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Adding vibrotactile feedback to a myoelectric-controlled hand improves performance when online visual feedback is disturbed

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ABSTRACT

We investigated whether adding vibrotactile feedback to a myoelectric-controlled hand, when visual feedback is disturbed, can improve performance during a functional test. For this purpose, able-bodied subjects, activating a myoelectric-controlled hand attached to their right hand performed the modified Box & Blocks test, grasping and manipulating wooden blocks over a partition. This was performed in 3 conditions, using a repeated-measures design: in full light, in a dark room where visual feedback was disturbed and no auditory feedback – one time with the addition of tactile feedback provided during object grasping and manipulation, and one time without any tactile feedback. The average time needed to transfer one block was measured, and an infrared camera was used to give information on the number of grasping errors during performance of the test. Our results show that when vibrotactile feedback was provided, performance time was reduced significantly, compared with when no vibrotactile feedback was available. Furthermore, the accuracy of grasping and manipulation was improved, reflected by significantly fewer errors during test performance. In conclusion, adding vibrotactile feedback to a myoelectric-controlled hand has positive effects on functional performance when visual feedback is disturbed. This may have applications to current myoelectric-controlled hands, as adding tactile feedback may help prosthesis users to improve their functional ability during daily life activities in different environments, particularly when limited visual feedback is available or desirable.

1. Introduction

1.1. Use of feedback resources during grasping

Grasping and manipulating an object, as simple as it may seem, requires a complicated motor control process, using visual, proprioceptive, and tactile feedback mechanisms (Flanagan, Merritt, & Johansson, 2009). Visual and proprioceptive feedback are used to guide the hand to the chosen position and to determine the correct distance to the object. When the hand is grasping the object, tactile feedback provides information about the shape, texture and size of the object. In this way, a successful performance of grasping or manipulating of an object can be achieved (Flanagan, Bowman, & Johansson, 2006).

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1.2. Lack of tactile feedback when using an artificial hand

In chronic deafferentation, when no tactile feedback is possible, deficits are observed in performance despite full vision of the object (Hermsdörfer, Elias, Cole, Quaney, & Nowak, 2008). Following limb loss, amputees may use myoelectric prosthesis, in which the artificial hand is activated by signals from the muscles of the residual limb. This is done by recording electrical activity (surface EMG) via two electrodes placed on the muscles of the forearm. When the prosthesis user contracts his or her muscles, the electric signal generated by the muscles is detected by the electrodes, and translated into a hand movement, e.g. opening or closing the prosthetic hand (Farina & Amsüss, 2016). Using these state-of-the art devices for functional grasping tasks may be a complex task. Since the prosthesis is controlled by contracting the residual muscles in order to activate different hand movements, this non-natural hand control is not trivial (Fougner, Stavdahl, Kyberd, Losier, & Parker, 2012).

Another difficulty in using myoelectric prostheses arises from the lack of tactile feedback from the artificial hand. Since tactile feedback is missing, the prosthesis user has to compensate using his or her visual feedback resources during performance of functional tasks (Cordella et al., 2016). A study that examined the correlation between functional performance and visual attention found that prosthesis users who were less successful in functional task performance tended to allocate their visual attention to their artificial hand (Bouwsema, Kyberd, Hill, van der Sluis, & Bongers, 2012). In a recently published study, Parr and colleagues analyzed the gaze behavior during the functional task of picking coins. They found that when using the prosthesis simulator, subjects focused significantly more on their hand, and their task performance time was prolonged (Parr, Harrison, Vine, & Wood, 2017). These results suggest that when using a prosthesis, the natural mechanism of eye-hand coordination during task performance is affected, so that visual feedback is used more prominently. Therefore, performance of simple tasks using a myoelectric-controlled hand, which does not provide tactile feedback, can be highly challenging for the common user (Wijk & Carlsson, 2015). This may be even more relevant to users with poor daily performance, where visual feedback is used as the main resource to provide data about the grasped object.

1.3. Grasping when visual feedback is disturbed

Due to the loss of tactile feedback following a limb loss, when encountering different scenarios in real life, where visual feedback is disturbed, prosthesis users may face a challenge not faced by other individuals. For example, they can be required to perform a dual task, where they need to divide their visual attention between both hands, e.g. holding a coffee cup while reading a paper. Since tactile feedback is missing from the artificial hand, this is not a trivial functional task. In order to evaluate the relationship between tactile feedback and visual attention levels during functional tasks, we have recently examined the effects of adding vibrotactile feedback (VTF) to a myoelectric-controlled hand on visual attention and performance in a dual-task paradigm (Raveh, Friedman, & Portnoy, 2017). In our study, the subjects were required to perform a functional task with the artificial hand, while controlling a video game with the other hand, repeated in two conditions: with and without VTF. However, no significant differences between the two conditions were found. These results could be attributed to the complexity of the dual-task scenario, making it difficult to assess the actual effect of tactile feedback on task performance.

In order to examine this effect from a different perspective, we examined the role of tactile feedback when visual feedback is disturbed. In this scenario, prosthesis users have to utilize their prosthetic hand in a dark environment, where they cannot rely on their visual resources. This may happen when they try to turn the light on in a dark staircase corridor, when they search for their keys in a bag, or in any other case where visual feedback is not available. In these cases, tactile feedback plays an essential role during grasping, and its lack is significant for the prosthesis user (Cordella et al., 2016). A recent study assessed daily prosthesis usage using wireless activity monitors, and found that the prosthesis users barely used the artificial hand during the evening times (Chadwell et al., 2017). This could be explained due to the additive challenge of using a prosthesis in nighttime, when there is less visual feedback, increasing the risk for dropping objects. Although prosthesis users are unlikely to use their artificial hand in the dark, it is important to examine the performance in a surrounding where visual feedback is limited or disturbed, in order to have more knowledge of the actual role of tactile feedback in the grasping process.

1.4. Disturbing visual feedback

Several studies used different methods to disturb visual feedback in order to evaluate the effects of adding tactile feedback to prosthesis users. One method is to cover the objects with dark material, so that the subjects cannot see the hand and its movements. Using this method with healthy subjects fitted with a robotic hand in a grasping task and tactile feedback, researchers showed that performance was improved (Saunders & Vijayakumar, 2011). Another method is to use a blindfold, so that the subject cannot see the object at all. This method was used in a novel case study with implanted tactile feedback, in order to examine if he could identify the stiffness and shape of three different objects by exploiting their different characteristics (Raspopovic et al., 2014).

1.5. Assessment of performance during grasping

All the aforementioned studies examined the effects of the addition of tactile feedback on performance time. Nevertheless, improvement in performance does not relate only to reduced performance time, but also to having the task performed in an accurate manner. Both time and accuracy are two important aspects of performance, and their assessment was widely studied (Latash & Fundamentals of Motor Control, 2012). In a review on using sensory feedback in upper limb prosthetics, the possible mechanism in which VTF has positive effects on the grasping of prosthesis users is working through a better control of grip force, and by lowering the number of errors during task performance (Antfolk et al., 2013). In our study, we aimed to examine not only performance time, but also the accuracy during grasping and manipulation, in which tactile feedback plays an important role (Bingham & Mon-Williams, 2013). Since performance of a grasping task is highly challenging with no vision at all, we occluded the vision only during the execution stage, so we could be able to see the actual role of the tactile feedback in the grasping phase. We therefore used a dark room, where visual feedback of the object is available to the subjects from a small LED light only for a very short time period, before the actual grasping of the objects. In that way, the subjects could not rely on the visual feedback during the actual grasping process, and were forced to use the provided tactile feedback. Despite the advances in recent research in this emerging field of myoelectric prostheses, the examination of tactile feedback in a functional task, performed with actual objects when visual feedback is disturbed, has not been fully explored yet. In addition, we used a myoelectric-controlled prosthetic simulator, mounted on the subject's hand, as presented in several studies (Bouwsema et al., 2012; Parr et al., 2017). Other studies used a virtual hand, presented on a screen and controlled by the myoelectric signals. Since we aimed to examine the addition of VTF when using a hand prosthesis, an actual prosthesis can better simulate the use of a myoelectric prosthesis for grasping. Furthermore, only few studies have used these simulators in combination with tactile feedback, rather they were used as a tool to demonstrate myoelectric control of an artificial hand in able-bodied subjects.

If the addition of tactile feedback is found to have a positive effects on successful performance when visual feedback is lacking, it may be an important addition to the current knowledge in this field, and a step towards future implementation of tactile feedback in artificial hands, which may encourage the amputee to use his or her prosthesis daily for more hours per day, even when visual feedback is reduced, e.g. at night. Furthermore, positive effects of adding tactile feedback may add to the accumulating literature on this topic, so that future developments may consider the transfer of sensory data in both non-invasive and invasive manners, along with the efforts to improve muscle activation of artificial hands. Therefore, the aim of this study was to evaluate the effects of using VTF on performance of a functional test, while using a myoelectric-controlled artificial hand when visual feedback is disturbed. We expected that the addition of VTF would improve performance when performing tasks without online visual feedback.

2. Methods

2.1. Participants

We calculated the sample size for the repeated measures design using MorePower software version 6.0.1 (Campbell & Thompson, 2012). A preliminary experiment with 5 subjects showed that the standard deviation of our primary outcome measure, the performance time of the modified Box & Blocks test, was 20% of the mean performance time. If the expected difference in the performance time between the trials with and without feedback is 10%, then the calculated sample size is 15 subjects with power of 80% and $\alpha = 0.05$. Twenty healthy subjects were recruited for the study. The data of 4 subjects were discarded due to technical issues (software problems and temporary malfunction of video camera). Inclusion criteria were right-handed individuals with normal or corrected eyesight. Exclusion criteria were orthopedic or neurologic problems. Overall, data collected from 16 subjects were analyzed (8 males and 8 females, mean and standard deviation age of 28.2 ± 9.9). The study was approved by the Institutional Helsinki committee (HMO-0099-16), and was registered at the U.S. National Institutes of Health website (Trial No. NCT02749643). All subjects read and signed an informed consent form pretrial.

2.2. Instrumentation

A myoelectric-controlled artificial hand was attached at the distal end of an off-the-shelf hand brace with Velcro straps (Manu Immobil Long 50P11, Ottobock, Germany) with the wrist and fingers of the right hand constrained in a functional position (wrist at 30° extension proximal interphalangeal joints at 50° flexion). Electromyographic (EMG) signals were recorded telemetrically from the forearm muscles, targeted to the Flexor Carpi Radialis and Extensor Carpi Radialis Longus muscles at 1500 Hz (Myon Radio Frequency Transmitting Devices (RFTD), Myon, Switzerland) using surface bipolar Ag/AgCl electrodes (Ambu Blue Sensor N electrodes, Ambu A/S, Denmark. The activation of each of the aforementioned muscles at a predefined threshold opened or closed a plastic artificial hand (Standard Gripper Kit B, Actobotics, USA) in real-time, similar to the configuration of a myoelectric prosthesis. Data from the EMG electrodes were band pass filtered (Butterworth 4th order, 5–500 Hz) and rectified. Once the electrodes were attached to the two muscles, baseline recordings of the EMG data were performed while the subject was ask to initiate light activation of the wrist flexors for 5 s and then light activation of the wrist extensors for 5 s, while the arm rested on the table in mid-position (0° supination-pronation). Then the subject began practicing in opening and closing the robotic hand, as the default cutoff value for activation of either action was when the EMG signal surpassed 55% of the maximal value recorded at baseline. This value was found to provide good control over the robotic hand in initial trials. The researcher manually adjusted the percentage separately for each action (close or open) in cases where the hand was operated without intent or did not operate when the user tried to activate it. This user-specific adjustment took place in the first couple of minutes of training. The robotic hand responded to a signal from the EMG electrodes if its duration was above 150 ms (set empirically). Two pairs of thin force sensors (Flexiforce, Tekscan Inc., USA) were attached to the two inner sides of the myoelectric-controlled artificial hand, i.e. to provide feedback on grip force. An elastic strap containing eight vibrotactile actuators (Shaftless vibration motor, Pololu, USA) in its interior was wrapped around the right arm above the elbow (See Fig. 1). The vibrotactile actuators were powered by a 3 V power supply and were activated at the maximum amplitude when the applied force was above a predetermined threshold level. The force from all force sensors was summed up, and a recording was performed where the force sensors were attached to the robotic hand, but with no external force applied. A sum force

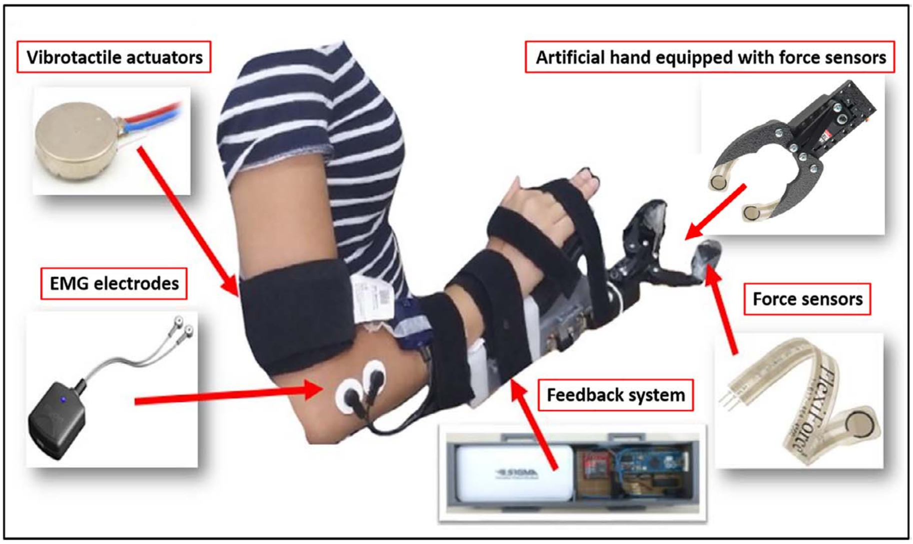

Fig. 1. Myoelectric-controlled hand with vibrotactile feedback system. The signals of the forearm muscles are captured by the EMG Electrodes (lower left), in order to open/close the artificial hand, which has force sensors attached to its inner sides (upper right). When the hand is in contact with an object, the force sensors (lower right) provide vibration to the upper arm via the vibrotactile actuators inside the cuff (upper left). The feedback is operated and controlled through the feedback system (lower middle).

of up to approximately 15.2 N was read, possibly resulting from some force applied to the sensors by the tape, attaching them to the hand. Then high force was applied to the sensors using manual force and the sum force reached approximately 117.6 N. We therefore set the threshold levels as follows: below 17.6 N from the 4 force sensors – no activation of the vibration motors, between 17.6 N and 41.2 N – activation of one pair of vibration motors, between 41.2 N and 70.6 N – activation of two pairs of vibration motors, between 70.6 N and 100 N – activation of three pairs of vibration motors, above 100 N – activation of all four pairs of vibration. The vibrotactile actuators we used in our study were previously used in several studies (Witteveen, de Rond, Rietman, & Veltink, 2012; Witteveen, Rietman, & Veltink, 2015). The overall performance for vibrotactile frequency discrimination was found to be similar for either hairy or glabrous skin, except when frequency is at the range of 50 Hz (Mahns, Perkins, Sahai, Robinson, & Rowe, 2006). Since the vibration frequency we used in our study was 233 Hz, we did not find it relevant to measure the resolution of skin discrimination (based on the manufacturer's specification of 14,000 rpm). When placing the vibrotactile actuators, we took care to allow good contact to the skin, and avoiding scars, in order to maximize immediate and easy detection of vibration by the subject. It should be noted that we did not focus on investigating the changes in VTF levels according to applied force, but rather on a binary distinction indicating whether the subject is holding the object or not. The feedback system (shown in the lower middle part of Fig. 1) was comprised of an Arduino-based controller unit (Arduino Holding, Genova, Italy), which received input from the aforementioned force sensors and activated the vibrotactile actuators accordingly. The controller unit was programmed using C code, such that the vibration actuators were activated at the maximum amplitude when the applied force was above a predetermined threshold level. The current supply was available through a small rechargeable battery, with average power consumption of 320 mA (Sigma Systems, Taiwan). The whole system was inserted to a small custom-made plastic box (size 17.4 × 4.4 × 2.6 cm). The total weight of the system was 30*g*, and it was attached under the subjects' forearm using Velcro straps. The myoelectric-controlled hand with vibrotactile feedback system is shown in Fig. 1.

2.3. Experimental setup

In order to evaluate the effects of adding vibrotactile feedback on functional performance we used the modified Box & Blocks test, which has been previously used in prosthetic hand research (Hebert & Lewicke, 2012). We chose to use the modified Box & Blocks test due to its simple character, allowing the subjects to transfer only 16 blocks in a certain order from certain places. Several studies have shown that simplifying the task to fewer block movements does not result in a loss of valid information on performance (Hebert, Lewicke, Williams, & Vette, 2014 Edwards et al., 2016, Cheng et al., 2016).

The subjects stood in front of a table, and were instructed to use the myoelectric-controlled hand to transfer 16 blocks over the wooden partition in the following order: starting with the lateral upper-corner block, going across row to most medial block, and then down to next row from outside block in. In that way, the task was to be completed as per the procedure outlined in the original aforementioned study design (Hebert & Lewicke, 2012). In order to prevent auditory feedback of a dropped block, the surface of the box was padded, and the subjects wore circumaural earphones. This was ensured by testing whether the subject responded to a spoken instruction. In order to measure and record the time for each transfer and the total performance time of the test, a micro-controller-based timer device (DCcduino UNO, DCc Electronics, China) with an LED light and an activation button was placed over the box in front of the subjects. The subjects stood naturally, with their left hand placed by this button, so that the pressing of the

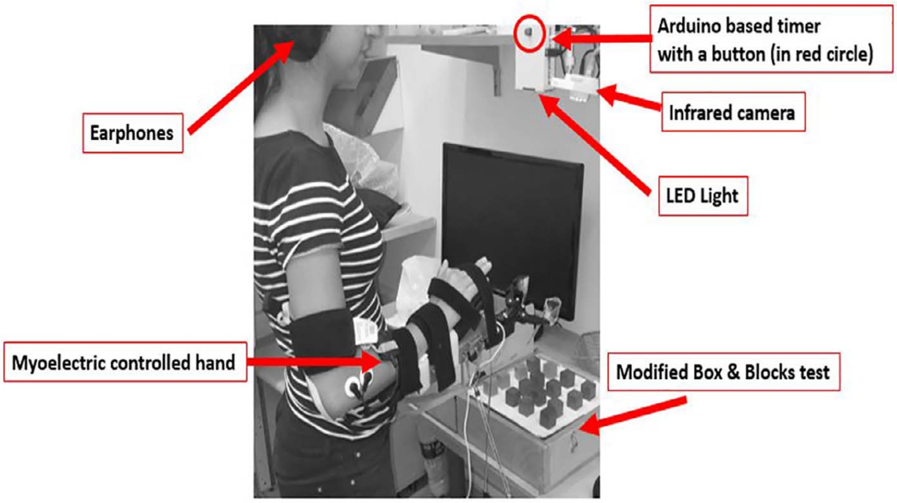

Fig. 2. Experimental setup. The subject uses the myoelectric-controlled hand to transfer 16 blocks of the modified Box & Blocks test over the partition. Following each transfer, the button of an Arduino-based timer is pressed in order to shortly activate the LED light and measure the transfer time. An infrared camera placed over the test box records the hand movements during block manipulation. The visual feedback is disturbed by darkening the room. Earphones are used to prevent auditory feedback.

button would not affect performance speed. In that way, after moving each block, they could instantly press the button and activate a timer based software measuring the transfer time of each block, as well as an LED light for 500 ms. This time was set following trial and error in order to have a visual glimpse of the block location, but to keep the grasping and manipulation in the darkness. Specifically, the duration of the light was sufficiently fast such that it did not enable visual feedback on the success of grasping the block. The experimenter confirmed that the subjects pressed the button before moving the first block, so that the timer was activated. Finally, an infrared camera (IR Fixed Lens Camera F-717, Provision-ISR, The Netherlands) was placed above the box, in order to record videos of the performance of the test. This test was performed three times: in full light with no tactile feedback, in a dark room with the VTF activated and finally in a dark room without VTF (the feedback system was disconnected). The room was in total darkness, with the only available light from the LED activated during the trial. The subjects had a 5-min rest between each condition. All the subjects started with a short 10-min training in full light, in order to acquire control of the myoelectric-controlled hand. This short training included a practice of holding and manipulating a block, in which the subjects were instructed to transfer all the blocks in an ordered manner. We did see significant learning during the first few minutes as subjects became familiar with the apparatus. After this time, we performed the full-vision condition (after the learning has assumedly reached a plateau), in order to act as a control for the other two conditions. In order to prevent bias of learning the task, the study was performed in a repeated-measures design with a counter-balanced order of the two remaining conditions (with and without VTF), so that the subjects started the trial either with feedback or without feedback. The experimental setup is presented in Fig. 2.

2.4. Data processing

Functional performance was quantified by two measures: (a) time, i.e. the mean time to move each block, as measured by the timer activated by pressing the button; and (b) accuracy, i.e. the number of grasping errors during the test, calculated by analyzing the videos taken with the infrared camera. Two grasping errors were counted during the grasping phase of the object: number of block drops from the artificial hand and number of empty grips. In addition, we also measured the number of ‘empty transitions’, when the subject thinks he has a block in his artificial hand and then moves his hand over the partition with no block. The number of empty transitions is less than the sum of the number of empty grips and the number of block drops because the subjects could try again to pick up the block before moving their hand over the partition.

2.5. Statistics

We used SPSS (Version 21, IBM, USA) for the statistical analyses. The Shapiro-Wilk test was used to assess the normality of distribution of continuous variables, and showed that all outcome measures were not normally distributed. We used the Mann-Whitney *U* test to examine the counter-balanced order of with and without feedback, in order to compare the outcome measures between the three trials, we used the Friedman test for 3-related samples analysis. If significant differences were found, we then used Wilcoxon signed-rank tests for post hoc analysis, in order to determine which pairs are different. Results were considered statistically significant if $p < 0.05$.

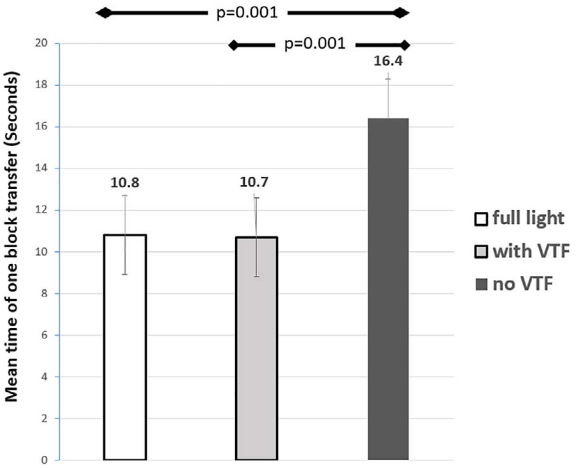

Fig. 3. Mean Performance time (seconds) of transferring one block on Modified Box & Blocks in full light and when visual feedback is disturbed - with and without vibrotactile feedback (VTF). When VTF was available, the mean time to transfer each block was significantly lower than when VTF was not available (p = .001). The mean time to transfer each block when VTF was available was similar to when the test was performed in full light.

3. Results

The results of the Mann-Whitney *U* test showed no significant difference between the outcome measures of the subjects who began the trial with the VTF activated compared to the subjects who began with the VTF off. This means that there was no learning effect while repeating the trial.

The time to transfer each block (seconds) for all three conditions is presented in Fig. 3. The number of times the block dropped from the artificial hand during grasping, the number of grips with no block in it, and the number of times the subjects moved their hand over the partition with no block in it, for all three conditions, are presented in Fig. 4.

We found a significant difference in performance time and grasping errors between the trials when VTF was available compared to when it was not. When visual feedback was disturbed but VTF was available, the subjects performed the test faster and made fewer errors than when there was no feedback at all. There was a significant difference in the mean time for block transfer between the three conditions ($\chi2$ (2) = 16.93, p < .001). Post-hoc tests showed that the mean time for block transfer with both full light (10.8 ± 0.9 s) and with VTF (10.7 ± 0.8 s) was significantly faster than without VTF (16.4 ± 1.5 s) (full light: z = -3.2, p = .001;

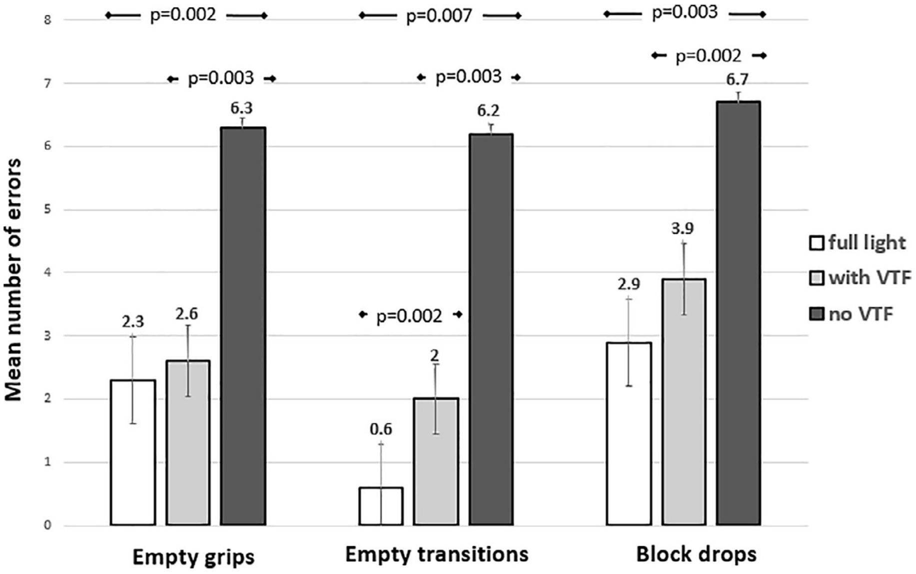

Fig. 4. Mean number of errors in grasping and manipulation during modified Box & Blocks test with versus without vibrotactile feedback (VTF). When VTF was available, the number of grasping and manipulation errors was significantly lower than when VTF was not available. This was presented in all error types: A lower number of empty grips (left), less times the subjects moved the hand over the partition with no block (middle), and reduced number of times a block fell out of the hand (right). A significant reduction of empty transitions was found in full light and when visual feedback is disturbed – with and without VTF (middle). When no VTF was available, the number of all error types was significantly higher than with full light.

VTF: z = −3.4, p = .001). The difference between full light and VTF was not significant. In addition, we found significant differences in number of errors during grasping and manipulation. The mean number of empty grips was found to be significantly different between the three conditions ($\chi2$ (2) = 17.783, p < .001). Post-hoc tests showed that the mean number of empty grips with both full light (2.3 ± 0.3) and with VTF (2.6 ± 0.4) was significantly lower than without VTF (6.3 ± 0.6) (full light: z = -3.07, p = .002; VTF: z = -2.9, p = .003). Furthermore, the mean number of empty transitions was significantly different between the conditions of the study ($\chi2$ (2) =22.136, p < .001). Post-hoc tests showed that the mean number of false transitions with no block in the hand, with both full light (0.62 ± 0.2) and with VTF (2 ± 0.3) was significantly lower than without VTF (6.2 ± 1.3) (full light: z = -2.7, p = .007; VTF: z = -2.9, p = .003). There was also a significant lower number of empty transitions between when VTF was available and full light (z = -3.07, p = .002). Finally, there was a significant difference in the mean number of times a block was dropped between the three conditions ($\chi2$ (2) = 18.13, p < .001). Post-hoc tests showed that the mean number of times a block dropped from the hand with both full light (3.9 ± 0.7) and with VTF (2.9 ± 0.4) was significantly lower than without VTF (6.7 ± 0.4) (full light: z = −2.98, p = 0.003; VTF: z = -3.08, p = 0.002). The difference between full light and VTF was not significant.

4. Discussion

In our study, we tested the effects of adding VTF to a myoelectric-controlled hand on functional performance. Our main finding is that when visual feedback is disturbed, the addition of VTF improves the performance time of a functional test, and reduces the number of errors during object grasping and manipulation.

In a recent review on different methods for providing sensory feedback to upper limb prosthesis users (Antfolk et al., 2013), VTF is said to enable the user with better task execution and a lower number of errors compared to using a regular prosthetic hand with no tactile feedback. Several studies, exploring the effects of adding VTF during grasping and release of an object, on both able-bodied subjects and transradial amputees have shown that performance was improved (Cipriani, Segil, Clemente, & ff Weir R. F. & Edin B, 2014; Clemente, D'Alonzo, Controzzi, Edin, & Cipriani, 2015). Our results are consistent with these findings, and show that adding VTF to a myoelectric-controlled artificial hand improves performance time of a functional grasping task, despite the lack of visual feedback (Fig. 3). This demonstrates that adding VTF can potentially allow prosthesis users to obtain a comparable level of performance when they are, or are not, have online visual feedback from the object being manipulated. This improvement in performance can allow the users a greater ability to perform multiple actions simultaneously, for example, to lift a cup while reading a book, or to perform in an environment with reduced visual feedback.

Our findings showed that the accuracy of grasping was improved when VTF was available to subjects, as the number of different errors, e.g. the number of block drops off the artificial hand, grips with no block, and hand movements over the partition with no block, was significantly lower (Fig. 4). As discussed, a simple grasping task may present a cognitive burden due to the increased demand from visual feedback. In a study examining the effect of tactile feedback on cognitive load, laparoscopic surgeons performed a virtual surgery with an additional cognitive task, with and without tactile feedback. It was found that when tactile feedback was available, the accuracy and speed of the surgical task were improved. This was explained by the larger cognitive capacity available to the surgeon with the addition of tactile feedback (Zhou, Jones, Schwaitzberg, & Cao, 2007). Our results support this finding, as when our subjects were provided with VTF, they could grasp in a more accurate and effective way, without the need to compensate with vision.

It should be noted that the number of empty transitions is lower than the sum of the number of empty grips and block drops (Fig. 4). If the grip is empty, or the block drops before reaching the partition, then the transition will necessarily be empty. There are multiple possible reasons that may contribute to the lower number of empty transitions. First, when feedback was available (visual or VTF), the subjects could re-grasp the object and thus avoid the empty transition. When no visual, auditory or tactile feedback was available (i.e. in the no VTF condition), the subjects may have used other forms of feedback available, including proprioception by noting incompatible arm postures, sensing a change (or lack of increase) in weight, or by visually observing the grasp failures (while the room was darkened as much as possible, a very small amount of ambient light may have been present).

Some innovative points were presented in our study, which we suggest future studies should implement in this developing field of prosthetic research. When evaluating functional performance, it is important to use actual objects in real life, rather than in a virtual environment, as formerly presented in several studies (Stepp, Chang, Malhotra, & Matsuoka, 2011, Walker, Blank, Shewokis, & O'Malley, 2015). When comparing grasping of virtual objects with that of real object, Cuijpers and colleagues showed that they are grasped substantially different, especially in the presence of tactile feedback. They even wondered whether research involving virtual objects could be generalized to grasping objects in real life, since it cannot simulate the real-life nature of functional grasping (Cuijpers, Brenner, & Smeets, 2008). Therefore, in our study we used a real-life functional test, with wooden blocks that are actually grasped and manipulated.

The effects of adding VTF to an artificial hand was explored in our study in a dark surrounding. Our findings suggest that when VTF is added and visual feedback is disturbed, the performance is similar to a full light surrounding (Fig. 3). As discussed, in a previous study we investigated the effects of adding VTF to an artificial hand in a dual-task environment, where the subjects had to allocate their visual attention to a video game, during performance of functional tasks (Raveh et al., 2017). Since during daily life functional tasks are performed in different situations, future research should focus on adding VTF to myoelectric prosthesis users during different setups, e.g. dual-task assignments and different methods to disturb visual feedback resources.

Finally, our study used a portable non-invasive VTF system, easily attached to a myoelectric-controlled hand, which showed positive effects on performance and accuracy during grasping. If the prosthetic industry is to develop similar VTF systems for daily functional use of prosthesis users, a simple and robust design is needed. Such systems will also be useful when the force requirements are stricter and visual feedback is disturbed, as presented in some studies where subjects were required to move "virtual eggs", i.e. fragile objects without crushing them (Clement et al., 2015, Fallahian, Saeedi, Mokhtarinia, & Tabatabai Ghomshe 2017). If portable tactile feedback systems will become available, future studies may aim to explore the effects of using tactile feedback as a substitution for other lost features following upper limb amputation, e.g. loss of temperature sensation and loss of dexterity.

4.1. Limitations

The main limitation of our study is its healthy population. Results may differ when repeating this study setup for prosthesis users. However, since the activation of the myoelectric-controlled hand we have used in our study is identical to current myoelectric prostheses, our results may predict a positive effect of adding VTF to prosthesis users with myoelectric hands. Another possible limitation is the method we have used to prevent visual feedback. As discussed, studies on the additive effect of tactile feedback have used a blindfold for visual disruption. However, since our trial was focusing on tactile feedback and its effects on functional performance, rather than on recognition of object shape or texture, we designed our study so that the subjects could see the object for a brief period of time, and then relocate it when visual resources are diminished. Therefore, we used a darkened room for the disturbance of visual feedback, so that the initial location of the object was possible, which may affect the subject's performance differently to using a blindfold.

5. Conclusions

In conclusion, vibrotactile feedback can be an effective addition to myoelectric-controlled artificial hands when visual feedback is disturbed, assisting the user in functional performance. If VTF is provided to current myoelectric-controlled hands as an inherent feature, it may help prosthesis users to improve their functional ability during daily life activities in different environments.

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