Grip Force Dynamics during Exoskeleton-Assisted and Virtual Grasping

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Motivation and Scientific Background

The analysis of grip forces during grasping and lifting diversely weighted objects is highly informative about an individual's level of sensorimotor control and potential neurological condition [1]. Thus, it provides a powerful tool to design and assess neurorehabilitation therapy.

Main Research Question

Are the natural characteristics of the grip force dynamics preserved during modern hand rehabilitation methods such as exoskeleton-assisted grasping and grasping of virtual reality objects?

Methods

Experimental Setup

Six healthy participants are instructed to perform three sets of repeatedly pinch grasping and lifting an object with varying weight under different conditions:

- Normal Grasping
- Exoskeleton-Assisted Grasping: The participants adjust the grasping force using a turn knob.
- Virtual Load Grasping: The virtual object in a video game can only be lifted if a specific force threshold is reached ("virtual load").

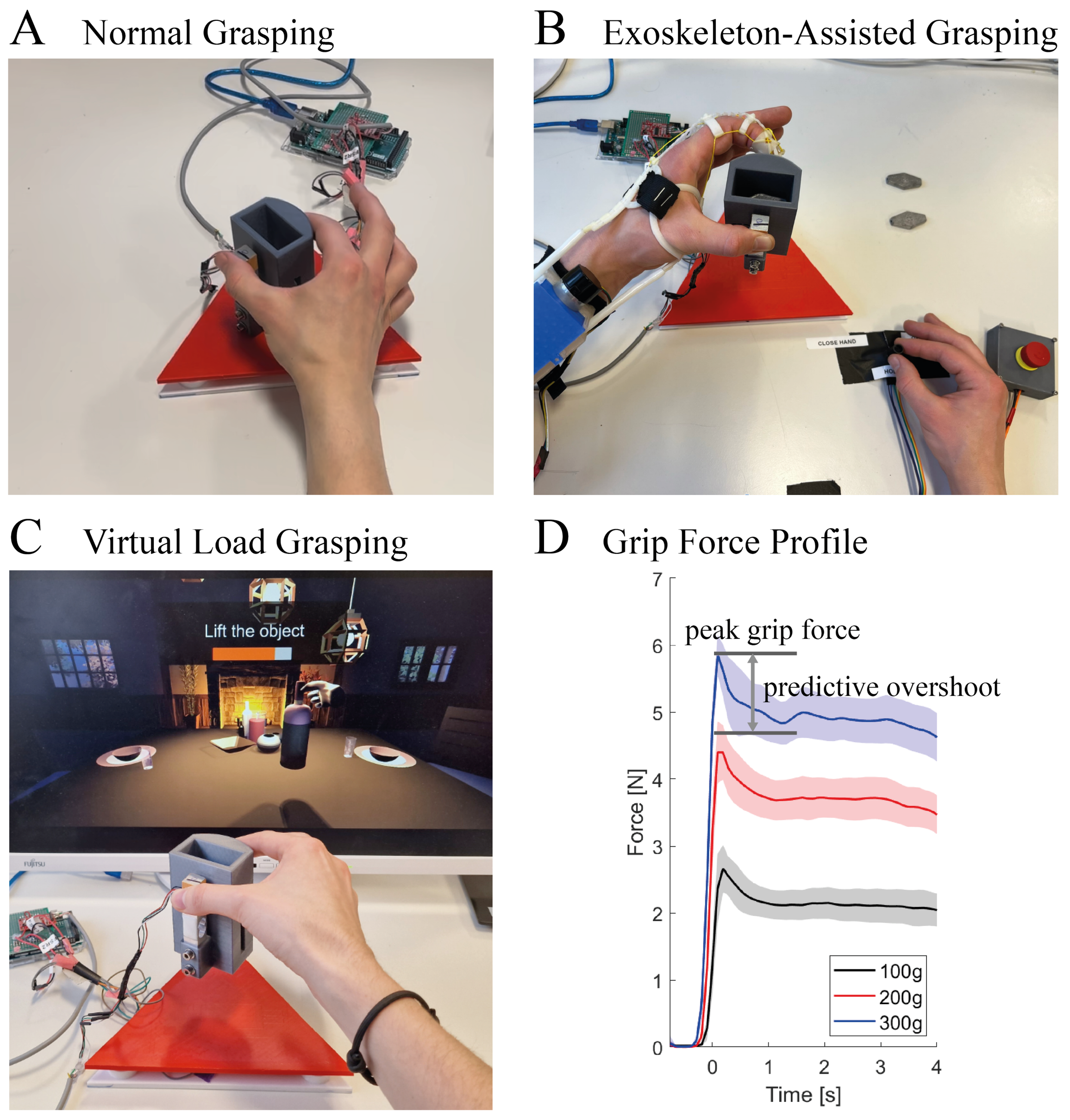

Figure 1: A-C) The grasping interface is lifted in three different experimental settings, while the grip force and ground contact are measured. D) A characteristic grip force profile of a healthy subject during normal grasping of different weights.

Technical Design

A soft, 3D-printed and tendon-driven exoskeleton actuates the index finger. As grasping interface we use a 3D-printed box that can be filled with different weights. This box is placed on a pressure plate (see Fig. 1).

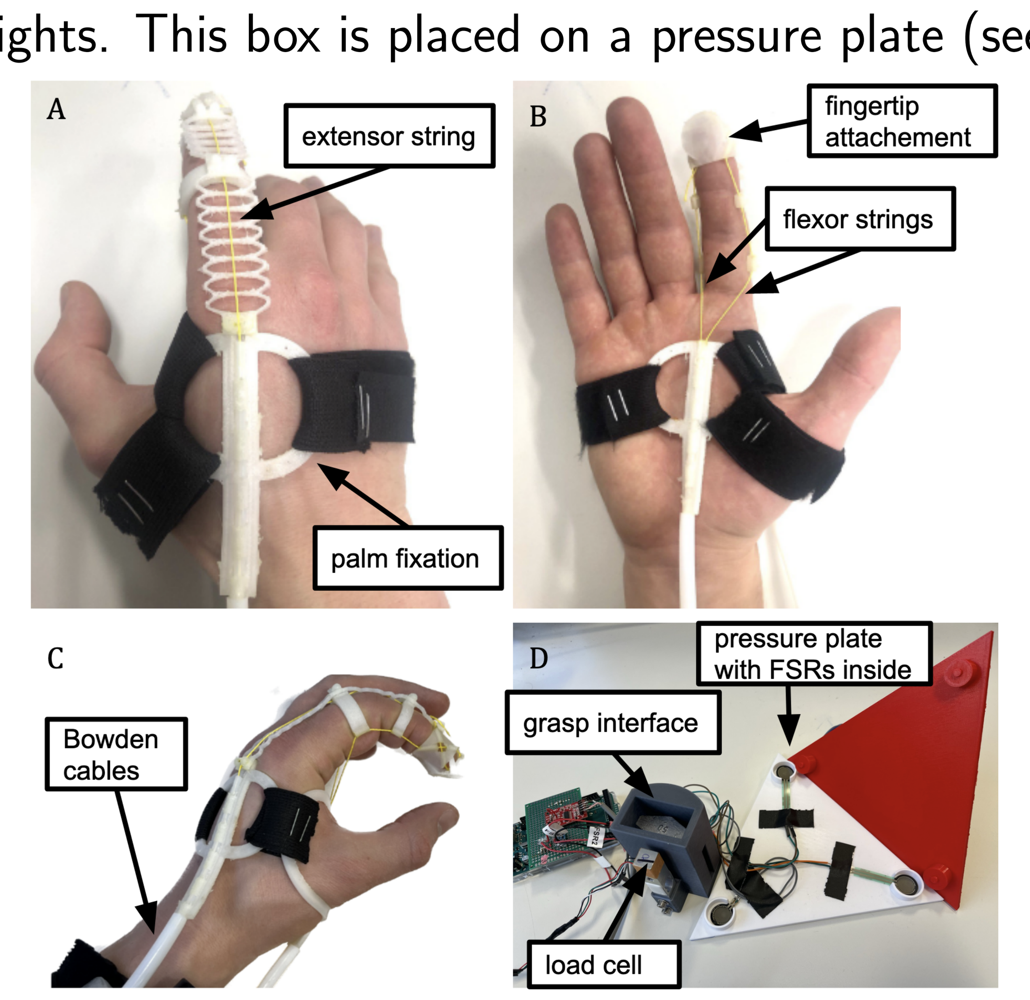

Figure 2: A-C) Minimalistic design of the index finger exoskeleton from different perspectives. D) A load cell is attached to the weight box to measure the grip force and force sensing resistors (FSRs) underneath the pressure plate inform about the timing of lifting and putting the object down.

Results

Characteristic Grip Force Profiles

- The positive correlation between grip force and object weight shows force efficient grasping, also during exoskeleton assistance.
- Inertial effects are compensated by an initial force overshoot at lift-off, even during exoskeleton assistance, where some participants contributed with their own muscle force. (Especially Participants 1 and 3.)
- The magnitude of this overshoot scales with the object weight.
- During virtual grasping the overshoot does not scale with the physical but virtual weight.
- The absence of time delay of the force adaption indicates that inertial effects are predicted instead of only perceived by sensory feedback [2].

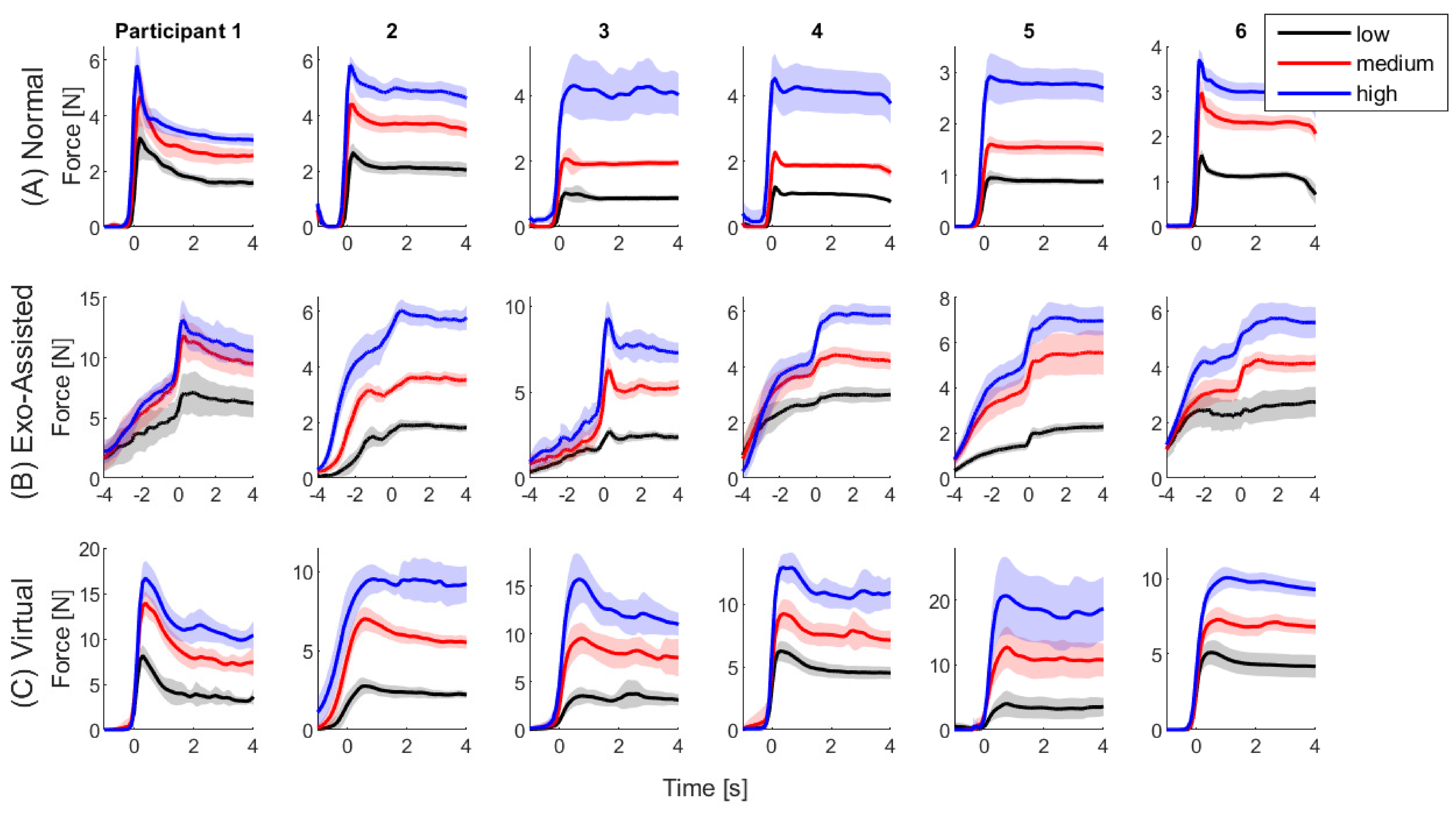

Figure 3: Average grip force and standard deviation of six participants under three different conditions: normal, exoskeleton-assisted and virtual load grasping. The grasps are aligned at the time of lift-off (0s). For conditions (A) and (B), weights of 100g, 200g and 300g are used.

Learning and Adaptation

- Over time, participants improve the grasp efficiency by applying smaller grip forces. This learning curve is steepest in the virtual condition and less significant during exoskeleton-assisted grasping.
- When changing from a high to low weight, participants initially apply more force than they learned is needed but adapt quickly to the new weight. This *wash out* or *aftereffect* [3] becomes visible in grasp 2, 8 and 14.

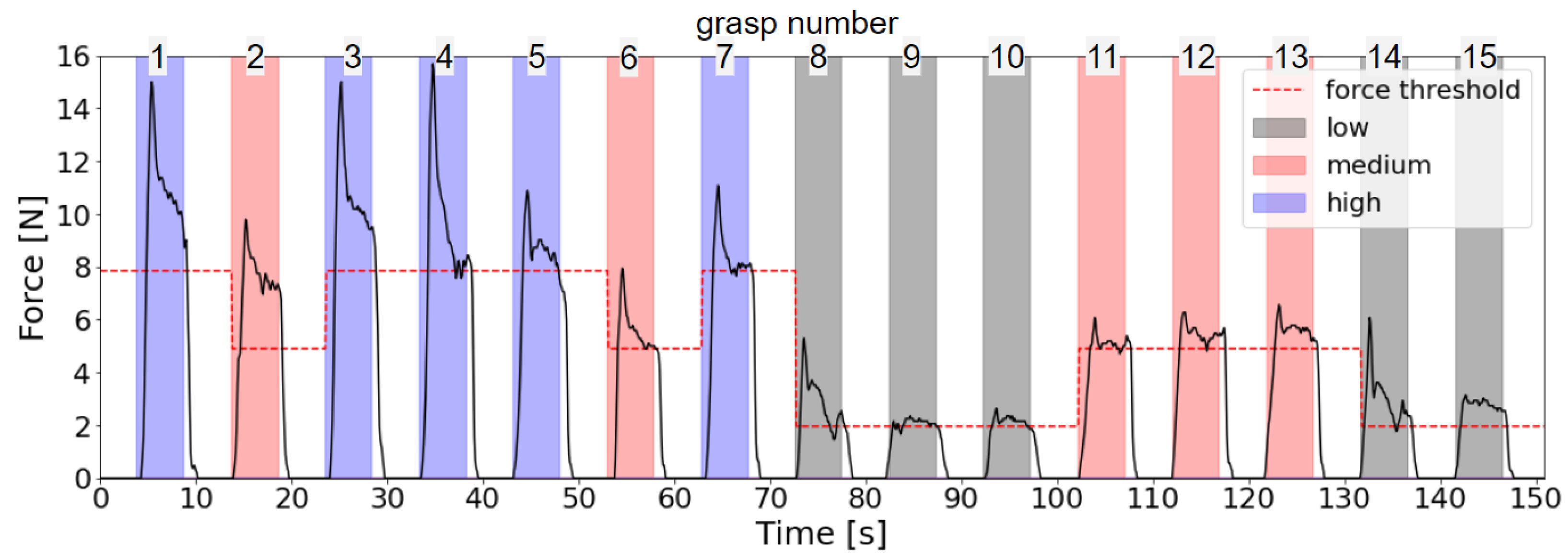

Figure 4: Grip forces of an exemplary sequence of grasping different virtual loads (low, medium and high) in random order. The filled sections indicate that the object is lifted.

Conclusion

- **The core characteristics of grip force dynamics are preserved under both rehabilitation settings exoskeleton-assisted and virtual load grasping in healthy participants.**
- Incorporating insights about grip force dynamics in the design of neurorehabilitation methods can improve their usability and rehabilitative function.
- For example: Designing compliant hand exoskeletons such that natural grip force dynamics are not disturbed allows to use grip force as bio-feedback signal.

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***Abstract*— The grip force dynamics during grasping and lifting of diversely weighted objects are highly informative about an individual's level of sensorimotor control and potential neurological condition. Therefore, grip force profiles might be used for assessment and bio-feedback training during neurorehabilitation therapy. Modern neurorehabilitation methods, such as exoskeleton-assisted grasping and virtual-reality-based hand function training, strongly differ from classical grasp-and-lift experiments which might influence the sensorimotor control of grasping and thus the characteristics of grip force profiles. In this feasibility study with six healthy participants, we investigated the changes in grip force profiles during exoskeleton-assisted grasping and grasping of virtual objects. Our results show that a light-weight and highly compliant hand exoskeleton is able to assist users during grasping while not removing the core characteristics of their grip force dynamics. Furthermore, we show that when participants grasp objects with virtual weights, they adapt quickly to unknown virtual weights and choose efficient grip forces. Moreover, predictive overshoot forces are produced that match inertial forces which would originate from a physical object of the same weight. In summary, these results suggest that users of advanced neurorehabilitation methods employ and adapt their prior internal forward models for sensorimotor control of grasping. Incorporating such insights about the grip force dynamics of human grasping in the design of neurorehabilitation methods, such as hand exoskeletons, might improve their usability and rehabilitative function.**

I. Introduction

Investigating the forces that are exerted during grasping can provide insights into the underlying mechanisms of neural control of hand function and can help inform the design of rehabilitation programs and hand exoskeletons. Following the seminal paradigm from Johansson and Westling [1] in which isometric finger forces are measured while objects are being grasped with a precision grip between thumb and index finger, researchers have discovered multiple characteristics of physiological and pathophysiological grasping [2].

One major finding was that grip forces are modulated by anticipated task demands such as varying weights of objects a person intends to lift and that the sensorimotor control of grasping is highly energy-efficient. Humans quickly adapt their grip forces to values only slightly larger than the minimum forces necessary to avoid object slippage [3].

Previous research found that the force profiles during grasping and lifting are characterized by an initial rapid increase in force leading to an overshoot beyond the required

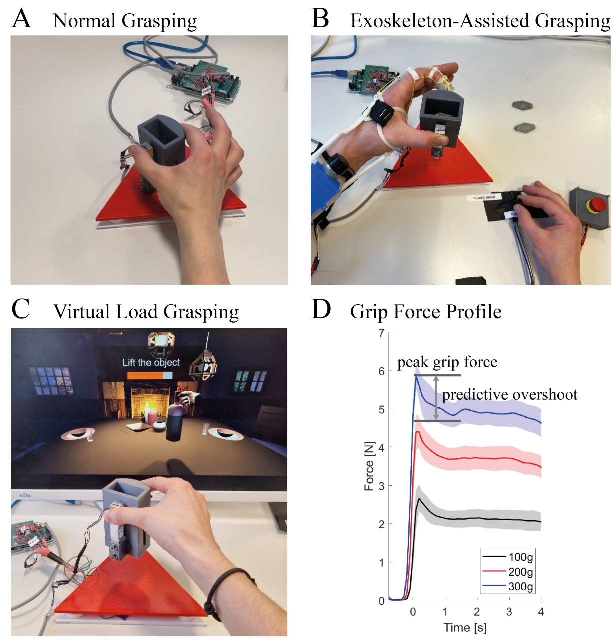

Fig. 1. Grasp force dynamics experiments in different neurorehabilitation settings: A) Participants grasp and lift an object with three different load weights while their pinch grip force is measured with a load cell attached to the object B) Participants control a tendon-driven soft hand exoskeleton to assist them during pinch grasping. The turn knob can be used to flex/extend the finger. C) Participants grasp and lift objects in a virtual environment. They can only lift the virtual object (bottle) if they apply more than the object-specific threshold force on the physical grasp interface D) The characteristic grip force profiles when healthy individuals grasp and lift objects of different weights.

gripping force [1], [4]. After the overshoot peak force is reached and the object is stabilized in the air, the force converges to a constant magnitude. The leading hypothesis for this overshoot characteristic is that the motor system predicts the acceleration-caused perturbations during the motion of lifting the objects by using the efferent signal to the biceps muscle [5]. These efferent signals, representing the person's intent to move their hand upwards, are fed into learned internal models in the brain, specifically, in the left supplementary motor area [6], which predict the sensory consequences of the intended movement (e.g. potential slippage). Tight sensory-motor integration allows the motor system to compensate these predicted perturbations by minimizing the error between the actual movement and the prediction. The almost non-existing delay between the grip force overshoot and the lift-off time point shows that this effect is not caused by a sensory-feedback adjustment.

Research on grip force modulation in patients with neurological disorders has shown changes of the ideosyncratic

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force profile, depending on the patient's sensorimotor deficit. For example, a study by Nowak et al. investigated the grip force modulation in patients with Parkinson's disease [7] and cerebellar disease [8]. The researchers found that these patients exhibited increased grip force during both power grip and precision pinch grasp tasks, compared to healthy individuals. Another example is the study of [9] showing that even though a hemiparetic stroke often leads to muscle weakness, in many cases, force modulation remains well-preserved.

Overall, these studies highlight the importance of understanding the force profile during gripping and its role in hand function. For neurorehabilitation methods, such as exoskeleton-assisted training and virtual-reality-based therapy [10], [11], to be effective, they should disturb these natural grip force patterns as little as possible and assist patients to achieve more coordinated and robust grasp-and-lift movements. To address this challenge, exoskeletons such as [12], [13], emulate natural grasping by optimizing grasp stability or applying Gaussian mixture regression to learn from human grasping. However, those exoskeletons are rigid and barely allow patients to contribute to the grasping with their own muscle force. Especially for soft exoskeletons, more research is needed on the analysis of human contribution during exoskeleton-assisted grasping.

In this paper, we investigate in a feasibility study with six healthy participants whether the natural characteristics of the grip force dynamics are preserved and how they differ when grasping is assisted by a lightweight soft hand exoskeleton. Additionally, we evaluate the changes in grip force profiles when grasping objects with virtual weights in a therapy game. In particular, we investigate how fast the motor system adapts to grasping and lifting virtual objects of different weights and if it is still capable to learn internal models for highly force-efficient grasping in a virtual environment.

II. Soft Hand Exoskeleton for Grip Assistance

For this study, we developed a soft, tendon-driven exoskeleton for pinch grasping, inspired by the design of [14]. The exoskeleton consists of a 3D-printed, flexible, modular, and compliant attachment, made of thermoplastic polyurethane (TPU). It covers the tip of the finger and two half-ring clips that can be fixed to the dorsal side of the proximal and intermediate phalanges (see Figure 2). Printing those components in different sizes allows to customize the exoskeleton. To maintain kinematic compliance and prevent shifts during finger flexion, we designed the dorsal part of the exoskeleton to be stretchable (Fig. 2). The index finger attachment is connected to a textile palm strap which can be fastened around the hand. The tendons are connected to the fingertip cover and the flexor tendons are rooted on the ventral side of the finger, whereas the extensor tendons are rooted on its dorsal side. The tendon routing consists of low-friction tubes made from Teflon that connect the finger attachment to a two-part spool with different diameters on which the flexor and extensor tendons are winded in opposite directions. The spool is turned by a DC motor,

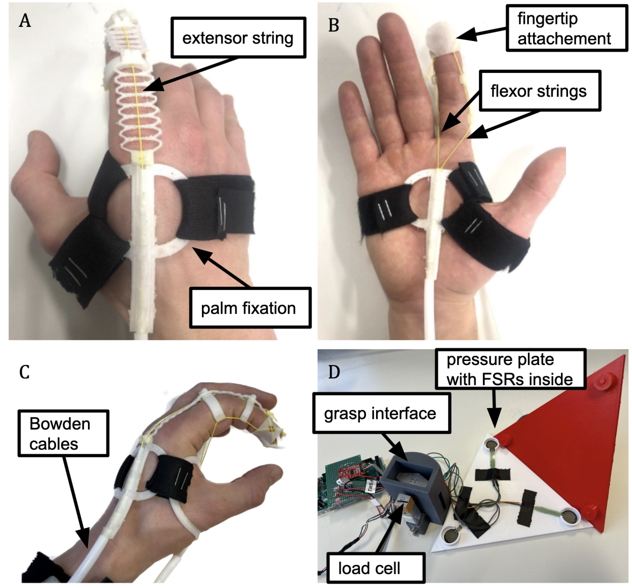

Fig. 2. Tendon-driven and light-weight soft exoskeleton composed from modular 3D-printed parts. A) Dorsal view on the hand exoskeleton with visible extensor tendons B) Palmar view on the hand exoskeleton with visible flexor tendons C) Side view on the hand exoskeleton during pinch grip. The tendons are routed inside Bowden cables towards the spool of the DC motor D) The adjustable weight box with the attached load cell is used as grasp interface for our grip force measurements. To detect the exact time points when the object is lifted and placed down, we use a triangular pressure plate with three force sensitive resistors underneath. All sensors are connected to a microcontroller where there data is processed and recorded.

which is controlled by a rotational encoder turn knob. The encoder position is linearly mapped to the motor speed. An exoskeleton user can thus control flexion and extension of the index finger as well as grip force by turning the knob either clockwise or counterclockwise. Finally, an emergency button was integrated as a safety measure to interrupt the power supply at any time, and we implemented mechanical joint stop limits to prevent hyperextension of the index finger.

In addition to their compliance, soft exoskeletons can be designed to be extremely light-weight, which is of critical importance for neurological patients with shoulder weakness. Rigid hand exoskeletons can support grasping well, but their weight often makes it difficult for patients to lift the object and can lead to fast muscular fatigue. Furthermore, the low compliance of rigid hand exoskeletons will interfere with a user's natural grasping and lifting behavior. Since one of our goals was to build an exoskeleton that does not disturb a user's gripping profile such that it could be used for assessment and bio-feedback training in neurorehabilitation therapy, we tried to optimize our design to be as light-weight and compliant as possible. The minimalistic design achieves a weight of below 20g (dependent on finger length) - which to our knowledge is amongst the lowest weights of a pinch exoskeleton hand component ever achieved and well below the reference weight of 200g deemed acceptable by patients and clinicians [15]. The motor box on the forearm weights 232g and thus does not strongly interfere with lifting objects.

III. Experiments

For the experiments, two custom-built measurement devices were used as shown in Figure 2D. To measure the grip force, we attached a load cell (11 Hz sampling frequency) to the 3D-printed grasp interface box carrying the weights. The participants were instructed to grasp the box between their index finger and thumb through a pinch grasp while placing their thumb on the upper part of the load cell. The box was then placed on a triangular pressure plate that functioned as a ground contact sensor using three force-sensitive resistors located under each edge. The sensor readings from these pressure sensors allowed us to precisely determine the exact time point of the lift-off, which we use to align the grasps in time during averaging (see Fig. 3). Figure 1 shows the setup of our three experimental conditions - A) normal grasping, B) exoskeleton-assisted grasping, and C) grasping virtual loads, which were performed with 6 healthy participants (four male, two female). The study plan was approved by the Ethics Commission of the Faculty of Medicine of the Technical University of Munich (2023-10-S-NP) according to the Declaration of Helsinki and the participants gave their informed consents before participation.

For the *normal grasping condition*, each participant performed six blocks of 1.5 min duration. After the third participant, we changed this setup to nine blocks of 1 min to achieve more changes between weights. During these blocks, the participants were instructed to continuously grasp and lift the grasp interface box at their own pace for following the classical experimental setup from Westling and Johannsson [1]. Only the holding phase was set to 5s. The blocks differed between three load weights (100g, 200g, and 300g), which were randomized in their sequence. Thus, every participant had either two or three grasping blocks per weight condition, except for Participant 1 where the first block (100g) was excluded from analysis due to excessive forces.

Before the *exoskeleton-assisted grasping condition* experiments, we helped each participant to put on the exoskeleton on their dominant hand with a fitting index finger attachment. They were then given approximately 10 min to get used to the turn knob-based control of the exoskeleton. Afterwards, they performed three grasping blocks per weight condition in randomized order. Each grasping block consisted of cued 8 to 10[1] trials in which the participants had 5s to perform a stable grasp and then had to lift the object for 5s, followed by 5s of rest. For instructions of the participants, we used a video that showed the current phase (grasping, lifting, resting) and the remaining time in seconds, as well as a visualization of a grasping motion. In total, each participant performed 24 to 30 grasps per weight using the exoskeleton.

For the *virtual load grasping condition*, we implemented a game-based paradigm that showed one of three objects that had to be grasped and lifted during each block, each with a different virtual weight. The recorded grasp force was sent from the load cell in the physical grasp interface to the game where it was compared against a predefined object-dependent force threshold (virtual load). The virtual object could only be moved upwards in the game when the grasp force surpassed the threshold set by the virtual weight. Participants were asked to complete three sets of 1 block per virtual weight condition, where each of these blocks consisted of 15 trials of grasping and lifting a virtual object. After each set we added a random block in which the order of the virtual weights was randomised during each grasp-and-lift trial. Each trial consisted of a 5s phase for grasping and lifting and a 5s rest phase where the participants had to put the object down and release it.

After completing the experiment, participants were requested to provide feedback on their personal experience with the system and the exoskeleton through a questionnaire. The responses were measured on a 5-point Likert scale, where 1 indicated strong disagreement and 5 indicated strong agreement.

[1]Participants 1, 2 and 6 performed 10 trials per block. To reduce the experiment duration, we changed the setup to 8 trials per block for the remaining participants.

IV. Results

A. Subjective Feedback

The participants found the exoskeleton easy to use (mean=3.83, std=0.37) and not unnecessarily complex (mean=4.33, std=0.47). However, only half of the participants found that the experience of grasping with the exoskeleton did closely resemble that of normal grasping (mean=2.67, std=1.11). All participants found that the exoskeleton was strong enough to move their index finger despite its small weight (mean=5, std=0).

B. Grasp-Force Efficiency and Predictive Overshoots

The grasp force dynamics of our participants during the *normal grasping experiment*, when the participants were grasping and lifting different weights without the exoskeleton, showed the same idiosyncratic characteristics as described in literature [16], [17], thus, confirming the validity of our experimental setup (see Fig. 3A). Average grip forces as well as the grip force rate were strongly positively correlated with the object weight, i.e., for smaller weights we observed smaller and thus more efficient grip forces and a less-steep initial ramp, resulting in the force peaks being almost at the same time point after lift-off, independent of weight. Additionally, we observed large force overshoots during the lift phase. The magnitude of the overshoots was positively correlated with the object weight. To quantify this effect, we present the distributions of overshoot magnitudes for each weight and participant in Fig.4.

In the *exoskeleton-assisted grasping experiment*, our results also show a significant positive force-weight correlation effect, indicating that the participants performed force-efficient grasps, even when they did not need to contribute with muscle force (Fig. 3 B). A clear difference to the grasp force profiles in the normal grasping condition is the longer force ramp time due to the limited grasp speed of the exoskeleton. For participants 1 and 3 we observe a bend in their force profile which shows the time point when the

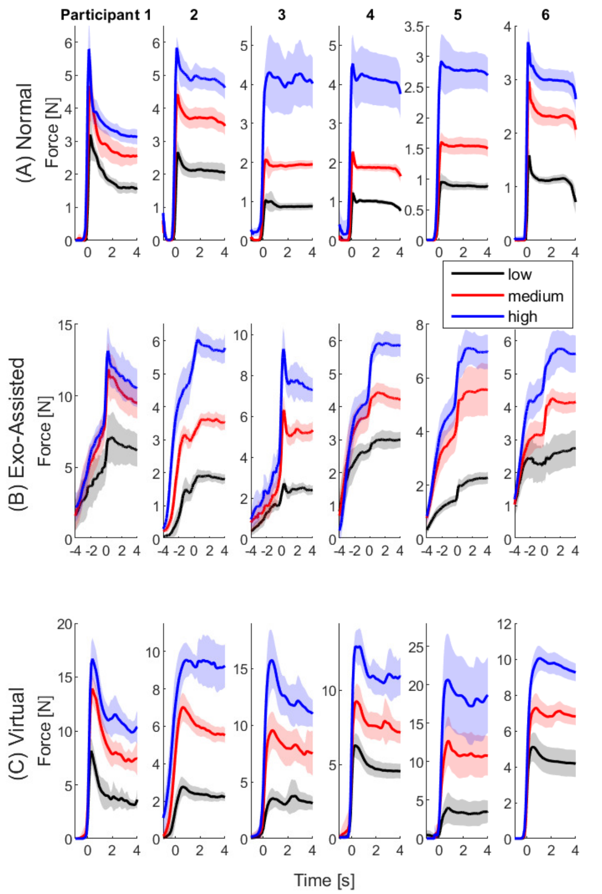

Fig. 3. The force dynamics profiles, with the lift-off aligned at 0s and averaged over all grasp-and-lift trials for all six participants, show the main characteristics of healthy human grasping - 1) the average grasp force correlates with the object weight 2) the grip force rate (steepness of force ramp) correlates with the predicted object weight 3) a predictive force overshoot at the time point of lift-off compensates inertial forces caused by lift-acceleration.

participants started contributing by themselves to the grasp instead of having the exoskeleton provide all of the grip force. As we instructed the participants to not change the motor speed during lift phase, this bend could not be caused by a change in motor control. This is verified by recordings of the motor speed that also showed no bend, indicating that the change in grip dynamics was caused by increased human force contribution.

The other participants do not show such a clear bend which fits their verbal report to have kept their hand as passive as possible to simulate the case of a neurological patient with flaccid paralyzed hands. For all participants, we observe a similar weight-proportional grip force gradient as in the physiologically normal grasping condition. We also observe grip force overshoots in the exoskeleton condition, however, these are more pronounced for participants 1 and 3, who contributed stronger to the grip force (Fig. 3B and 4B).

In the grip force profiles obtained in the *virtual load experiments* we also observe a positive correlation between grip force and virtual object weight as well as between steeper maximum grip force gradients for virtually heavier objects (Fig. 3C). Similar to the grasping-and-lifting of physical objects, we observe clear overshoots during lift-off, whose magnitudes correlate with the virtual object weight (Fig. 4C). We also observe a second peak about 2s-3s after object lift-off which might be caused by visual feedback. Since the participants can't feel the object sliding in this virtual grasping experiment they have to use the visual feedback from the therapy game to detect when their grip force has decreased below the object-specific force threshold, which takes some time before they can initiate a compensatory increase in their grip force.

C. Grasp-Force Adaptation and Learning

Our participants improved their grasp efficiency over time both during the normal grasping condition and virtual condition. The *normal grasping experiment* of Participant 2, shown in Figure 6A, shows a decrease in the applied force for all blocks and weights over time converging to an efficient value. A learning effect can also be observed in the *virtual grasping experiment*, where the participant shows a very steep learning curve, especially for the lightest virtual weight, while receiving only visual feedback. After learning the weights, this learning effect is no longer visible to the same extent, as the optimal force is reached more quickly (e.g. block 4, 5, 8 in Fig. 6C). This effect can also be seen in the random experiment (Fig. 5), when the same weight appeared three times in a row (grasp 11-13). We also see adaptation of exoskeleton-assisted grasp forces in block 1, 4 and 8, even though it does not cost the participant to grasp less energy-efficient with the exoskeleton (Fig. 6B).

Another effect that was visible during the experiments, is an *after-effect* or *wash-out* as described in [18]. They observed force adaptation over time when changing task dynamics, with largest errors immediately after the change. This effect is also visible in all experiments that we conducted. After lifting an object with a high weight and then switching to a lighter one, participants tend to apply more force than they learned is needed, even though they were aware of the weight and lifted it before. For the *normal grasp experiment*, this after-effect effect can be seen in Figure 6A at the beginning of block 2, 5 and 6. During the *virtual grasp experiment*, this effect was observed in both the block-based (Fig. 6C block 2) and the random parts (Fig. 5 grasp 2, 8 and 14). In the *exoskeleton-assisted grasping experiment*, the adaptive wash-out effect is seen the strongest in block 5 (Fig. 6B).

V. Discussion

Overall, our results from the three different experimental conditions show that the core characteristics of grip force dynamics in healthy individuals are preserved when they perform grasp-and-lift exercises as they are employed in neurorehabilitation therapy. A consistent finding was that the participants applied more force as the weight of the (physical or virtual) object increased, and that, for all conditions and participants, the gradient of the force ramp was chosen according to the predicted object weight. Interestingly,

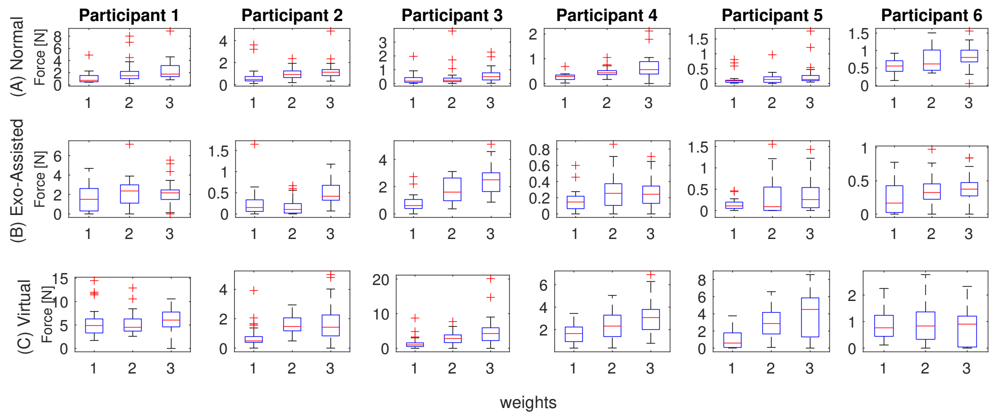

Fig. 4. The box plots show the magnitude of the grip force overshoot during the initial phase of the lift-off for all six participants and conditions. The overshoot is quantified as the force difference between the peak of force after the lift-off and the lowest point of the force pattern in the range of 1s after the peak. A correlation between the overshoot magnitude and the weight is observed for the majority of participants.

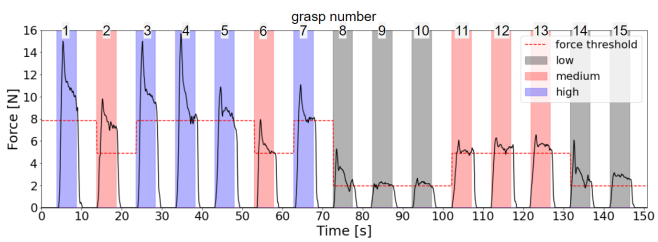

Fig. 5. Grip forces of Participant 2 during the third randomized virtual weight block. Just like in the normal grasping condition, an adaptation effect is visible. Whenever the virtual weight changes, the required force threshold is exceeded by a large amount. The excessive force decreases over subsequent trials of the same virtual weight as the participant learns how much force is necessary to lift the virtual object and thus improves his grip force efficiency.

participants chose to grasp energy-efficiently even in the exoskeleton condition instead of always choosing a large exoskeleton grip force independent of object weight. For lighter weights, they chose smaller exoskeleton grip forces but also smaller force ramp gradients, which shows that they did not optimize for time. Our interpretation is that the sensorimotor system is reusing already learned internal forward models of grasping that are dependent on predicted object weight. This hypothesis of reused previously learned internal models is further supported by the results from the virtual grasping experiment, in which the overshoot magnitude correlates with the virtual object weight. We consider this as evidence that the motor system is trying to compensate for the inertia forces of the virtual weight and not for the inertia forces of the light-weight grasp interface as this is constant and would therefore require a constant overshoot force. The different ramp gradients between the different virtual loads show that participants predict the necessary grasp force as the initial gradient of the force ramp is considered to reflect a person's prediction of the weight [3].

Since earlier research showed that tactile sensation from the fingertips is used for the efficient force-weight scaling [16], we infer that wearing the exoskeleton (and especially its attachment on the index finger tip) does not strongly block the tactile feedback. Our results show that our light-weight and compliant hand exoskeleton is transparent to a user's force contribution, which might allow to assess and train their grip force profile even during exoskeleton-assisted grasping.

The observed adaptation effects that often occur when a weight condition changes is in line with earlier results by Nowak et al. [4] where both healthy controls and individuals with dystonia adapted to the object weights within 1-2 lifts. Additional to this fast adaptation when the external dynamics (object weights) changes, we observed a slower adaptation effect during the course of most blocks. The fast-adaptation effect might be caused by switching to a different internal model while the slow adaptation effect might be caused by grasp efficiency optimization using tactile sensory feedback.

When the hand is intentionally held passive during exoskeleton training, we observe a smaller compensatory overshoot during lift-off which might occur also in patients with strongly paretic or even paralyzed hands. Due to their sensorimotor impairment they will not be able to produce the necessary compensatory forces during lifting movements which can lead to grasp failures. Future assistive hand exoskeleton should therefore integrate these neuroscientific insights into their robotic design through neuroengineering approaches [19] that recognize and compensate for these missing functions of patients, e.g., by measuring and amplifying residual muscle activity [20] or predicting necessary compensatory forces during arm movements.

VI. CONCLUSION

In this paper we have presented first results of the analysis of grip force dynamics during grasp-and-lift experiments in settings of modern neurorehabilitation therapy. We show that for healthy participants, even in these novel grasping conditions we can still observe the core characteristics of sensorimotor pinch grasping such as weight-dependent grip force and force ramp gradient as well as a predictive grip force overshoot to compensate inertial forces during lifting the object. In line with results from related grip force experiments we observe fast adaptation effects whenever

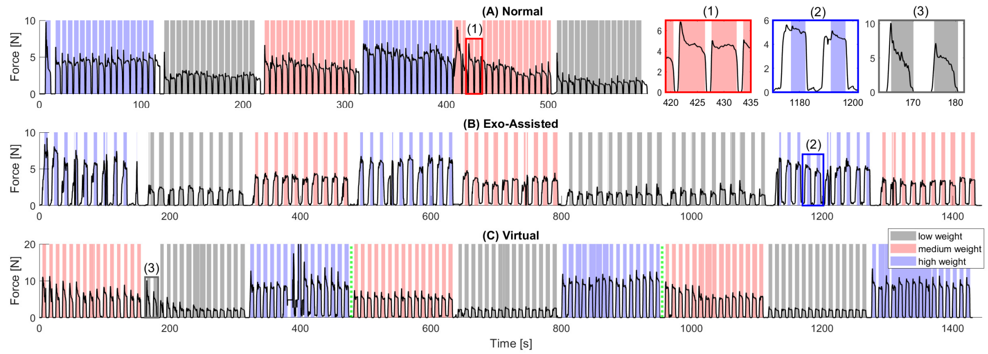

Fig. 6. Course of grap-and-lift trials during the complete experiment of Participant 2. For each condition (normal, exo-assisted and virtual), multiple blocks of different physical or virtual weight were conducted. Note that after every three blocks of virtual grasping, a randomized block, as shown in Fig. 5, was performed. At the beginning of each block, participants often show inefficiently large grip forces which are reduced from trial to trial as cutaneous sensory feedback is used to optimize grasp force efficiency. In the case of exo-assisted grasping, the first grasps of multiple blocks show inefficiently large grip forces but this is rapidly adapted to the object weight despite partial tactile blocking due to the finger exoskeleton attachment. In virtual grasping, only a few grasp trials are sufficient to adapt to a force-efficient grip although only visual but no tactile feedback is received. Note: In the third block of the virtual condition, an sensor reading error occurred. The respective trials were excluded from the analysis.

the grasped weight changes and slower adaptation effects during repeated grasps of the same object, which indicates the learning of energy-efficient grip forces.

Overall, our findings suggest that since these neurorehabilitation conditions do not block the core characteristics of natural grip force profiles, it might be possible to use grip force analysis during exoskeleton-based and virtual-reality-based exercises for the assessment of progress in neurorehabilitation therapy and also as bio-feedback signal for rehabilitative training. Following our successful feasibility experiments this can be verified with patients in future studies. In conclusion, we argue that incorporating insights about the grip force dynamics of human grasping in the design of neurorehabilitation methods, such as hand exoskeletons, might improve their usability and rehabilitative function.

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