A Cosmetic Prosthetic Digit with Bioinspired Embedded Touch Feedback

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***Abstract*— Partial hand amputation is the most frequent amputation level worldwide, accounting for approximately 90% of all upper limb amputations. Passive cosmetic prostheses represent one of the possible choices for its treatment, probably the most affordable one. However, these devices restore very limited motor function and subtle sensory feedback. The latter is an important component for restoring the body schema. In this work we present a simple yet potentially effective and low cost cosmetic digital prosthesis that embeds touch feedback; we dubbed this DESC-finger. It delivers short-lasting vibrotactile bursts when it makes and breaks contact with the environment, based on the *Discrete Event-driven Sensory feedback Control* (DESC) policy. One prototype was developed and used by one amputee at home, for two months. The effectiveness of the device was experimentally assessed by means of an interview and a *virtual eggs test*, which showed, albeit preliminarily, that time discrete feedback can improve the motor control of a partial hand prosthesis in daily life conditions. Besides targeting people that already use cosmetic digits, the DESC-finger targets those that do not use them complaining for loss of sensibility. The production costs and manufacturing process makes the DESC-finger suitable for exploitation in high- and low-income countries.**

I. INTRODUCTION

Recent epidemiological studies revealed that 68% to 78% of total traumatic amputations involve the upper extremities and approximately 90% of these are partial hand amputations [1]. The latter may cause psychological distress, permanent disability, loss of work to the individual and poses a significant financial burden on patients and society [2]. Besides surgical procedures, which are effective and possible only under specific conditions, prostheses represent a viable solution to the treatment of digital amputation. These prostheses can be divided into passive and active (powered) devices; the latter can be either body- or battery-powered. Passive prostheses molded in cosmetic viscoelastic materials, have been the only affordable solution for a long time [2], [3]. High definition silicone prostheses mimic the color and the shape of the missing digits and thus can help the individual to forget the disability and in turn to enhance the rehabilitation process. While they can be used to protect sensitive stumps, to stabilize hand-held objects, to push against items, and (if present) to oppose the other digits, these devices do not restore active grasp.

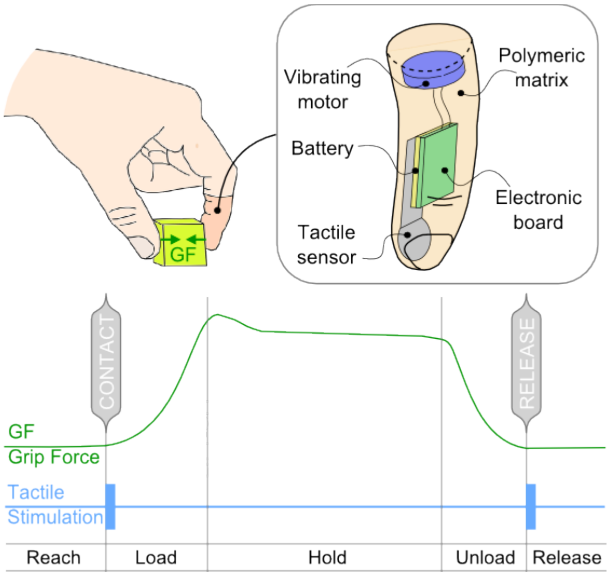

Figure 1. Phases and sub-goals of a pick-lift-replace manipulating task. Vertical lines indicate the mechanical events that separate consecutive grasp phases and represent completed task sub-goals. These events are signaled through tactile events to the central nervous system and are used to apply control signals or to trigger corrective actions (modified from [12]). In the DESC-finger the events pertaining contact and breaking of contact are signaled artificially by means of short-lasting vibrotactile bursts.

Contrariwise, body-powered prostheses can provide active grip or pinch force. The forces developed by freely-moving body parts are mechanically transmitted to a terminal device. Because of this, they also convey useful kinesthetic and proprioceptive feedback to the user through the control cable or the mechanism itself [3], [4]. Battery-powered partial hand prostheses became clinically available in the last decade; these are motorized devices activated by user-dependent input signals, picked-up from the individual's residual limb and (electrically) processed to control the terminal device [3], [4]. The components required to operate these prostheses (i.e. batteries and controller) make them bulky and for this reason an effective aid only when they are able to restore a lost opposition movement [3]. In addition, and paradoxically, although more modern they lack the sensory awareness that the mechanical transmission used to provide to the user of a body-powered prosthesis.

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However sensory feedback is an important component in a device which should operate in symbiosis with a human being. Besides the possibility of improving the closed-loop control of a prosthesis [5], [6] sensory feedback was shown functional in reducing phantom limb pain [7]. Our group has demonstrated unobtrusive feedback systems using miniature vibrators [8] that coupled with sensors in the hand, enhance closed-loop controllability and embodiment of the device in transradial amputees [9], [10].

Building on this expertise, in this work we present for the first time a simple yet potentially effective and low cost cosmetic digital prosthesis with embedded touch feedback. The motivation behind this was twofold: first, to exploit and extend the range of application of a sensory feedback paradigm which is the only one that already demonstrated to improve the controllability of closed-loop myoelectric prostheses in a non-invasive fashion [11]; second, to enhance the very primitive features and limited value of a passive digital prosthesis by including in it a compact device for tactile feedback to the individual. The feedback paradigm we exploited was based on the Discrete Event-driven Sensory feedback Control (DESC) model postulated by Johansson and Edin [12]. This model posits that motor tasks in humans are organized in phases delimited by means of sensory encoded discrete events, e.g., object contact and lift-off. The nervous system monitors such events and uses them to apply control signals and, if necessary, to initiate corrective actions that are appropriate for the task and the current phase [12]. In particular, the digital prosthesis presented in this work was designed to deliver discrete vibrotactile bursts to the stump, with respect to the object contact and release. These events are known to be highly significant for the normal grasp-and-lift control, and, as such, the feedback is expected to be naturally associated with the corresponding mechanical events, as shown in our previous studies [9], [11].

A prototype of digital prosthesis with DESC-based feedback was developed. The design proved to be compact, lightweight, low-cost, easy to manufacture and rugged enough to undergo a home study with one partial hand amputee. The newly dubbed DESC-finger was preliminary assessed by means of a modified version of the *virtual egg test*, described in our previous work [11], and an interview. Although very preliminary, the results are promising because they suggest that the device enabled the participant to improve her manual dexterity.

II. ARCHITECTURE OF A DESC-FINGER

The DESC-finger builds on our previous sensory feedback system which exploited the DESC policy [12] (i.e. the DESC-glove [11]). The DESC-finger informs the user on the completion of some grasp phases through discrete stimulations delivered synchronously with respect to touch and breaking of touch events, providing in such way a temporal information about transitions between phases (Fig. 1). To our knowledge this policy is the only one which demonstrated to enhance closed-loop controllability of myoelectric hands by trans-radial amputees, using a wearable interface [11].

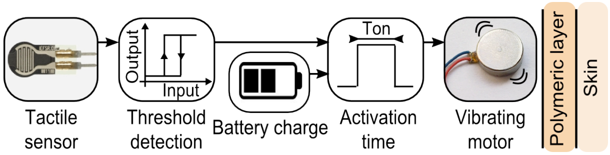

Figure 2. Block diagram of the DESC-finger. Contact events at the fingertip are detected using a tactile sensor and a threshold system, which triggers a short-lasting time-discrete (T_{ON}) vibrotactile stimulus to the skin. The vibration is mediated by the polymeric layer that embeds the device.

The DESC-finger is envisioned as a miniaturized biomechatronic device that can be integrated into a silicone rubber prosthetic finger. Indeed it includes a tactile sensor (in the fingertip), an electronic circuit for signal processing, a battery and a miniaturized vibrator close to the stump (inset in Fig. 1). The electronic circuit monitors the grip force recorded by the tactile sensor and each time it overcomes or goes below a certain threshold, activates the vibrator for a certain time (T_{ON}), according to the DESC model (Fig. 2).

III. IMPLEMENTATION OF A DESC-FINGER PROTOTYPE

A. Design of the Device

A DESC-finger prototype was developed following the architecture described in paragraph II (Fig. 1, Fig. 2). Miniaturization, robustness and autonomy were the requirements that led the design. As a fact the FSR (Force Sensing Resistor) technology was chosen for the tactile sensor: FSR sensors are inexpensive, easy to include in a design, robust and can be found off-the-shelf in a compact fashion (e.g. the model we used: the FSR 400 by Interlink Electronics Inc., Westlake Village, CA). The electronic circuit to process the FSR signal and to activate the miniature vibrator was based on analog discrete components rather than digital microcontrollers. This allowed for negligible delays between the detection of a contact event and the stimulation of the user. In addition, the power consumption of the device is minimized, thus maximizing the autonomy of the battery. For the latter we chose a 3.7 Volts, 9 mAh LiPo (Lithium Polymer) battery because it offered a good trade-off between autonomy (~ 3000 stimuli) and size (15 x 9 x 3 mm). Finally, we included in the design a coin vibrator (model 310-113 from Precision Microdrives Ltd, London, UK), i.e. a small DC motor with unbalanced mass. The latter was chosen for its dimensions (diameter: 10 mm, height: 3 mm) which were compatible for integration in a digital prosthesis.

The voltage provided by the LiPo battery (V_{BAT}) was used to drive the vibrator directly, i.e. without using a voltage regulator; this choice was dictated by dimensions, voltage levels and power constraints on the board. In particular, the circuit was designed to provide perceivable stimuli ($T_{ON} \geq 50$ ms – [11]) in the working range of the battery[1] ($3 \text{ V} \leq V_{BAT} \leq 4 \text{ V}$) and to disable the stimuli when the battery was about to deplete (i.e. $V_{BAT} \leq 3$ V – this precaution was taken to avoid activating vibrations with unpredictable features, thus unclear stimuli). In our circuit the V_{BAT} affected not only the driving

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[1] When fully charged LiPo cells with nominal voltage of 3.7 V, provide nearly 4.3 V that quickly drops to 3.7 V under normal use. When depleted, the cell is around 3 V.

voltage to the vibrator but also its activation time; in particular T_{ON} ranged between 85 ms and 50 ms when V_{BAT} ranged between 4 V and 3 V. However, even the weakest and shortest vibration was perceived more than 95% of the times (tested with ten able-bodied participants for a total of 300 stimulations).

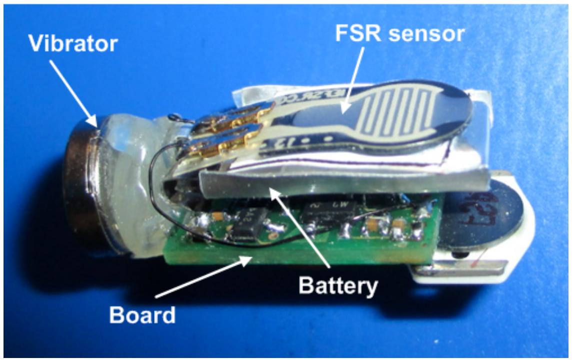

Figure 3. Internal components of a DESC-finger. Note: opposite to the FSR the black circle is the ferrite of the coil used for wireless battery charging.

The developed system exhibited a power consumption in the orders of 100 mW while vibrating, which decreased to 100 µW when not vibrating; the autonomy in idle mode was thus, theoretically, in the order of 10-15 days.

The electronic circuit included a wireless battery charging stage based on a coil and a LiPo battery charger IC (LTC4071 by Linear Technology). This allowed sealing all the components within the cosmetic finger, thus protecting the device from water, dirt and dust. The dimensions of the electronic board of the prototype were 15 x 10.5 x 4.5 mm.

B. *Integration and Manufacturing Process*

The components of the DESC-finger were assembled and embedded into a silicone rubber finger in three steps. First: the electronic board, the battery and the FSR were electrically connected and glued together forming a stack, with the FSR on the top of it (Fig. 3). Second: the stack was assembled with the coin vibrator by means of a cold cast polymer and a mold, forming a capsule made of stiff rubber (SORTA-Clear, Smooth-On Inc., shore 40A – Fig. 4a). The length of the capsule could be lengthened/shortened based on the length of the missing digit, so that the stack and the vibrator could result at the extremities of the capsule, after the polymerization. In particular, the stack was positioned in the mold so that the FSR could sense touch events on the fingertip of the final digit, whereas the vibrator was positioned close to the surface of the digit in contact with the stump. In the third and final step the capsule was included inside the cosmetic layer of a digital monochromatic prosthesis manufactured by prosthetists at the Centro Protesi INAIL, in Budrio (BO) Italy (Fig. 4b and Fig. 4c). The measured sensibility threshold of the developed DESC-finger was found to be ~500 mN.

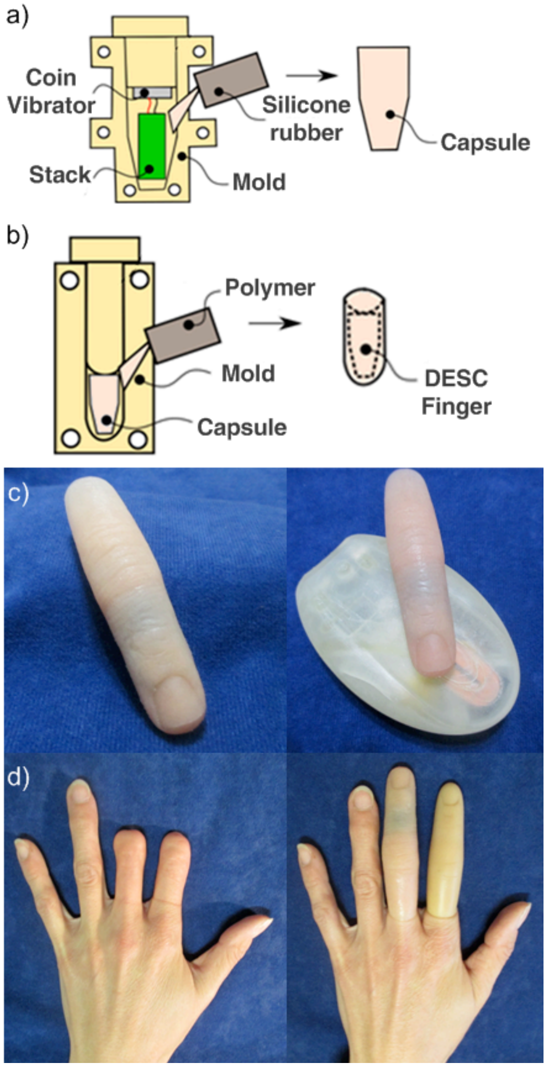

Figure 4. Manufacturing process of the DESC-finger: the stack of components are molded with silicone rubber in order to form a stiff capsule having the length customized to the missing digit (a); then, the capsule is molded with the cosmetic layer using a cast which replicates the contours of the stump and of the final digit (b). c) DESC-finger prototype and its wireless charger. d) Residual limb of and fitting of the DESC-finger to the participant involved in the home study. Note that only one DESC-finger was fitted (on the middle finger) during the experimental sessions.

C. *Assessment of the Stimulus*

An instrumented bench with a load cell was used to record the shear forces generated by the vibrator, while replicating the operational conditions of the DESC-finger. The recordings revealed that the vibrator produced stimuli with peak to peak shear forces ranging between ~45 mN and ~550 mN and frequencies ranging between ~30 Hz and ~80 Hz, as recorded by the load cell (Fig. 5). These vibrations were recorded when the vibrator was placed directly on top of the load cell; when spacers made of stiff rubber (akin to the device) were inserted in between, as the thickness of the spacers increased, the shear forces recorded from the base improved (Fig. 5).

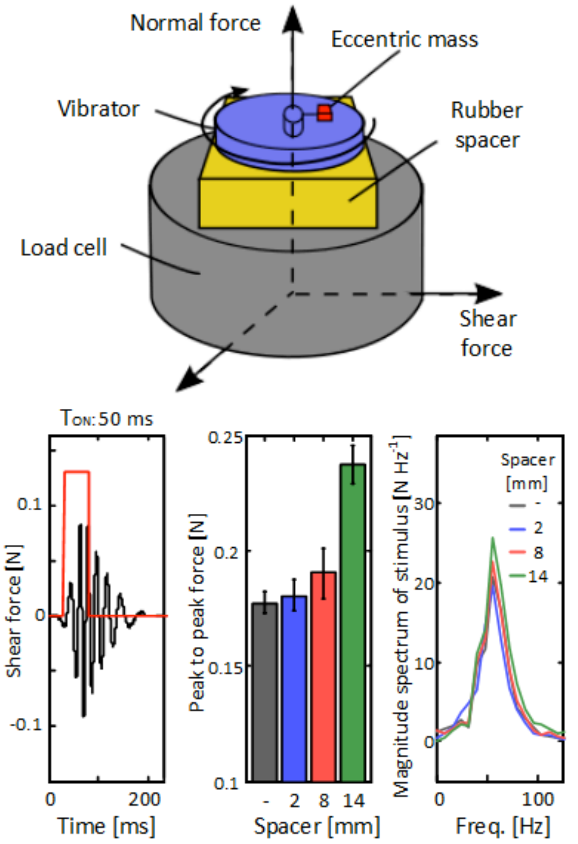

Figure 5. Top panel: vibrotactile stimuli as recorded by a ATI nano17 load cell in worst-case battery charge conditions (T_{ON} 50 ms; V_{BAT} 3V) . Bottom left panel: time-series of the stimulus (recorded with the vibrator directly mounted on the load cell). Bottom center panel: peak to peak shear force of the stimulus recorded with polymeric spacers with different thicknesses in between (2, 8, 14 mm). Bottom right panel: power spectrum of the stimulus recorded with the same spacers.

IV. EXPERIMENTAL ASSESSMENT – CASE STUDY

A. *Methods*

The DESC-finger was assessed through a case study involving one partial hand amputee (ES). ES was a 41 years old woman, who had her index and middle fingers of her left hand amputated at the intermediate phalanx, due to a work injury, twelve years before the study (Fig. 4d). Prior to this work she was fitted with two passive digital prostheses, which she wore/used at work and domestically practically at all awake hours, albeit she complained for limited sensibility of these devices. ES gave informed consent to participate in the study according to the Declaration of Helsinki.

She was provided with one DESC-finger (for her middle digit) for eight weeks; she was informed that the device delivered short lasting vibrations when grasping and releasing objects and instructed to use it normally during daily life activities (at work as well as at home) even if the feedback initially would seem useless. After four weeks ES was interviewed regarding her thoughts and experience with the new device.

After eight weeks of home use ES participated to a functional test, aimed at assessing the sensorimotor control of the hand fitted with the DESC-finger; with and without artificial feedback. The test was based on the Virtual Eggs Test (VET), recently introduced by our group to assess the integration of artificial feedback into one's sensorimotor control [11]. The VET resembles the task of picking and repositioning fragile objects (eggs). It is itself based on the well-known box and blocks test [13] with the exception that *breakable* blocks (the virtual eggs) are used instead of the standard wooden ones. The participant is instructed to transfer the virtual eggs from one side to the other of a 15 cm high wall, as fast as possible without crushing them (Fig. 6). The protocol of the VET includes multiple trials, lasting for one minute, to be tested with the different feedback conditions in randomized order. In the present case the conditions were: (i) with touch feedback (using the DESC-finger) and (ii) without feedback (using ES' own cosmetic prosthesis). The performance metrics of the test are: the number of saved and broken eggs transferred in one minute.

As the DESC-finger was fitted on ES' middle finger residual, the VET prescribed to pick and transport the virtual eggs using a thumb-middle precision grasp. This implied that ES could use her own unimpaired thumb, with intact sensibility and perfect motor control. Hence we expected that the original VET would not be sensitive enough to unveil differences between the feedback ON and the feedback OFF conditions (in other words, be too simple). For this reason, we complicated things: we set the breaking thresholds of the eggs rather low, 1.2 N, just above the minimum grip force to lift them, and we added in parallel a cognitive task. The latter aimed to distract the participant and consisted in reading a list of random different words displayed on a screen, meanwhile transporting the eggs (Fig. 6). The words were taken from a list of common Italian words but their randomization prevented that they could be simply guessed (based on the context). The number of properly and wrongly read words were counted and used as additional performance metrics.

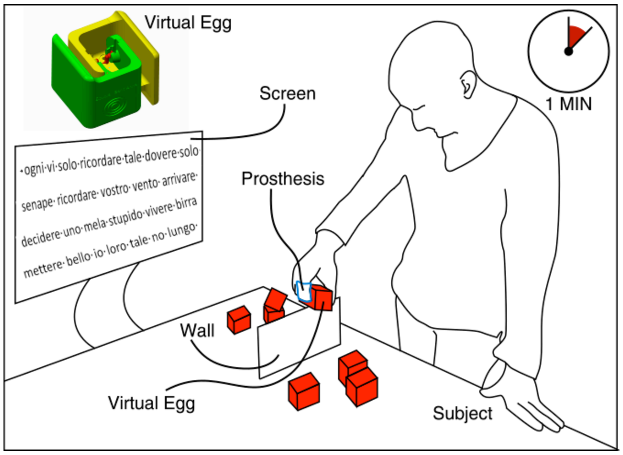

Figure 6. Experimental assessment. The participant performed a modified version of the virtual eggs test [11] using the prostheses with fragile blocks for a total of six 1-min-long trials: three with and three without the DESC-finger. Meanwhile the participant had to read (loudly) the list of random words displayed on the computer screen.

The VET plus cognitive task, was performed three times with the DESC-finger and three times with ES' own cosmetic prosthesis. In both conditions ES did not wear her index finger prosthesis. The test was video-recorded in order to assess the four performance metrics.

B. Results

After four weeks ES reported that she used the device, especially at work (she worked in a hatchery performing a manual job), five days a week and 8 hours a day. She recharged the device every other day (corresponding to a daily use of ~750 grasps). Interestingly she reported to pay less attention to her hand while grasping with the DESC-finger and for this reason it was especially useful at work (at home ES would wear a high definition cosmetic silicone prosthesis). Moreover, in agreement with our previous work ES reported that she sometimes expected vibrotactile stimuli when she wore her conventional cosmetic prosthesis [11].

The subjective opinions were confirmed by the functional VET and cognitive task (Fig. 7). The overall number of eggs transferred in the three trials was almost the same for the two conditions (difference < 3%): 115 with feedback ON; 118 with feedback OFF (Fig. 7). Overall 2 eggs were broken when the feedback was ON (1.7%) and 7 when it was OFF (5.9%). The cognitive task showed closely matching results. The number of words read was larger (210 vs. 194 – variance 8%) and with less errors (3 vs. 5) when the feedback was ON. All in all, ES: (i) transferred more intact eggs, (ii) read more words, with (iii) less errors when she used the DESC-finger, compared to when she used her cosmetic prosthesis.

Finally, ES asked to keep and use the DESC-finger after the end of the study.

V. Discussion and Conclusion

This work presents a miniature biomechatronic device that generates time-discrete vibrotactile sensory stimuli which takes inspiration from the sensorimotor control in humans and from evaluation studies, and can be embedded into cosmetic digital prostheses to provide touch-related sensory feedback to the user. Besides targeting people that already use cosmetic digits, the DESC-finger targets those that do not use them complaining for loss of sensibility [14].

The crucial feature of the DESC-based feedback is that it is quickly incorporated into one's sensorimotor control [9] and because of this, it can enhance the controllability of closed-loop systems, like myoelectric prostheses [11]. From an engineering perspective the DESC feedback is an interesting choice too because compared to other approaches that rely on continuous feedback, it stimulates the individual only at specific times, hence requires only a fraction of the energy - this is of particular relevance in battery operated devices (like prostheses) and/or when the stimulus is conveyed by electromagnetic actuators (like miniature vibrators). These were the scientific and engineering reasons that suggested us to further investigate on the potentials of the DESC approach, applied to the case of partial hand amputation. In the DESC policy the synchronization of the stimulation with regards to the event is more important than the actual modality used to stimulate (and thus the sensation generated by the stimulus); in the DESC-finger we chose mechanical vibration, a modality known to be more acceptable than other ones (e.g. electro-tactile stimuli) [15].

The durations of the stimuli produced by the DESC-finger prototype were in substantial agreement with the work by Kaaresoja and Linjama [16], which suggested that when the vibration functions as an alert (as in this case), people prefer its duration to be between 50 and 200 ms. Stimuli of longer durations are perceived as annoying; notably, the developed prototype produces vibrations which fall within this range. With regards to the amplitude, instead, the stimuli reached almost-instantaneously levels that are known to be largely above the sensation threshold (10^{-3} N [15]) and within the range of perceivable frequencies. It is worth noting that the electronic design of the DESC-finger allows easy tuning of the stimulation parameters, in order to match the sensibility of individuals, in particular, those with tactile hyper- or hypo-sensibility of the stump.

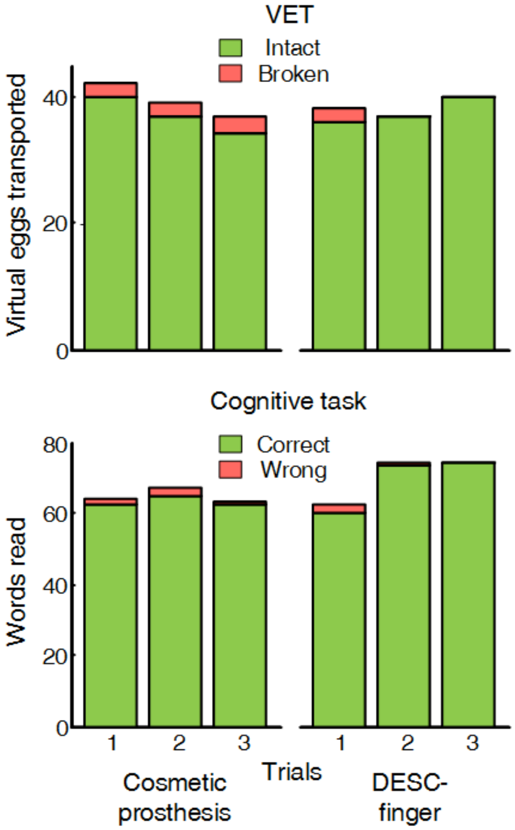

Figure 7. Functional test results. Overall, when wearing the DESC-finger (right panels) the participant transferred more intact eggs, properly read more words and made less errors, compared to when she used her cosmetic prosthesis.

DESC-fingers are prosthetic digits with enhanced functions with respect to trivial cosmetic replacements. Not only, as the prototype is based on commercially available components and since it can be manufactured using prosthetists' techniques [17], the whole system is a truly low-cost device and holds the potential to be exploited not only in high-income countries but also in poorer ones. In addition, the wireless recharging stage makes the design waterproof, thus robust against real-life working conditions. Finally, the system is flexible: the capsule containing the core components could be embedded inside any passive partial hand prosthesis including high-definition silicone digits, children-sized digits or even inside complete cosmetic hand prostheses. The latter possibility is rather intriguing as it would implement –for the first time– the idea proposed back in 1953 by Conzelman and colleagues of a prosthetic device sensory attachment [18].

The positive results from the home study with one partial hand amputee strengthened the idea that the DESC-finger is clinically viable. The comment that the DESC-finger increased ES' confidence in her prosthesis was not given for granted before this study. Indeed, depending on the injury, partial hand amputees maintain one or more intact digits with unimpaired sensory functions (exactly like ES), and in addition, the forces generated on the prosthesis are per se partially transferred to the stump trough the prosthesis. These two aspects made us uncertain whether the redundant vibrotactile feedback would provide usable information to the individual or not.

Instead, the ability of the subject in transferring more intact eggs and making less reading errors show that the subject learned how to get advantage of the redundant DESC feedback during activities of daily living, and was able to transfer this ability to a specific task, viz., the VET plus cognitive task. This corroborates the DESC policy, as it shows that humans rely on temporally correlated sensory information that signifies the completion of sub-tasks, regardless of the stimulation modality. Indeed, even if natural sensory information was partially available (both from the healthy thumb and the stump), the subject relied on the vibrotactile artificial feedback. We argue that this was possible because the artificial feedback, being synchronous with salient events of the motor tasks, reinforced the partial kinesthetic feedback and the visual input.

Although still preliminary, these results suggest that the DESC-based feedback provides additional information that can be promptly integrated into one's sensorimotor control even in the case of partial hand amputations. However, it still remains to be shown whether the DESC-finger can improve functional performance during use. Hence, this work paves the way for a larger clinical study of the DESC-finger and for other studies in which inexpensive, non-invasive technology is used to provide physiologically appropriate sensory feedback in upper limb cosmetic prostheses.

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REFERENCES

[1] A. M. Giladi and K. C. Chung, "Surgical Principles and perspectives on upper extremity amputations," in *Prosthetic Restoration and Rehabilitation of the Upper and Lower Extremity*, 2013, pp. 127.

[2] N. Gavrilova, A. Harijan, S. Schiro, C. S. Hultman and C. Lee, "Patterns of finger amputation and replantation in the setting of a rapidly growing immigrant population.," *Ann. Plast. Surg.*, vol. 64, no. 5, pp. 534–536, 2010.

[3] I. Imbinto, C. Peccia, M. Controzzi, A. G. Cutti, A. Davalli, R. Sacchetti and C. Cipriani, "Treatment of the partial hand amputation: an engineering perspective," *IEEE Rev. Biomed.l Eng.*, vol. 9, pp. 32-48, 2016.

[4] J. E. Uellendahl, and E. N. Uellendahl, "Experience fitting partial hand prostheses with externally powered fingers." in: *Grasping the Future: Advances in Powered Upper Limb Prosthetics*, 2012, pp. 15–27.

[5] D. W. Tan, M. A. Schiefer, M. W. Keith, J. R. Anderson, J. Tyler and D. J. Tyler, "A neural interface provides long-term stable natural touch perception.," *Sci. Transl. Med.*, vol. 6, no. 257, 2014.

[6] S. Raspopovic, M. Capogrosso, F. Petrini, M. Bonizzato, J. Rigosa, G. Di Pino, J. Carpaneto, M. Controzzi, T. Boretius, E. Fernandez, G. Granata, C. M. Oddo, L. Citi, A. L. Ciancio, C. Cipriani, M. C. Carrozza, W. Jensen, E. Guglielmelli, T. Stieglitz, P. M. Rossini and S. Micera. "Restoring natural sensory feedback in real-time bidirectional hand prostheses," *Sci. Transl. Med.* vol. 6, no. 222, pp. 222ra19, 2014.

[7] C. Dietrich, K. Walter-Walsh, S. Preißler, G. O. Hofmann, O. W. Witte, W. H. Miltner and T. Weiss, "Sensory feedback prosthesis reduces phantom limb pain: proof of a principle.," *Neurosci. Lett.*, vol. 507, no. 2, pp. 97–100, 2012.

[8] C. Cipriani, M. D'Alonzo and M. C. Carrozza, "A miniature vibrotactile sensory substitution device for multi-fingered hand prosthetics," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 2, pp. 400–408, 2012.

[9] C. Cipriani, J. Segil, F. Clemente, R. Weir and B. Edin, "Humans can integrate feedback of discrete events in their sensorimotor control of a robotic hand," Exp. Brain Res., vol. 232, no. 11, pp. 3421–3429, 2014.

[10] M. D'Alonzo, F. Clemente and C. Cipriani, "Vibrotactile sensory substitution elicits feeling of ownership in transradial amputees," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 23, no. 3, pp. 450–457, 2015.

[11] F. Clemente, M. D'Alonzo, M. Controzzi, B. B. Edin and C. Cipriani, "Non-invasive, temporally discrete feedback of object contact and release improves grasp control of closed-loop myoelectric transradial prostheses,". *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 12, pp. 1314–1322, 2016.

[12] R. S. Johansson and B. B. Edin, "Predictive feed-forward sensory control during grasping and manipulation in man," *Biomed. Res.,* vol. 14, no. 4, pp. 95-106, 1993.

[13] V. Mathiowetz, G. Volland, N. Kashman, and K.Weber, "Adult norms for the Box and Block Test of manual dexterity," *Am J Occup Ther*, vol. 39(3160243), pp. 386-391, 1985.

[14] E. Biddiss, D. Beaton and T. Chau, "Consumer design priorities for upper limb prosthetics," *Disabil. Rehabil. Assist. Technol.*, vol. 2, no. 6, pp. 346- 357, 2007.

[15] K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita, and W. J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems,", *IEEE Trans Biomed Eng*, vol. 38, pp. 1-16, 1991.

[16] T. Kaaresoja, and J. Linjama, "Perception of short tactile pulses generated by a vibration motor in a mobile phone," in *Proc.WHC*, 2005, pp. 471–472.

[17] C. Lake, "Partial Hand Amputation : Prosthetic Management." In *Atlas of Amputations and Limb Deficiencies: Surgical Prosthetics And Rehabilitation Principles*, pp. 209–218, 2004.

[18] J. E. Conzelman, H. B. Ellis, and C. W. O'Brien. "Prosthetic Device Sensory Attachment" U.S. Patent 2,656,545, 1953.