the vibrotactile motor. This procedure resulted in a continuous mapping of the force value to a analog motor output.

Another sensor used for prototyping was the flex sensor. Similar to the force sensor, its raw values were normalized and tested for use in different scenarios, like detecting the finger movement intention of the participant. This will be explored in a later section. The Arduino setup can be seen in Figure 7.

3.3 EMG Data Acquisition

To detect the execution of the pinch-grasp movement, Myo gesture control armband is used. This wireless armband consists of 8 EMG sensors and is located on the forearm of the user. To focus on the pinch-grasp movement measurements, the channel that is located on the flexor pollicis longus muscle is evaluated.

3.4 Intention Recognition

The system was designed with neurorehabilitative purposes in mind. So, it was assumed that the patients using the hand exoskeleton would have only a weak

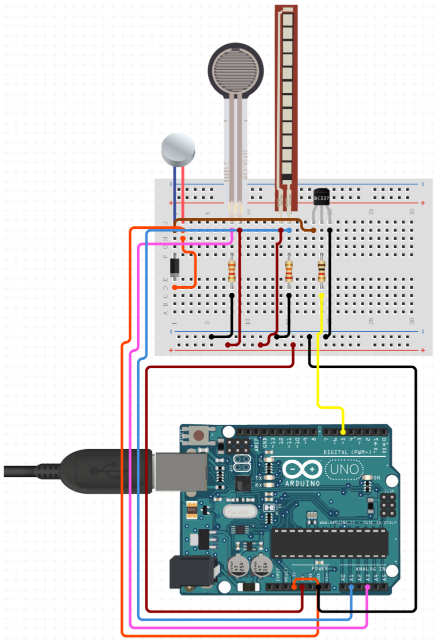


Figure 7 The Arduino Uno setup used for reading in values from the sensors and controlling the vibrotactile motor. The flex and force sensor values were used to evaluate system performance and the vibrotactile motor was used to give the participant feedback based on the strength of the pinch grip.

muscle activity to control it. To detect the intention of moving the index finger to initiate the pinch grasping proved to be a serious challenge.

It was first assumed that the Myo EMG band would be able to detect the index finger movement and classify it against a rest state to be used as a control signal. However, the trained classifiers could not discriminate between these two states.

Then, a force sensor was placed on the index fingertip to detect the pushing of the finger to initiate the pinching. Unfortunately, when placed on the fingertip the force readings became unreliable to detect minuscule changes.

Lastly, the flex sensor was tested to detect the pinching intention of the participant. Different sensor placements and algorithms were used to detect the small bending of the index finger to initiate the closing of the exoskeleton. This worked for some configurations but was very unreliable to rely on in the final design.

After all these steps, it was decided to control the exoskeleton using the buttons on the motor driver to conduct the experiments to evaluate the usability and performance of the system.

3.5 Safety Measurements

Exoskeletons are made to help and support people. By enabling them to become stronger or regain lost functions, they are popular in both industry and rehabilitation. However, in addition to these benefits, one must also consider the dangers that exoskeletons may carry. The pinch-grasping exoskeleton presented in this work helps the user to both flex and extend his or her index finger. A DC motor pulls the wires for this purpose. Therefore, it is necessary to build in safety mechanisms to prevent the finger from being placed in an unnatural position or being overstretched. For this reason, three major safety precautions have been implemented.

Emergency Button An emergency button is built into the connection to the power source, which allows a quick stop in case of unusual behaviour of the electronics. It is a big red button that is self-explanatory and easy to press. Since our target group only has a one-sided muscle weakness, it is possible for them to press this button at any time using their healthy hand.

Software Motor Constraints Another safety measure that has been implemented is the restriction of the motor movement by software. Through the motor encoder, it is possible to read the motor position. By specifying fixed values that define the motor position at maximum flexion and maximum extension, the motor can be prevented from moving further in the problematic direction.

Flex Sensor Monitoring A flex sensor is attached to the back of the exoskeleton and positioned on the index finger. The change in the sensor resistance when bending the finger can be used to determine the current flexion state. If no flexion is detected, it is assumed that the user's finger is in full extension position and should not be moved further. This again leads to the software preventing the motor from moving further in the extension direction.

4 Evaluation Tests

4.1 9-Hole Peg Test

To evaluate the usability of the proposed exoskeleton, first, 9-hole peg test is used. This test holds a good basis for the quantification of finger dexterity. Evaluation is done by placing small pegs into the holes on the board. Participants should perform well coordinated rapid eye, hand and finger movements to complete the experiment.

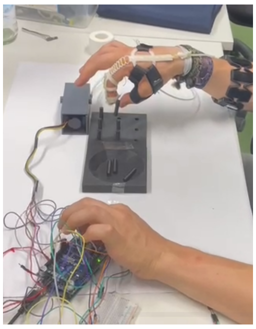


Figure 8 Setup of the 9-Hole Peg Test used for evaluating the usability and performance of the system. The exoskeleton is controlled by the user via button clicks and the Myo EMG band measures the muscle activity to be used as a metric for exoskeleton assistance.

4.2 Minnesota Manual Dexterity Test

As another usability evaluation of the proposed exoskeleton with a similar alternative, Minnesota manual dexterity test is used. This test is a standardized test for the evaluation placing of small objects within various distances. Main assessment of this test represents the rapid eye, hand and finger coordination, thus, it holds a good basis to test the performance of a pinch-grasp exoskeleton. Within this scope, 12 targets in 4x3 layouts are used. Within the experimental procedure, participants performed the tasks both with the help of the exoskeleton aid and the mapped sensory feedback through a vibrotactile motor.

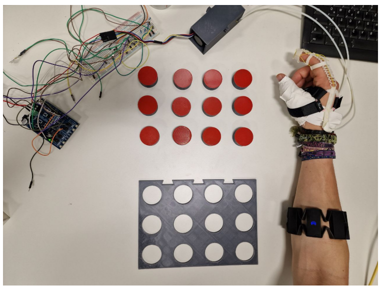


Figure 9 Setup of the Minnesota Test used for evaluating the usability and performance of the system. The exoskeleton is controlled by the user via button clicks and the Myo EMG band measures the muscle activity to be used as a metric for exoskeleton assistance.

4.3 Vibrotactile Feedback Discriminancy

Before combining the vibrotactile feedback with the hand exoskeleton, it was studied whether different levels of vibration could be discriminated by the participants.

To test this, the vibrotactile motor was taped to the arm of each participant. In each trial, the task of the participant was to decide whether the current vibrotactile feedback he/she received was of level low, medium or high. Low was defined as 0-30% of the maximum activation. Whereas medium was 30-70% and high was 70-100% of the maximum activation.

Each class was repeated 7 times, so the participants had to make 21 guesses. This test was repeated two times to test two different sites of feedback. The first site was the inner side of the wrist and the second was the inside of the bicep. The assumption was that the wrist would be more sensitive.

Lastly, the participant predictions and the true labels were compared to create confusion matrices in Figure 12 to evaluate feedback discriminancy.

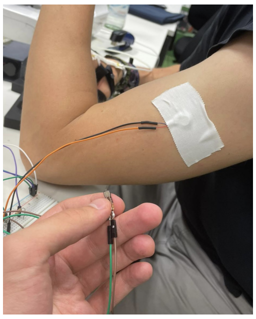


Figure 10 Setup of the Vibrotactile Feedback Discriminancy used for evaluating the usability and performance of the sensory feedback. The participants guess the force levels that is applied on the force sensor from the 3 categories LOW, MEDIUM, and HIGH.

5 Results

5.1 9-Hole Peg Test

The 9-hole peg test is performed using the exoskeleton assistance. The experiment was successfully performed on the application of picking and removing the pegs from the placed holes. However, picking the pegs and placing them back to the holes only worked under the condition of the pegs being placed vertically, otherwise they slipped away. Therefore, due to this limitation, no further analyses are performed for the 9-hole peg test.

5.2 Minnesota Manual Dexterity Test

EMG Activation

To analyze the motor-support of the exoskeleton, muscle activation profiles for both exoskeleton aided case and not aided case are compared. To reproduce the same task, Minnesota manual dexterity test is performed.

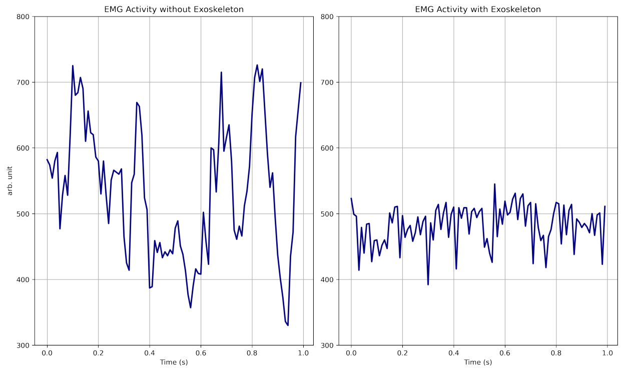


Figure 11 Muscle activity of the user while performing the Minnesota Manual Dexterity Test. Left: The recorded muscle activity when the test is performed without exoskeleton aid. Right: The recorded muscle activity when the test is performed with exoskeleton aid.

From Figure 11, it can be seen that when the test is performed with exoskeleton assistance, required muscle activation drops compared to non-assisted case. This shows that the pinch-grasp exoskeleton can both be a rehabilitative and an assistive solution for muscle weakness.

5.3 Vibrotactile Feedback Discriminancy

Within only one session participants could discriminate between different levels of vibrotactile feedback. The chance level was at 33% whereas the accuracy scores for placing the motor at the outer bicep was $0.75\% \pm 0.07\%$ and $0.90\% \pm 0.08\%$ for the inner wrist.

The results further indicate that high activation could be discriminated against the other two classes. However, the number of errors increased for discriminating between low and medium activation.

6 The Future of Neurorehabilitation Technologies

For the patients that suffer from muscle weakness and sensory feedback loss, the future solutions are expected to focus more on the medical side, i.e. addressing these problems within the body instead of

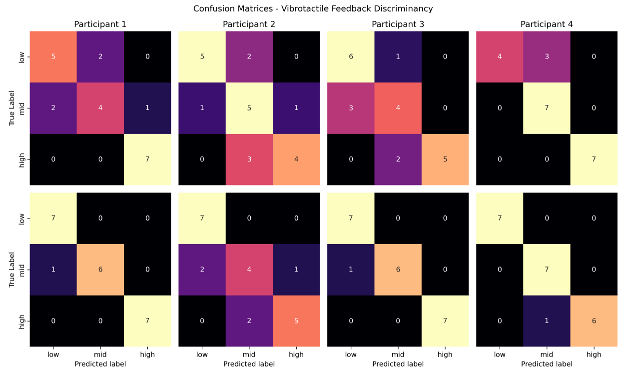


Figure 12 Confusion matrices of the participant predictions for the vibrotactile feedback discriminancy test. It can be seen that participants could guess (Top) Vibrotactile motor placed outside the bicep. (Bottom) Vibrotactile motor placed inside the wrist.

providing assistive extensions. As long as the medical solutions can be easily accessed by the majority, the need for the exoskeletons will drop in rehabilitative cases. Otherwise, the need for external support, assistive and rehabilitative exoskeletons will steadily grow. The new generation of exoskeletons would ideally be more bio-intuitive, adaptive and natural.

As for the people from different fields, it would be expected that they cooperate more to bring the novelties of their fields together in order to help the patients in need. Just like the present, the future requires strong collaborations amongst all relevant fields.

7 Human-Centered Engineering

During the whole project, a huge emphasis was put onto the human-centered engineering approach. This entailed, for example, improving the exoskeleton design to improve user comfort and paying attention the safety aspect first, before starting to evaluate the system.

Since the project itself consisted of the rehabilitation of the sensory network and muscle weakness, it was naturally intended as a human-centered application. During the design of the exoskeleton, for instance, materials were selected in a way that they would not harm the hand of the participant under long-term usage. For the movement assistance, flexible materials were used to mimic a more intuitive movement and to ensure a comfortable usage. Furthermore, initial glove exoskeleton design was improved to enhance breathability to serve as a more natural extension to the hand.

The exoskeleton being tendon driven, required less parts and less resulted stress on the fingers.

As for the mapping of the absent sensory feedback, emphasis was put onto finding a safe and intuitive alternative. Thus, due to its human-centered usability, vibrotactile motors were preferred rather than other stimulation techniques.

Finally, a big emphasis was put into the safety of the exoskeleton as mentioned under the safety measurements.

8 Conclusion

From the experiments, it was observed that a tendon-driven pinch-grasp exoskeleton can be used to perform activities of daily living and that it compensates lack of muscle activation and coordination.

Moreover, sensory feedback substitution using the vibrotactile motor coupled with a force sensor assists the perception of tactile information. Therefore, it seems as a promising approach for the compensation of sensory loss, however, further testing with neurological patients that are not able to naturally perceive tactile information from their fingertips would be essential to make a full scoring of the combined technologies.

Appendix

The code for this project can be found under https://gitlab.lrz.de/neuro1/neurorehabilitation-pincher-glove

References

[1] Richard A C Hughes. "Peripheral neuropathy". In: *BMJ* 324.7335 (2002), pp. 466–469. ISSN: 0959-8138. DOI: 10.1136/bmj.324.7335.466. eprint: https://www.bmj.com/content/324/7335/466.full.pdf. URL: https://www.bmj.com/content/324/7335/466.

[2] S. R. Soekadar et al. "Hybrid EEG/EOG-based Brain/Neural Hand Exoskeleton Restores Fully Independent Daily Living Activities after Quadriplegia". In: *Science Robotics* 1.1 (Dec. 6, 2016), eaag3296. ISSN: 2470-9476. DOI: 10.1126/scirobotics.aag3296. URL: https://www.science.org/doi/10.1126/scirobotics.aag3296 (visited on 12/26/2021).

[3] Tiaan du Plessis, Karim Djouani, and Christiaan Oosthuizen. "A Review of Active Hand Exoskeletons for Rehabilitation and Assistance". en. In: *Robotics* 10.1 (Mar. 2021). Number: 1 Publisher: Multidisciplinary Digital Publishing Institute, p. 40. ISSN: 2218-6581. DOI: 10.3390/robotics10010040. URL: https://www.mdpi.com/2218-6581/10/1/40 (visited on 06/18/2022).

[4] A. Chiri et al. "HANDEXOS: Towards an exoskeleton device for the rehabilitation of the hand". In: *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2009, pp. 1106–1111. DOI: 10.1109/IROS.2009.5354376.

[5] Brian Byunghyun Kang et al. "Development of a polymer-based tendon-driven wearable robotic hand". In: *2016 IEEE International Conference on Robotics and Automation (ICRA)*. 2016, pp. 3750–3755. DOI: 10.1109/ICRA.2016.7487562.

[6] Hyunki In et al. "Exo-Glove: A Wearable Robot for the Hand with a Soft Tendon Routing System". In: *IEEE Robotics & Automation Magazine* 22.1 (Mar. 2015). Conference Name: IEEE Robotics & Automation Magazine, pp. 97–105. ISSN: 1558-223X. DOI: 10.1109/MRA.2014.2362863.

[7] Hong Kai Yap et al. "Design and Preliminary Feasibility Study of a Soft Robotic Glove for Hand Function Assistance in Stroke Survivors". In: *Frontiers in Neuroscience* 11 (2017). ISSN: 1662-453X. URL: https://www.frontiersin.org/article/10.3389/fnins.2017.00547 (visited on 06/18/2022).

[8] Christopher N. Schabowsky et al. "Development and pilot testing of HEXORR: Hand EXOskeleton Rehabilitation Robot". In: *Journal of NeuroEngineering and Rehabilitation* 7.1 (July 2010), p. 36. ISSN: 1743-0003. DOI: 10.1186/1743-0003-7-36. URL: https://doi.org/10.1186/1743-0003-7-36 (visited on 07/28/2022).

[9] Pilwon Heo et al. "Current Hand Exoskeleton Technologies for Rehabilitation and Assistive Engineering". In: *International Journal of Precision Engineering and Manufacturing* 13 (May 2012). DOI: 10.1007/s12541-012-0107-2.

[10] Panagiotis Polygerinos et al. “Soft robotic glove for hand rehabilitation and task specific training”. In: *2015 IEEE International Conference on Robotics and Automation (ICRA)*. 2015, pp. 2913–2919. DOI: 10.1109/ICRA.2015.7139597.

[11] Kayla Matheus and Aaron M. Dollar. “Benchmarking grasping and manipulation: Properties of the Objects of Daily Living”. In: *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2010, pp. 5020–5027. DOI: 10.1109/IROS.2010.5649517.

[12] Lucas Gerez, Junan Chen, and Minas Liarokapis. “On the Development of Adaptive, Tendon-Driven, Wearable Exo-Gloves for Grasping Capabilities Enhancement”. In: *IEEE Robotics and Automation Letters* PP (Dec. 2018), p. 1. DOI: 10.1109/LRA.2019.2890853.

[13] B. B. Kang et al. “Exo-Glove Poly II: A Polymer-Based Soft Wearable Robot for the Hand with a Tendon-Driven Actuation System.” In: *Soft robotics* (2019). DOI: 10.1089/soro.2018.0006.

[14] Christopher J. Nycz et al. “Design and Characterization of a Lightweight and Fully Portable Remote Actuation System for Use With a Hand Exoskeleton”. In: *IEEE Robotics and Automation Letters* 1.2 (July 2016). Conference Name: IEEE Robotics and Automation Letters, pp. 976–983. ISSN: 2377-3766. DOI: 10.1109/LRA.2016.2528296.

[15] Jamshed Iqbal et al. “A Portable Rehabilitation Device for the Hand”. In: Jan. 2010.

[16] Jaeyoung Park, Inchan Hwang, and Woochan Lee. “Wearable Robotic Glove Design Using Surface-Mounted Actuators”. In: *Frontiers in Bioengineering and Biotechnology* 8 (Sept. 2020), p. 1069. DOI: 10.3389/fbioe.2020.548947.