Digital Extensions with Bi-axial Fingertip Sensors for Supplementary Tactile Feedback Studies

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Leonard F. Engels*†, Leonardo Cappello*, Christian Cipriani, *Senior Member, IEEE*

Abstract— **Using a hand prosthesis means grasping without tactile information. Although supplementary sensory feedback has been investigated extensively, few study results could translate into clinical applications. Unreliable and imprecise feedforward control of current hand prostheses hinders the investigation of supplementary sensory feedback, so an ideal feedforward tool should be used. Thus, we aimed to create a device that would allow to use the sensory deprived human hand as an ideal tool without the need for local anesthesia. For this, we fashioned silicone digit extensions with integrated force sensors and tested the performance of 12 volunteers in grasping with these extensions. Two tests were performed: a simple pick and lift test to compare performance to anesthetized digits, and a virtual egg test to assess grasping efficiency. We found that the extensions significantly alter grasping. In future studies, these extensions will help us investigate how to artificially restore the information necessary for successful and efficient grasping with an ideal feedforward tool.**

I. Introduction

Missing a hand and the corresponding motor and sensory functions can have striking consequences on the quality of life and autonomy of the affected. Clinically available myoelectric prostheses can restore rudimentary grasping capabilities, although they do not provide any intentional sensory feedback [1]. While it is generally agreed that users would profit from supplementary sensory feedback (SSF) [2] beyond the crude, incidental feedback of current prostheses (e.g., vision, socket vibration, motor sound), so far only few studies actually demonstrated this to be the case [3]–[5]. Thus, further studies on how to restore the missing sensory functions of the hand are needed.

Notably, many studies on how to provide SSF have not been entirely conclusive and were sometimes even contradictory [1], [3], [5]. This may be, in part, due to unreliable and imprecise control [6], which could limit the subjects' ability to exploit feedback. Saunders and Vijayakumar [7] suggested that uncertainties in the feedforward path should be minimized, and ideal SSF should allow to overcome this currently unavoidable uncertainty and complement the incidental feedback that is available.

Much of the uncertainty stems from how these experiments are carried out. In particular, since they mimic the conditions of an individual wearing a myoelectric prosthesis, myoelectric signals (EMG) are used for feedforward control. However, EMG-based control is susceptible to environmental noise, and signal acquisition and classification cause intrinsic delays in the control loop. In addition to this, any mechanical hardware in the loop introduces further delays and inaccuracies.

Yet, to conclusively investigate different SSF strategies, the assessment should be free from any of the aforementioned constraints. To assess different SSF, we propose to use the sensory deprived human hand as the feedforward tool, since it provides the best possible movement accuracy.

Many basic studies on the neural mechanisms of grasping and on the importance of sensory input from the digits have been conducted by anesthetizing the digits or

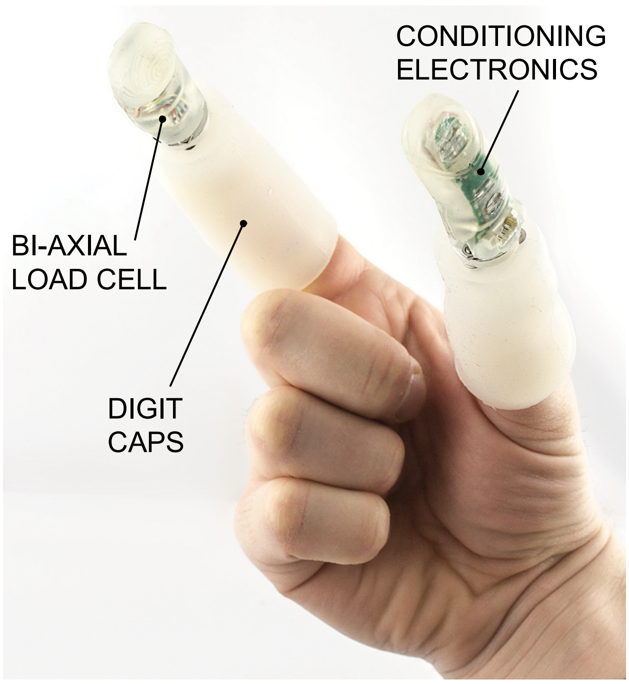

Figure 1. The digit extensions as worn by the subjects. Normal and tangential force sensors are embedded in the fingertip. The silicone digit caps were available in two sizes to fit the subjects tightly but comfortably.

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fingertips to deprive them of sensory feedback [8]. However, in studies involving SSF, it is desirable to collect high quality normal and shear contact forces, but due to size constraints, it is not possible to attach sensors directly to the fingertips. Additionally, the application of anesthesia has procedural constraints and introduces a risk, making it impractical for extended investigations. Wearing gloves also diminishes sensory feedback, and Kinoshita [9] found that, the thicker rubber or cotton gloves are, the more they affect grip force. However, they do not affect the individual grasping phases, as anesthesia does.

Hence, as a more convenient alternative, we propose silicone digit extensions with embedded bi-axial force sensors. These extensions are meant to be worn on unimpaired digits in order to conduct SSF experiments in which the motor abilities of the hand are preserved while the natural tactile flow from the fingertips is blocked and replaced using the force sensor and a SSF method. Before this, however, we need to know if the extensions do indeed suppress significant information from fingertip mechanoreceptors.

To that end, we assessed volunteers' performance in a pick and lift test with the unimpaired hand as the baseline and quantified the difference in performance with the digit extensions. Then we discuss our findings in the light of those by Johansson et al. [10]–[13], and Nowak et al. [14], [15] who quantified the performance difference of volunteers with and without anesthetized digits. We aim to validate that the extensions have an effect similar to anesthesia on the mechanics of pick and lift for many of the outcome measures. We argue that they will serve as a novel means to re-test inconclusive hypotheses, test new hypotheses, and compare these to promising approaches, e.g., the *discrete event-driven sensory feedback* [3], thus facilitating the design of meaningful SSF for prostheses and shedding light on how SSF is processed by the nervous system.

II. Materials and Methods

A. Subjects

Twelve right-handed subjects (24 to 32 years old; 8 women) with no known neurological conditions participated in this study. None of the subjects had used the digit extensions before. The experimental protocols were in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Scuola Superiore Sant'Anna (approval number 2/2017). All subjects gave written informed consent before participating in the study.

B. Materials/Setup

The extensions consisted of custom-made silicone digit caps (20 shore A silicone; 2 different sizes, fitted to the subject's digit's circumference) connected to artificial fingertips (available in our lab). The latter were instrumented with bi-axial force sensors based on micro-machined cantilevers topped by semiconductor strain gauges that measure the normal and shear forces at the tip of the digit (Fig. 1; force ranges: 0 – 15 N for the normal axis, -8 to 8 N for the shear axis). The fingertip included a printed circuit board with conditioning circuits for both channels.

For the pick and lift test, we used an instrumented object (~200 g), consisting of three load cells (S215, Strain Measurement Devices, UK) in a 3D-printed plastic housing, connected to a custom conditioning board (Fig. 2). On the grasping surface of the object, different materials with different frictional properties (rayon, suede and rough sandpaper, in order of increasing friction) could be attached by hook and loop fasteners [16].

The sensors of the extensions, the instrumented object, as well as a push button were connected to a data acquisition board (USB-6211, National Instruments, USA), which was connected to a PC via USB. Data were recorded with a script running in the LabView environment (National Instruments, USA), and analyzed with MatLab (MathWorks, USA).

C. Protocol

The subjects performed four experimental sessions consisting of two different tests, namely the Pick and Lift Test (PLT) and the Virtual Eggs Test (VET), each performed once with and once without the extensions. The administration order was randomly sorted across subjects.

During the PLT, the subject, sitting in a comfortable position at a table (Fig. 2), was instructed to repeatedly pick and lift the instrumented object. Each of 15 trials started when the subject pressed the push button, indicating the start of the trial; then the subject grasped the instrumented object using a two-digit precision grasp, lifted it to an indicated height, held it there for about two seconds, and set the object back down. After that, the subject pressed the push button again to signal the end of the trial.

The subjects were instructed to close their eyes after each trial while the experimenters changed the surface finish of the object in pseudo-random order until each surface had been presented five times. To prevent that subjects would see the differences among the surface finishes, all of them were painted black. In addition, the

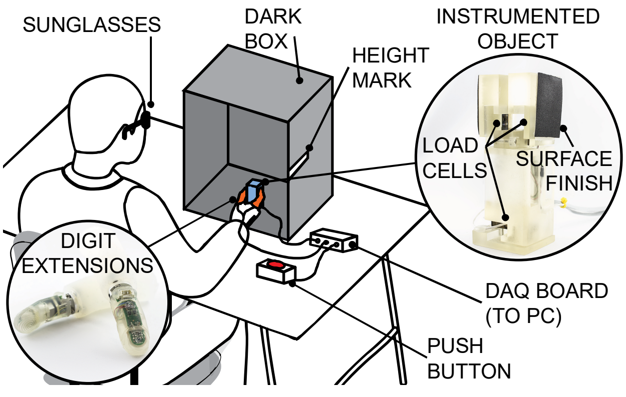

Figure 2. The experimental setup of the Pick and Lift Test. The subject sat at the table and grasped the instrumented object either with or without the extensions. The surface finish on the object was changed pseudo-randomly from trial to trial between rayon, suede, and sandpaper. The background and the surfaces were black, and the subject wore sunglasses to make the surfaces visually indistinguishable.

object stood in a dark box, the light in the room was dimmed, and the subjects wore sunglasses.

The VET [3] replicates the task of picking up and repositioning fragile objects. It is itself based on the well-known box and block test with the exception that 'breakable' blocks (called 'virtual eggs'; weight: ~80 g, size: 40x40x40 mm^3, breaking force: 1 N) are used instead of the standard wooden ones. This test provides an immediate measure of grasping performance and efficiency, and the breaking blocks make it more sensitive to differences in feedback than the original test. The subject was instructed to stand in front of the table and to repeatedly grasp the virtual eggs with a precision grasp and transfer them from one side of a 15-cm high wall to the other as fast as possible within one minute, while avoiding crushing them. The primary and secondary outcome measures for the VET were the total number of transferred blocks and the number of broken blocks, respectively.

D. Data analysis

The force signals were low-pass filtered (4th order Butterworth filter; cutoff frequency: 30 Hz). The grasp force (GF) and load force (LF) were measured by the instrumented object. In particular, the GF was defined as the sum of the normal forces applied by thumb and index as measured by the instrumented object.

To compare grasping with the extensions to grasping without extensions and to the works of Johansson et al. [10]–[13], the PLT trials were divided into the following phases: preload, loading, hold, unloading, and postload (Fig. 3). The preload phase lasted from the moment of contact with the object (GF increase) to the start of the loading (LF increase); the subsequent loading phase lasted until the moment of liftoff (LF steady); the holding phase lasted until the object touched the table again (LF decrease); it was then unloaded; the postload phase was the time between replacement (LF = 0) and release of the object (GF = 0). From these phases, the following, well-known relevant metrics were extracted to describe the pattern of the forces during the grasp and to compare the different conditions: GF at the beginning of the loading phase, GF at liftoff, GF at the moment of object replacement, and the maximum GF throughout the entire trial. In addition, we calculated the rate of change of the GF and LF during the phases, computed as the coefficient of the linear fitting of the force data in the desired phase.

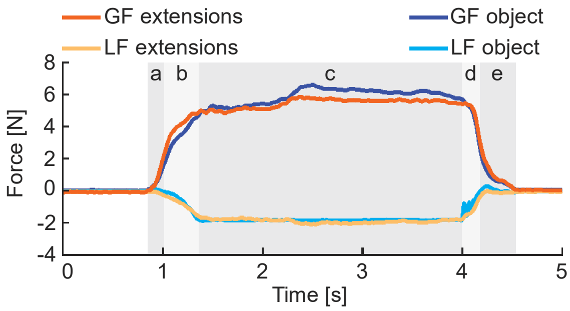

Figure 3. Grasp phases with digit extensions. The phases we discerned are: a – preload, b – loading, c – hold, d – unloading, and e – postload. The signals show grasp force (GF; dark) and load force (LF; light) of one representative trial, recorded from the object (blue) and the digit extensions (orange). The normal and tangential force measurements of the extensions are comparable to the measurements of the instrumented object in the PLT task. LF is presented negative to increase clarity.

Furthermore, we assessed the change of GF with respect to the changing LF from the beginning of the grasp to the beginning of the hold phase (i.e., force coordination [10]). Last, we counted the number of 'unstable releases', i.e., the number of times the subjects released the object before stably replacing it on the table.

After testing data for normality with the Kolmogorov-Smirnov test, we compared the outcome measures of the PLT and VET trials with the extensions to those without, using the Wilcoxon signed-rank test. Unless explicitly stated otherwise, all reported numbers and errors are median and interquartile range (IQR, reported in brackets after the median).

III. Results

A. Pick and Lift Test

1) Grasping phases

The principal structure of a pick and lift test could be observed during grasping without, as well as with the digit extensions (Fig. 3). We found that all grasping phases, except for the postload phase in trials with suede, were significantly longer with the extensions for all three surfaces than without (Fig. 4). Furthermore, the number of unstable releases was significantly higher with the extensions (37) than without (2).

2) Grasp and load forces

While GF with the extensions was significantly higher

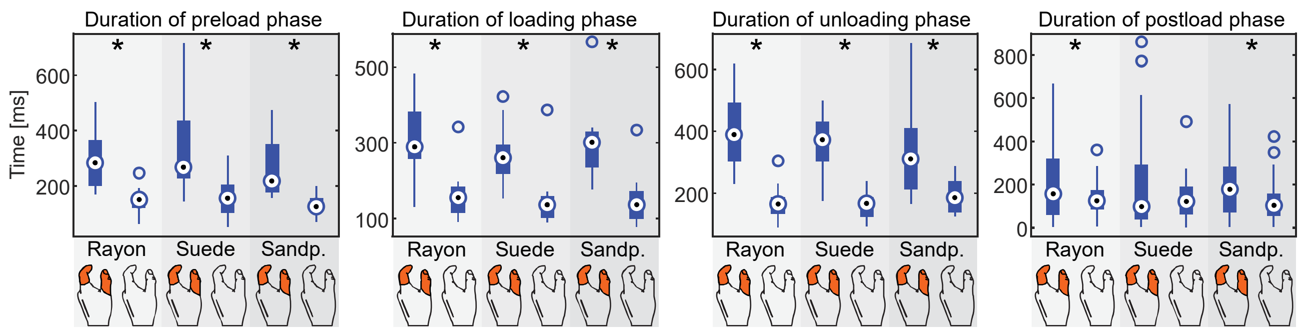

Figure 4. Duration of the grasp phases. This figure shows the duration of the preload, loading, unloading and postload phases as boxplots for each surface (gray columns), with and without the extensions (as indicated by the icons). Significant differences ($p<0.05$) between the two conditions are denoted by the '*' symbol for every surface. Circles denote outliers. Sandp. = sandpaper.

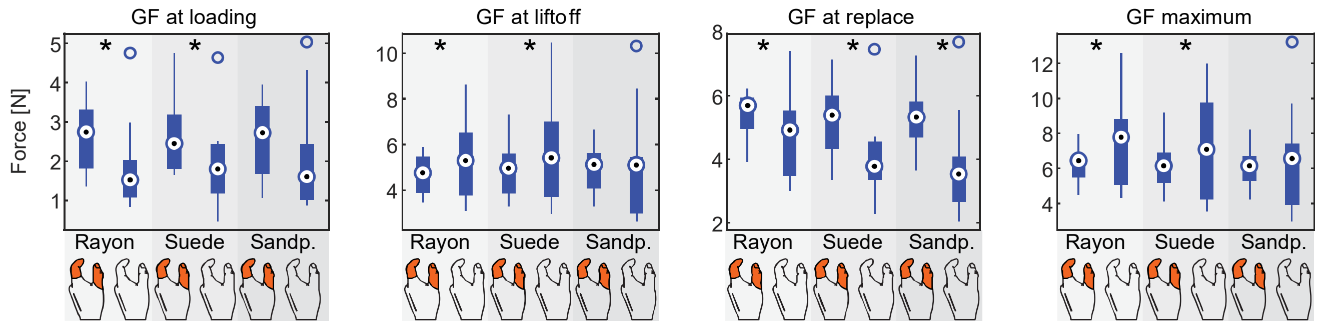

Figure 5. Grasp forces at specific time points. These boxplots show the grasp forces at the beginning of the loading phase, at object liftoff, and replace, as well as the maximum grasp force during the whole trial. GF = grasp force, Sandp. = sandpaper.

at the beginning of the loading phase for rayon and suede, the difference was not significant for sandpaper (Fig. 5). Furthermore, the GF at the end of the loading phase (i.e., at object liftoff) was significantly lower with the extensions for rayon and suede (Fig. 5 and 7). At the beginning of the unloading phase (i.e., when the object touched the surface again), however, the GF was significantly higher with the extensions for all surfaces. For rayon and suede, the maximum GF was significantly lower with the extensions.

The rates of increase of GF and LF during the loading phase were significantly higher without the extensions for all three surfaces (Fig. 6). During the hold phase, the GF decreased without the extensions but increased with the extensions. This difference was significant for all surfaces. During unloading, the rate of decrease of the GF was not significantly different between the two groups, but the rate of decrease of the LF was significantly higher without the extensions for all three surfaces.

Force coordination, moreover, was consistent across subjects and surfaces but differed between the two conditions (Fig. 7). When wearing the extensions, subjects applied more GF before starting lifting the object.

B. *Virtual Egg Test*

With the extensions, subjects transferred 20 (6.5) blocks (median and IQR), whereas without the extensions, subjects transferred 29 (5.5) blocks in one minute (Fig. 8). This difference was statistically significant. Regarding the secondary outcome measure, subjects broke 18.8 (31.9) % of all transferred blocks with the extensions and 19.9 (23.3) % of blocks without. This difference was not statistically relevant.

IV. Discussion

A. *Pick and Lift Test*

In this study, we aimed to test whether sensorized silicone digit extensions would remove crucial information about grasping from the skin receptors in the fingertips to simulate anesthesia. We found that, as with anesthetized digits, the task of grasping and lifting an object could clearly be separated into individual phases akin to those without any intervention [10], [15]. Importantly, with digit anesthesia compared to without, the duration of the phases, as well as the rate of GF and LF application are different, resulting in differing forces at specific, well-defined timepoints. Our results suggest that the extensions had a similar but not entirely equal effect.

1) *Grasping phases*

We found that the preload phase was significantly prolonged with the extensions, which agrees with the data from the literature about anesthetized digits [10], [11]. The literature describes preload phases of up to 0.5-1 s in length. We found slightly shorter preload phases: with the extensions they lasted up to 0.7 s. We further found that the loading and unloading phases were significantly prolonged, and the variability (IQR) increased, too. All of this suggests that the subjects felt much less secure during grasping with the extensions, and thus grasped more carefully, but were not as affected as with anesthesia.

We found that, in some trials, the subjects released the object before completely unloading it (i.e., before it was stably replaced on the table). This poor coordination resulted in the object rocking or toppling over. It seems that

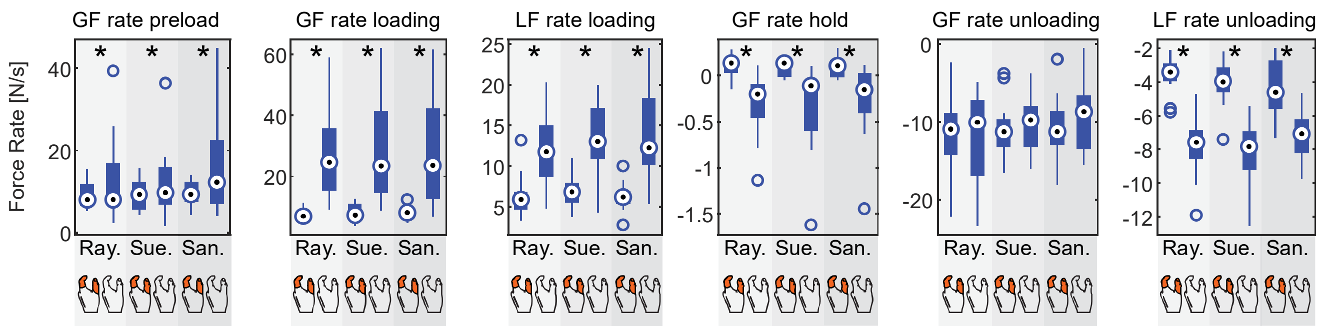

Figure 6. Grasp and load force rates. The boxplots show the grasp force rates during the preload, loading, hold, and unloading phases, as well as the load force rates during the loading and unloading phases. GF = grasp force, LF = load force, Ray. = rayon, Sue. = suede, San. = sandpaper.

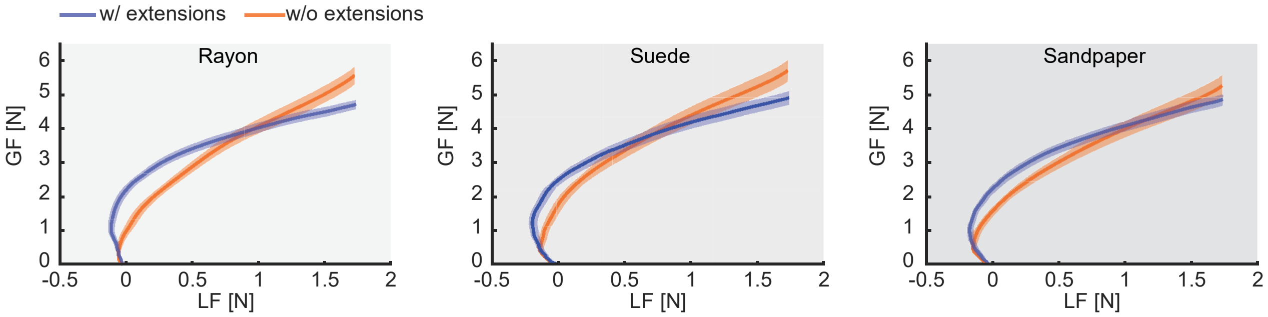

Figure 7. Coordination of grasp and load forces. This figure shows the mean grasp (GF) and load forces (LF) during the preload and loading phases for each of the surfaces across all trials. The orange trace shows forces without and the blue one with the digit extensions. The lighter areas around the mean correspond to the 95% confidence intervals.

the information necessary to coordinate this movement well [3], [8] was altered or removed by the extensions. We suspect that subjects relied on vision instead to coordinate the release of the object, resulting in a significantly prolonged postload phase for two out of three surfaces. Difficulties in coordinating the grasp with the extended digits could also have contributed to the extended duration of all phases, as well as the premature releases of the object.

2) Grasp and load forces

Since the preload phase was prolonged, we expected that the GF at the beginning of the loading phase was higher, too [10]. Indeed, we found significantly elevated GF for two out of three surfaces, although the increase was less than two-fold, not five-fold as reported in experiments with anesthetized fingertips [10]. That can be explained by the significantly slower increase in GF during the preload phase with the extensions compared to without. It is possible that subjects with anesthetized digits still grasped somewhat confidently, resulting in a fast increase of the GF before the start of the loading phase, whereas subjects in our experiment grasped the object more carefully, probably due to altered grasping mechanics.

Indeed, due to the much lower rate of GF during the loading phase, the GF at liftoff was, in fact, lower with the extensions (for two out of three surfaces). Without the extensions, we also observed a peak in GF shortly after liftoff, due to inertia of the object. We do not see this peak with the extensions because the load force rate was significantly lower, i.e., the object was loaded and lifted more slowly. Consequently, the maximum GF during the

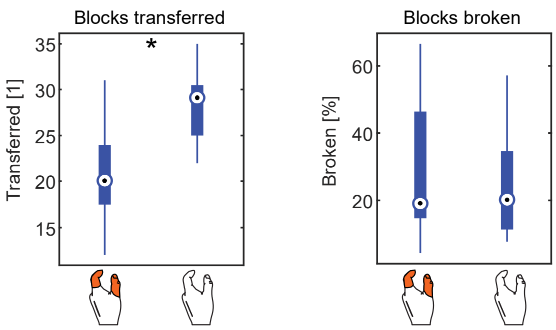

Figure 8. Results of the Virtual Egg Test. The figure shows the number of blocks transferred from one side of the barrier to the other within one minute, as well as the percentage of blocks broken during transfer.

whole trial was higher without the extensions. However, during the hold phase, the GF decreased without the extensions, and the grasp became more economical [15]. With the extensions, on the other hand, the GF generally kept increasing throughout the hold phase, similar to what has been observed with anesthetized fingertips [11], [14], leading to a significantly higher GF at the end of the hold phase. This suggests that the sensory-driven feedback mechanisms for economical scaling of the GF according to the actual loading condition were disturbed or suppressed by the extensions.

While we found that unloading was significantly prolonged, similar to findings with anesthetized digits, and the rate of decline of the LF was much smaller with the extensions, we did not find a significant difference in the rate of decline of GF during unloading, as reported with anesthesia [12].

B. Virtual Egg Test

Since the explicit instructions were to break as few blocks as possible, the subjects grasped them more carefully with the extensions to keep the percentage of broken blocks to a minimum, resulting in less transferred blocks but a comparable percentage of broken blocks.

The significantly lower number of transferred blocks supports our hypothesis that the extensions deprived the subjects of crucial information from their tactile receptors [3]. Subjects had to visually confirm a secure grasp on each block before starting to lift it and thus transferred the blocks much slower.

C. Limitations

In this study, we did not anesthetize the subjects' digits to quantify the within-subject difference of anesthesia and digit extensions. While the results of this study are encouraging and seem to largely support our hypothesis that the extensions block crucial information about grasping, it is also evident that they do not eliminate all information. Low frequency tactile information was still relayed to the subjects through the silicone, although likely distorted. Furthermore, the deformation of the silicone seems to limit the maximum force that can be applied, which may be another reason the maximum applied force with the extensions was lower than or comparable to the maximum force without. Additionally, the higher friction of silicone compared to human skin most likely allowed the subjects to lift both the instrumented object and the blocks in the VET with less force. Hence, future studies should repeat these tests with equalized friction on digits and extensions.

Despite these limitations, the digit extensions blocked feedback substantially. Moreover, preliminary comparisons show that the forces recorded by the sensors in the fingertips are comparable to those recorded by the instrumented object. This encourages further studies where natural sensory information from the fingertips is blocked, and force data are collected with these sensors, which are then used to deliver accurate and reliable sensory feedback to the wearer; this makes the instrumented object redundant and allows to use common every-day objects in those studies. This work paves the way for assessing which kind of feedback and which way of providing it will lead to an improvement in the reported outcome measures and, hence, approach meaningful SSF for the hand prostheses of the future in a novel, quick and convenient way.

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