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ORIGINAL RESEARCH

Myoelectric Prosthesis Users Improve Performance Time and Accuracy Using Vibrotactile Feedback When Visual Feedback Is Disturbed

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Abstract

Objective: To evaluate the effects of adding vibrotactile feedback (VTF) in myoelectric prosthesis users during performance of a functional task when visual feedback is disturbed.

Design: A repeated-measures design with a counter-balanced order of 3 conditions.

Setting: Laboratory setting.

Participants: Transradial amputees using a myoelectric prosthesis with normal or corrected eyesight (N=12, median age 65±13y). Exclusion criteria were orthopedic or neurologic problems.

Interventions: All participants performed the modified Box and Blocks Test, grasping and manipulating 16 blocks over a partition using their myoelectric prosthesis. This was performed 3 times: in full light, in a dark room without VTF, and in a dark room with VTF.

Main Outcome Measures: Performance time, that is, the time needed to transfer 1 block, and accuracy during performance, measured by number of empty grips, empty transitions with no block and block drops from the hand.

Results: Significant differences were found in all outcome measures when VTF was added, with improved performance time (4.2 vs 5.3s) and a reduced number of grasping errors (3.0 vs 6.5 empty grips, 1.5 vs 4 empty transitions, 2.0 vs 4.5 block drops).

Conclusions: Adding VTF to myoelectric prosthesis users has positive effects on performance time and accuracy when visual feedback is disturbed.

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An integral part of a successful rehabilitation after upper limb amputation is the fitting and use of a hand prosthesis.[1] The state of the art is myoelectric prostheses, where the artificial hand is controlled by signals from the muscles of the residual limb. This is done by detecting electrical activity (surface electromyography) via electrodes placed on 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, for example, opening or closing of the prosthetic hand.[2] Because the prosthesis user must adapt to an abnormal motor control, that is, learn to manipulate and control movement of the artificial hand by contracting specific muscles, simple grasping tasks may be slower compared with our biological hand and lack fine coordination.[3] This difficulty is also attributed to the lack of tactile feedback from the prosthetic hand when grasping an object. Although users of mechanical prostheses can sense the state of the prosthesis (closed or opened hand, with or without object) by detecting the transfer of grip force through the control cable and harness, this is not the case when using a myoelectric prosthesis.[4] With the absence of tactile feedback, the prosthesis user is forced to use visual feedback during grasping and manipulation of objects. Because daily motor tasks are sometimes performed when visual feedback is disturbed or not available, myoelectric prosthesis users encounter difficulties during object grasping and manipulation. This may occur while searching for keys in a bag, or when trying to turn the light on in a dark corridor. In these cases, objects may fall from the hand, and the time to task completion may increase. Therefore, it is not

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surprising that myoelectric prosthesis users ranked having tactile feedback as a desired priority in prosthesis design.[5] Despite relatively low number of individuals using a myoelectric prosthesis in daily life, predictions show that this number is increasing and continue to increase in the next decades.[6] Emerging technology in prosthetic design and manufacturing offer low-cost and accessible solutions for upper limb amputees, including the addition of tactile feedback, aiming to increase the percentage of prosthesis usage among upper limb amputees.[2]

Over the years, several studies investigated the benefits of adding VTF to a myoelectric prosthesis.[7,8] Most of these studies evaluated the role of VTF in assisting the prosthesis user to better control the applied force when grasping an object[9-11] or to have an improved object discrimination.[12,13] It was reported in these studies that adding VTF to prosthesis users can improve force control in conditions of full vision. Other studies evaluated the effects of adding VTF to myoelectric prosthesis users when visual feedback was available; however, these studies also focused on using VTF to distinguish object stiffness,[14] or on controlling of the grasping force.[15] When prosthesis users were asked for their views on tactile feedback and prosthesis use, vision was reported as the most common way to compensate for the lack of tactile feedback.[16] Because daily motor tasks are sometimes performed when visual feedback is disturbed or not available, myoelectric prosthesis users encounter difficulties in different scenarios, as while searching for keys in a bag, or when trying to turn the light on in a dark corridor. In these everyday situations, in the absence of tactile feedback, objects may fall from the hand, and the time needed for task completion may increase. Therefore, there is a need to examine the effect of VTF on performance, when both visual and auditory feedback are disturbed. Improvement in performance can be measured by a reduction of performance time, and by having the task performed more accurately, because both time and accuracy are important aspects of performance.[17] Another important aspect in prosthetic rehabilitation research is the use of valid outcome measures. As pointed out by a recently published review, most studies in this field of interest used different outcome measures, not always reflecting the actual function the of prosthesis during grasping and object manipulation.[18] To better understand the added value of VTF during grasping when using a prosthesis, there is a need to use valid functional tests, which can be generalized to the actual use of prostheses during daily tasks. In a recently published study, we examined the effects of adding VTF to a myoelectric-controlled artificial hand, used by nonimpaired participants to perform a functional test.[19] When comparing performance with and without VTF, we found significant improvements in both performance time and accuracy when VTF was available. In this study, we further explored whether the effect generalizes to transradial amputees, who have significant experience in using a myoelectric prosthesis in daily life. The aim of this study was to evaluate the effects of using VTF on the performance in a functional test in transradial amputees while using a myoelectric hand when visual feedback is disturbed. We hypothesized that, based on the literature and our study with able-bodied individuals, the addition of VTF will improve performance time and accuracy when visual feedback is disturbed.

List of abbreviations:
VTF vibrotactile feedback

Table 1 Personal characteristics of the study participants (N=12)

Sex	11 men, 1 woman
Age (y)	65.0±13.0
Prosthesis hand type	8 regular myoelectric, 4 multiarticulated
Time since amputation (y)	43.0±11.3
Wearing prosthesis during day (h)	15.5±6.0
OPUS-UEFS questionnaire score	29.0±2.5
TAPES-R questionnaire score	8.4±0.1

NOTE. Quantitative values are presented as median ± interquartile range.
Abbreviations: OPUS-UEFS, Orthotics and Prosthetics User Survey-Upper Extremity Functional Status; TAPES-R, Revised Trinity Amputation and Prosthesis Experience Scale.

Methods

Participants

A total of 12 myoelectric prosthesis users were recruited for the study. We calculated the sample size using an interactive program for performing power and sample size calculations.[a] A preliminary experiment with 20 nonimpaired participants showed that the standard deviation of our primary outcome measure, the performance time of the modified Box and 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 10 participants with power of 80% and alpha=.05.[20] Inclusion criteria were unilateral transradial amputation patients, 18 to 70 years old using a myoelectric prosthesis, with the ability to follow simple instructions, understand and sign an informed consent form, and with normal or corrected eyesight. The exclusion criteria were elbow or wrist disarticulation or partial hand amputations, neuropathy or skin ulcers on the amputated limb, and cognitive or mental deficits that limit their ability to participate fully in the study protocol. Overall, data collected from 12 participants were analyzed (table 1 for personal characteristics of the participants). All the participants completed 2 questionnaires (see table 1): (1) the Orthotics and Prosthetics User Survey-Upper Extremity Functional Status, concerning the ability to perform daily tasks[21] and (2) the Revised Trinity Amputation and Prosthesis Experience Scales questionnaire of psychosocial aspects.[22] The study was approved by the Hadassah Medical Center ethical committee. All participants read and signed an informed consent form pretrial.

Study tools and protocol

A lightweight, battery-activated VTF system was attached to the myoelectric prosthesis of the participants. Two pairs of thin force sensors[b] were attached to the index finger, middle finger, and thumb of the hand, which are involved in any kind of grip pattern, to detect the grip force and provide information on the object held by the hand (fig 1, right frame). Eight vibrotactile actuators[c] were embedded in the interior of an elastic strap which was wrapped around the upper arm (see fig 1, left frame) and were activated to their maximum amplitude when the applied force was above a threshold level. The threshold levels from the 4 force sensors were

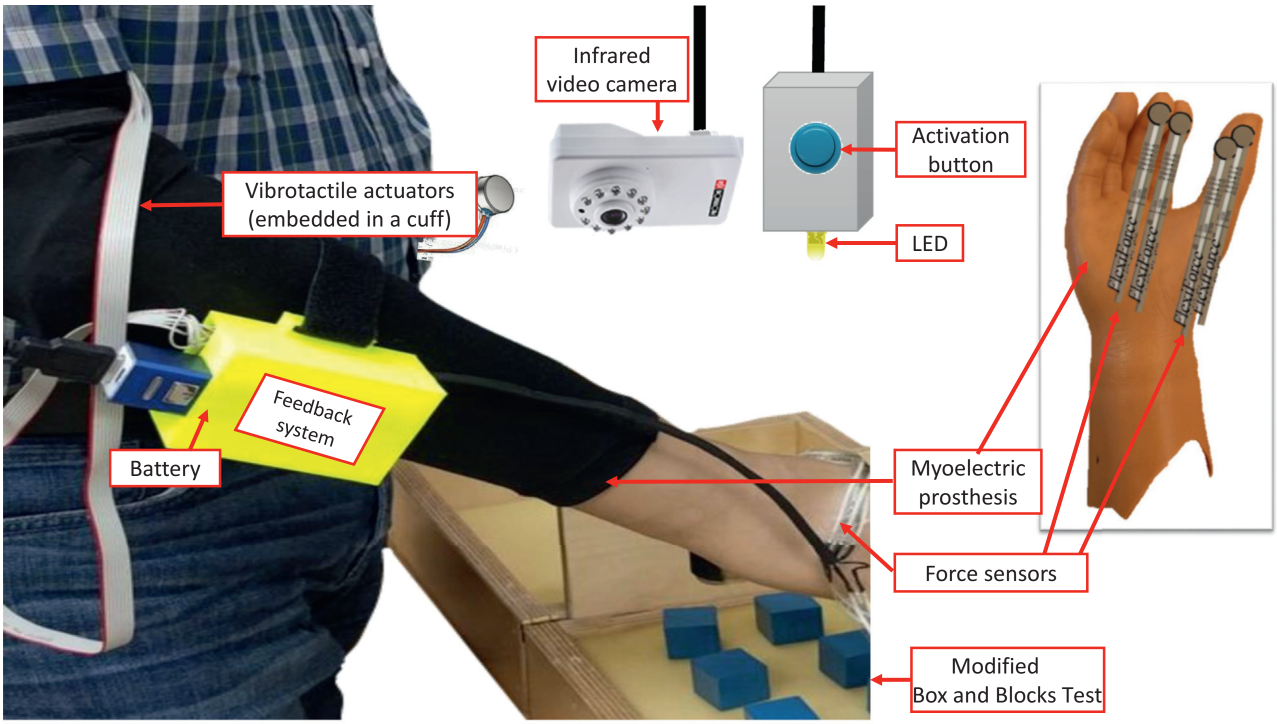

Fig 1 Setup of a trial. The participant was wearing transradial myeoelectric prosthesis equipped with portable feedback system, with an elastic cuff containing 8 vibrotactile actuators wrapped around the arm (left). Two pairs of thin force sensors were attached to the distal phalanges of the myoelectric prosthetic hand (right). The participant was instructed to move the blocks over the partition of the Box and Blocks Test (lower right). The VTF was provided to the upper arm of the amputated limb when the participant closes the prosthetic hand over an object. After each block transfer, he/she was instructed to press the blue button (upper right) with his or her intact hand, so that an LED light was briefly triggered. An Arduino-based timer was activated by the button and recorded the performance time. A video camera (middle) was placed above the box to record the grasping movements. The trial was performed in full light, and in the dark with and without VTF.

determined as follows: below 17.6N—no actuator was activated, between 17.6N and 41.2N—1 pair of actuators was activated, between 41.2N and 70.6N—2 pairs of actuators were activated, between 70.6N and 100N—3 pairs of actuators, and above 100N—activation of all vibrotactile actuators. We used vibrotactile coin actuators,[c] which were previously used in several studies.[10,23] The number of actuators was determined after several preliminary empirical tests and was found sufficient for perceiving whether an object is grasped or not. The vibrotactile actuators were powered by a 3V power battery.

The feedback system (see fig 1) was composed of an Arduino-based controller unit,[d] which received input from the 4 force sensors and activated the vibrotactile actuators as described above. The controller unit, which was responsible for measuring the force and applying the appropriate feedback, was programmed in C using the Arduino software.[e] The current was supplied through a small rechargeable battery.[f] The whole system was placed in a small custom-made 3D-printed plastic box (size 7 × 4.5 × 3 cm). The total weight of the system was 130 g, and it was attached using Velcro straps (see fig 1).

To evaluate the effects of adding VTF on the performance level, we used the modified Box and Blocks Test,[g] which has been previously used in research with prosthetic hand users.[24-26] This is a modification to the original Box and Blocks Test, which has minimal detectable change values. For the modified Box and Blocks Test, normative data were reported for performance time and required range of motion during the test.[27] In the original version of the Box and Blocks Test, performance is determined by the total number of blocks transferred in 1 minute.[28] Therefore, it is mainly used in research where gross dexterity of the upper limb is evaluated, for example, poststroke.[29] However, as pointed out in previous studies, it lacks the ability to assess specific grasping and manipulation patterns in prosthesis users.[24,27] Because our aim was to examine both performance time and accuracy during the transfer of each single block, we preferred to use the modified version of the test, where participants transfer 16 blocks in a specified order from certain places over the partition with no time limitation. Because of its more structured nature, this version of the test better enables calculations of the desired quantities. Several studies have shown that using a simpler task with fewer block movements does not affect the received information on performance.[24-26] Because we aimed to examine the effects of tactile feedback on performance when visual feedback is disturbed, rather than on recognition of object shape or texture, we used a dark room, with an LED activated only for a short period of time (see fig 1). In that way, the initial location of the object was clearly known by the participant, but the grasping and manipulation were performed in darkness.

The participants stood in front of a table and were instructed to use their myoelectric prosthesis to transfer 16 blocks over the partition. The participants wore circumaural earphones, and the box of the test was padded with a soft sponge layerto prevent auditory feedback. A microcontroller-based timer device[h] with an LED and an activation button were placed over the test box in front of the participants (see fig 1). After transferring each block, the participants were requested to press the button with their intact hand, thus activating a timer-based code measuring the transfer time of each block (time between button press events), as well as illuminating an LED for a duration of 500 ms. This time was set to provide a temporary visual glimpse of the block location, but to keep the grasping and manipulation of the block in the dark. Finally, an infrared camera[i] was placed above the box (see fig 1) to record videos of the performance of the test. This test was performed 3 times: in full light with no VTF, in a dark room with the VTF, and in a dark room without VTF. In that way, we could eliminate the dominant effect of vision during grasping and evaluate the actual effect of VTF during the test in an isolated manner. All the participants started with the full visibility trial. Then, to prevent bias of learning the task, the study was performed in a counter-balanced order of the 2 remaining conditions (with and without VTF).

Data analysis

Performance of the functional test was quantified by 2 measures: performance time, that is, the mean time to move each block, and accuracy, defined as the number of grasping errors during the task. This number was calculated by analyzing the videos taken with the infrared camera, with 3 outcome measures for grasping errors: (1) number of blocks dropped from the prosthetic hand; (2) number of grips with no block; and (3) number of times the participant moved his or her hand over the partition without a block.

We used a commercial statistical software[j] 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 order effects of with and without feedback. To compare the outcome measures between the 3 trials, we used the Friedman test for 3-related samples analysis. If significant differences were found, we used the Wilcoxon signed-rank tests for post hoc analysis to determine which pairs were different. With Bonferroni correction applied, results were considered statistically significant if $P<.016$.

Results

The participants in our study were experienced prosthesis users, with a median time of 43 years after their limb loss. The median duration of time for using the prosthesis per day was 15.5 hours (see table 1). All participants were also highly adjusted to using a prosthesis, both socially and physically, as was indicated by the high scores in the Orthotics and Prosthetics User Survey-Upper Extremity Functional Status and Revised Trinity Amputation and Prosthesis Experience Scales questionnaires (see table 1).

We found a significant difference in the duration of transferring 1 block between the 3 conditions (χ^2 [2] $=17.17$, $P<.001$). Post hoc tests showed that the median times for block transfer with both full light (3.1±1.2) and with VTF (4.2±2.2s) were significantly faster than without VTF (5.3±2.5s) (full light: $z=-2.4$, $P=.002$; VTF: $z=-3.1$, $P=.002$). The difference in duration of a block transfer between full light and VTF was not significant. The median and interquartile range of the time to transfer each block (seconds) for all 3 conditions is presented in fig 2A.

In measures of accuracy, there was a significant difference in the number of grips with no block in the hand between the 3 conditions (χ^2 [2]$=21$, $P<.001$). Post hoc tests showed that the median number of empty grips with both full light (2.0±2.0) and with VTF (3.0±4.0) was significantly lower than without VTF (6.5±6.0) (full light: $z=-3.1$, $P=.002$; VTF: $z=-3.1$, $P=.002$, see fig 2B). The number of empty grips was also significantly lower in full light than with VTF ($z=-2.4$, $P=.02$, see fig 2B).

Furthermore, the median number of empty transitions, in which the participants moved their hand over the partition with no block in it, was significantly different between the conditions of the study (χ^2 [2]$=21.0$, $P<.001$). Post hoc tests showed that the median number of transitions with no block in the hand, with both full light (0.0±*0*.0) and with VTF (1.5±1.0), was significantly lower than without VTF (4.0±4.0) (full light: $z=-2.9$, $P=.003$; VTF: $z=-2.8$, $P=.005$; see fig 2B). There was also a significantly lower number of empty transitions between conditions of full light and when VTF was available ($z=-2.8$, $P=.005$, see fig 2B).

Finally, the median number of block drops between the 3 conditions was also significantly different (χ^2 [2]$=20.8$, $P<.001$). Post hoc tests showed that the number of times a block fell from the hand with both full light (1.0±1.0) and with VTF (2.0±4) was significantly lower than without VTF (4.5±3.0) (full light: $z=-3.1$, $P=.002$; VTF: $z=-3.0$, $P=0.003$, see fig 2B). There was also a significant lower number of block drops between conditions when VTF was available and full light ($z=-2.1$, $P=.003$, see fig 2B).

There were no significant differences between the outcome measures of the participants who began the trial with the VTF than the participants who began without the VTF. This implies that there was no order effect.

Discussion

In this study, we tested the effects of adding VTF to a myoelectric prosthesis on the performance time and accuracy of a grasping and transferring task. Our main finding is that when visual feedback is disturbed, the addition of VTF improves performance time and reduces the number of errors when performing a functional grasping test. Unlike previous studies, which provided different feedback combinations (visual, auditory, tactile),[30-32] in this study we deprived the participants of both auditory and visual feedback in a dark room, with only VTF remaining as their feedback resource.

During grasping and manipulation of an object, visual feedback and tactile feedback play different roles. Although visual feedback is used both to guide the hand to the correct position and to determine the correct distance to the object, tactile feedback provides information about the shape and size of the object.[33] Normally, feedback from the visual sensory system dominates over information from the other senses during the process of sensory integration.[34] However, when visual feedback is disturbed in nonimpaired people, for example, at night or in a dark surrounding, the use of tactile feedback as a reliable resource of information about the surrounding is amplified to improve performance.[35] Myoelectric prosthesis users, who lack the tactile feedback from the prosthesis, tend to rely on their visual feedback resources.[5] Our results support these data, showing that adding VTF during grasping can assist the users when visual feedback is

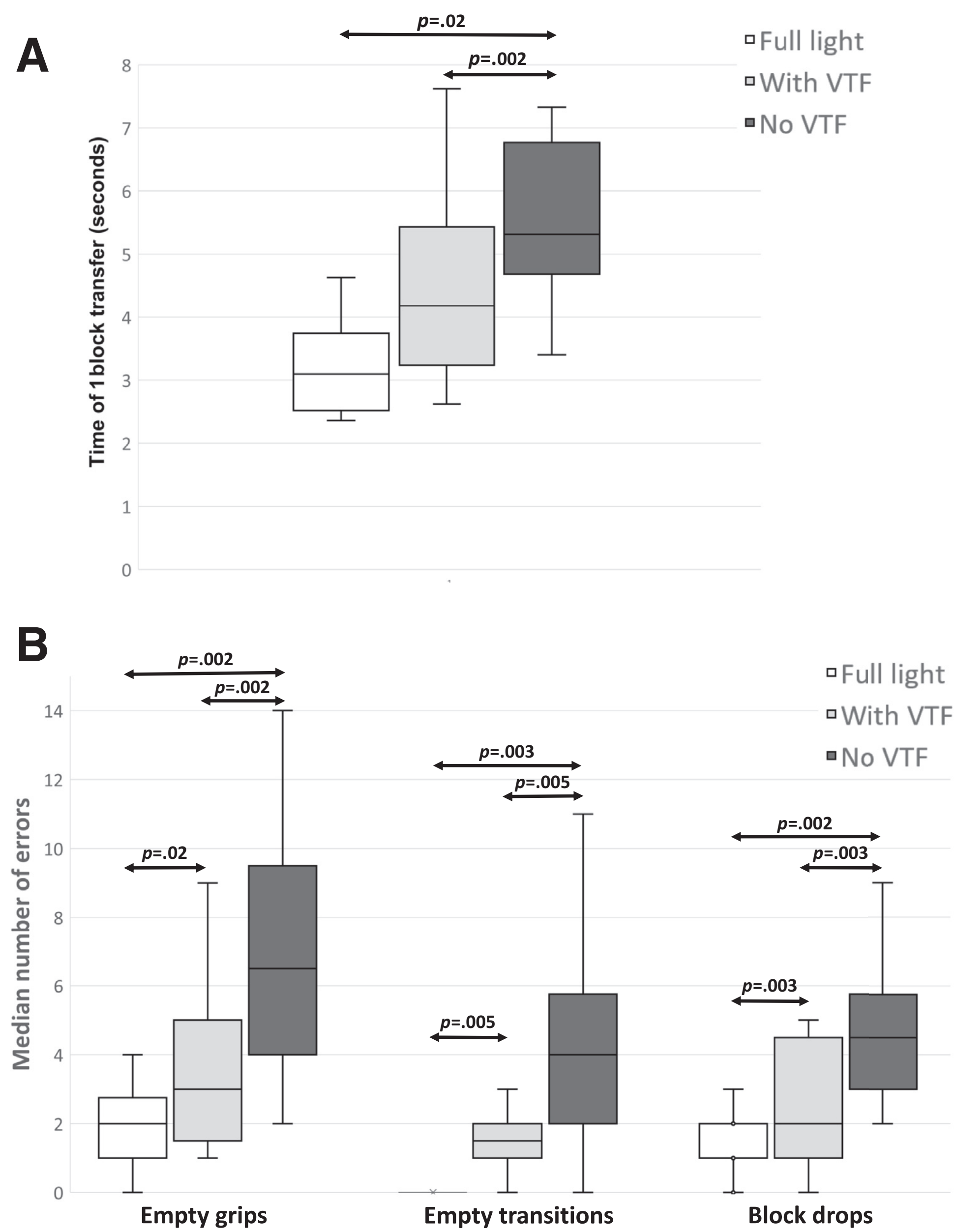

Fig 2 **(A)** Performance time (seconds) of 1 block transfer of the modified Box and Blocks in full light and when visual feedback is disturbed—with and without VTF. When VTF was available, the time to transfer each block was significantly lower than when VTF was not available ($P=.002$). The time to transfer each block when VTF was available was not significantly different to when the test was performed in full light. Median and interquartile range of all conditions are presented. (**B**) Number of errors during modified Box and Blocks Test with versus without VTF. When VTF was available in the dark, or in full light, the number of errors was significantly lower than when VTF was not available in the dark. This was present in all error types: a lower number of empty grips (left), less times the participants moved the hand over the partition with no block (middle), and reduced number of times a block dropped off the hand (right). Median and interquartile range of all conditions are presented.

disturbed (see fig 2A). Nevertheless, when visual feedback was available, that is, in full light, the performance was significantly better compared with the 2 other conditions. The reason that even with VTF the participants performed worse in the absence of visual feedback, is likely because the use of visual feedback provides valuable information on the task performance. This finding is consistent with the well-established literature on multimodal interfaces[36] that visual feedback provides the most reliable information to the brain, with minimal external distortions of the true location of an object. Similar results were found by Witteveen et al,[10] who examined the effects of adding VTF to transradial amputees on grasping force and hand aperture during the activation of a virtual hand, compared with visual feedback. When visual feedback was available to participants, the results were always better compared with the VTF condition.

Grasping an object in an accurate manner is also an important aspect of performance, for example, successfully catching a ball.[17] Studies have shown that tactile feedback does not affect only performance time, but can also affect accuracy.[37] Researchers measured the number of errors during a motor tracking test and found that when tactile feedback was limited using different gloves, accuracy was reduced.[38] Bozzacchi et al[39] tested the execution of reach-to-grasp actions in 4 groups of participants trained with 4 different combinations of tactile and visual feedback. They found that when tactile feedback was absent, accuracy was reduced. Similar to prosthesis users, who have lost their limb, Nowak et al[40] demonstrated that individuals with polysensory neuropathy, who have a complete loss of afferent sensation, also show marked deficits in accurate control of grip forces. Finally, in a review on using sensory feedback in upper limb prostheses, VTF was found to have positive effects on grasping, due to a better control of grip force and lowering the number of errors during task performance, that is, improving accuracy.[8] Our findings are consistent with the results reported in these studies, because we demonstrated a significant reduction in the number of errors during performance when VTF was available (see fig 2B), which indicates that the participants could perform the functional test in a more accurate manner because of the addition of VTF. However, unlike an intact hand, the muscle groups used to control the opening and closing of a myoelectric prosthesis, as well as the associated neural pathways act in a different manner, sometimes causing an involuntary contraction that may lead to an unplanned opening or closing of the hand.[41] Therefore, despite the fact that the light was on and visual feedback was available, there were some empty grips when performing the task in full light (see fig 2B).

One outcome measure for accuracy in our study was the number of block drops during the test, which was reduced when VTF was available (see fig 2B, right). In a survey performed among myoelectric prosthesis users, they were asked to prioritize their desired features for a myoelectric prosthesis design. The features that were mentioned by the users were having the ability to prevent objects from slipping, to improve grip accuracy, and to add sensory feedback to the prosthetic device.[5] The ability to hold an object safely without looking at it is trivial for nonimpaired individuals, but prosthesis users feel its absence in daily life. Our findings suggest that adding VTF to prostheses may assist in this aspect, allowing them to exploit the VTF and prevent object slippage, even when visual feedback is disturbed.

When comparing the effect of adding VTF to prosthesis users on functional performance, we found that when VTF was not available to the participants, grasping and manipulation of each block required a significantly longer time (3.1±1.2s in full light, 4.2 ±2.2s with VTF, compared to 5.3±2.5s without VTF, $P=.002$, see fig 2A). Although we are not aware of previous studies that defined the level of clinical relevant significance in terms of this test, we claim that the observed difference is clinically meaningful—as we perform a large number of grasping actions each day, a reduction of approximately 1 second for each grasp would certainly be noticeable and thus likely lead to greater satisfaction in using the prosthesis. In a study comparing the performance of 3 different prosthetic hands, significant differences were found in the Box and Blocks Test in favor of one of the devices: 30 blocks per minute compared with 22 and 17 blocks, respectively.[42] The authors concluded that these results enable an objective comparison, which suggests that the performance is best when using this prosthetic hand. Another study used the modified Box and Blocks Test to examine the functional advantages of a new advanced myoelectric prosthesis than a regular prosthesis in a group of experienced prosthesis users.[43] The achieved Box and Blocks scores were significantly worse with the new prosthesis (15.3s) than a regular prosthesis (9.5s). These results were interpreted as a lower level of performance when using the new prosthesis. Finally, in a recently published study,[44] the clinical relevance of adding VTF to a myoelectric prosthesis was examined using the Box and Blocks Test and other functional tests. In this study, no significant differences were found in the Box and Blocks Test time scores, which led the authors to conclude that performance of simple tasks may not benefit from the addition of VTF. Despite the use of this test as an objective tool to evaluate performance in prosthesis users in both our study and in multiple previous studies, there is still a need to determine what the minimal level of change is in this functional test that reflects clinical significance in performance of daily tasks.

Study limitations

The main limitation of this study is the small sample size which may not represent the entire transradial amputee population. Nevertheless, in a literature review of studies on upper limb prostheses, the median sample size was 12 participants, and most studies using functional tests were performed with a range of 1-10 participants.[4] The reason for these small sample sizes may be the low level of prosthesis use among this population, as well as the current relative high cost of myoelectric prostheses. In addition, our study was conducted in a laboratory setting, with the use of the modified Box and Blocks as a test that evaluates the performance of the participants. In a review of clinical assessments for upper limb injuries, the Box and Blocks Test was classified as a measure of activity.[45] However, using our setup does not fully reflect the use of hand prosthesis during all daily life activities. As pointed out in a recent study, current performance assessment methods for prosthesis users are insufficient, and there is a challenge to generalize the knowledge acquired in the laboratory to clinical settings.[46] Nevertheless, clinical tests, for example, the modified Box and Blocks Test, still offer the most realistic prediction of the system performance in daily use,[18] despite their limitations, and more closely model common real-world object manipulation scenarios. Recently, a new model for assessment of using hand prostheses in real life was suggested,[47] using activity monitors placed on the prosthetic hand during the day. If the effects of tactile feedback would be assessed using such a model, its potential added value in daily life may be further noticed. For example, adding VTF in more ecological tasks, for example, getting dressed in the morning, where visual feedback is not always fully available. Future studies may also aim to explore the effects of using tactile feedback as a substitution for other lost features after upper limb amputation, for example, loss of temperature sensation and loss of dexterity. When prosthetic hands can provide feedback in a successful manner, this might substantially increase the use of hand prostheses among upper limb amputees.

Conclusions

In conclusion, VTF can be an effective addition to myoelectric prostheses when visual feedback is disturbed, assisting the user to improve performance time and accuracy of grasping and manipulation. If VTF is added to current myoelectric hands, it may assist them to improve their functional ability during daily life activities in different environments.

Suppliers

a. PS Power and sample size calculation software, version 3.1.2; Vanderbilt University.
b. Flexiforce A201; Tekscan Inc.
c. Shaftless vibration motor 10 × 2.0 mm; Pololu.
d. Arduino Uno Rev3; Arduino Holding.
e. Open-source Arduino software, version 1.8.5; Ardunio Holding.
f. Miracase 2600 mAh portable power bank; Hong Kong Miracle Technology Co, Ltd.
g. Box and Blocks Test; Patterson Medical.
h. DCcduino UNO; DCc Electronics.
i. IR fixed lens camera F-717; Provision-ISR.
j. IBM SPSS statistics, version 21; IBM.

Keywords

Amputation; Prosthesis; Rehabilitation; Sensory feedback; Visual feedback

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References

1. Solarz MK, Thoder JJ, Rehman S. Management of major traumatic upper extremity amputations. Orthop Clin North Am 2016;47:127-36.
2. Farina D, Amsüss S. Reflections on the present and future of upper limb prostheses. Expert Rev Med Devices 2016;13:321-4.
3. Fougner A, Stavdahl O, Kyberd PJ, Losier YG, Parker PA. Control of upper limb prostheses: terminology and proportional myoelectric control - a review. IEEE Trans Neural Syst Rehabil Eng 2012;205: 663-77.
4. Carey SL, Lura DJ, Highsmith MJ. Differences in myoelectric and body-powered upper-limb prostheses: systematic literature review. J Rehabil Res Dev 2015;52:247-62.
5. Pylatiuk C, Schulz S, Döderlein L. Results of an Internet survey of myoelectric prosthetic hand users. Prosthet Orthot Int 2007;31:362-70.
6. Ziegler-Graham K, MacKenzie EJ, Ephraim PL, Travison TG, Brookmeyer R. Estimating the prevalence of limb loss in the United States: 2005 to 2050. Arch Phys Med Rehabil 2008;89:422-9.
7. Svensson P, Wijk U, Björkman A, Antfolk C. A review of invasive and non-invasive sensory feedback in upper limb prostheses. Expert Rev Med Devices 2017;14:439-47.
8. Antfolk C, D'Alonzo M, Rosén B, Lundborg G, Sebelius F, Cipriani C. Sensory feedback in upper limb prosthetics. Expert Rev Med Devices 2013;101:45-54.
9. Clemente F, D'Alonzo M, Controzzi M, Edin B, Cipriani C. Non-invasive, temporally discrete feedback of object contact and release improves grasp control of closed-loop myoelectric trans-radial prostheses. IEEE Trans Neural Syst Rehabil Eng 2016;24: 1314-22.
10. Witteveen HJ, Rietman HS, Veltink PH. Vibrotactile grasping force and hand aperture feedback for myoelectric forearm prosthesis users. Prosthet Orthot Int 2015;39:204-12.
11. Saunders I, Vijayakumar S. The role of feed-forward and feedback processes for closed-loop prosthesis control. J Neuroeng Rehabil 2011;8:60.
12. Schiefer M, Tan D, Sidek SM, Tyler DJ. Sensory feedback by peripheral nerve stimulation improves task performance in individuals with upper limb loss using a myoelectric prosthesis. J Neural Eng 2016;13:016001.
13. Raspopovic S, Capogrosso M, Petrini FM, et al. Restoring natural sensory feedback in real-time bidirectional hand prostheses. Sci Transl Med 2014;6:222ra19.
14. Witteveen HJ, Luft F, Rietman JS, Veltink PH. Stiffness feedback for myoelectric forearm prostheses using vibrotactile stimulation. IEEE Trans Neural Syst Rehabil Eng 2014;22:53-61.
15. Patterson PE, Katz JA. Design and evaluation of a sensory feedback system that provides grasping pressure in a myoelectric hand. Rehabil Res Dev 1992;29:1-8.
16. Wijk U, Carlsson I. Forearm amputees' views of prosthesis use and sensory feedback. J Hand Ther 2015;28:269-77.
17. Latash ML. Fundamentals of motor control. 1st ed. London: Academic Press; 2012.
18. Wang S, Hsu CJ, Trent L, et al. Evaluation of performance-based outcome measures for the upper limb: a systematic review. PM R 2018;10:951-62.e3.
19. Raveh E, Portnoy S, Friedman J. Adding vibrotactile feedback to a myoelectric-controlled hand improves performance when online visual feedback is disturbed. Hum Mov Sci 2018;58:32-40.
20. Dupont WD, Plummer WD Jr. Power and sample size calculations for studies involving linear regression. Control Clin Trials 1998;19: 589-601.
21. Burger H, Franchignoni F, Heinemann AW, Kotnik S, Giordano A. Validation of the orthotics and prosthetics user survey upper extremity functional status module in people with unilateral upper limb amputation. J Rehabil Med 2008;40:393-9.
22. Gallagher P, Franchignoni F, Giordano A, MacLachlan M. Trinity amputation and prosthesis experience scales: a psychometric assessment using classical test theory and rasch analysis. Am J Phys Med Rehabil 2010;89:487-96.
23. Witteveen HJ, de Rond L, Rietman JS, Veltink PH. Hand-opening feedback for myoelectric forearm prostheses: performance in virtual grasping tasks influenced by different levels of distraction. J Rehabil Res Dev 2012;49:1517-26.
24. Hebert JS, Lewicke J. Case report of modified Box and Blocks test with motion capture to measure prosthetic function. J Rehabil Res Dev 2012;498:1163-74.
25. Cheng N, Amend J, Farrell T, et al. Prosthetic jamming terminal device: a case study of untethered soft robotics. Soft Robot 2016;3: 205-12.
26. Edwards AL, Dawson MR, Hebert JS, et al. Application of real-time machine learning to myoelectric prosthesis control: a case series in adaptive switching. Prosthet Orthot Int 2016;40:573-81.
27. Hebert JS, Lewicke J, Williams TR, Vette AH. Normative data for modified Box and Blocks test measuring upper-limb function via motion capture. J Rehabil Res Dev 2014;51:918-32.
28. Mathiowetz V, Volland G, Kashman N, Weber K. Adult norms for the Box and Block Test of manual dexterity. Am J Occup Ther 1985;39: 386-91.

29. Alt Murphy M, Resteghini C, Feys P, Lamers I. An overview of systematic reviews on upper extremity outcome measures after stroke. BMC Neurol 2015;15:29.
30. Rombokas E, Stepp CE, Chang C, Malhotra M, Matsuoka Y. Vibrotactile sensory substitution for electromyographic control of object manipulation. IEEE Trans Biomed Eng 2013;60:2226-32.
31. Ninu A, Dosen S, Muceli S, Rattay F, Dietl H, Farina D. Closed-loop control of grasping with a myoelectric hand prosthesis: which are the relevant feedback variables for force control? IEEE Trans Neural Syst Rehabil Eng 2014;22:1041-52.
32. De Nunzio AM, Dosen S, Lemling S, et al. Tactile feedback is an effective instrument for the training of grasping with a prosthesis at low- and medium-force levels. Exp Brain Res 2017;235: 2547-59.
33. Flanagan JR, Bowman MC, Johansson RS. Control strategies in object manipulation tasks. Curr Opin Neurobiol 2006;16:650-9.
34. Ernst MO, Banks MS. Humans integrate visual and haptic information in a statistically optimal fashion. Nature 2002;415:429-33.
35. Gori M, Vercillo T, Sandini G, Burr D. Tactile feedback improves auditory spatial localization. Front Psychol 2014;5:1121.
36. Helbig HB, Ernst MO. Optimal integration of shape information from vision and touch. Exp Brain Res 2007;179:595-606.
37. Bingham GP, Mon-Williams M. The dynamics of sensorimotor calibration in reaching-to-grasp movements. J Neurophysiol 2013;110: 2857-62.
38. Polechoński J, Olex-Zarychta D. The influence of tactile feedback on hand movement accuracy. Hum Mov 2012;13:236-41.
39. Bozzacchi C, Volcic R, Domini F. Effect of visual and haptic feedback on grasping movements. J Neurophysiol 2014;112:3189-96.
40. Nowak DA, Glasauer S, Hermsdörfer J. Grip force efficiency in long-term deprivation of somatosensory feedback. Neuroreport 2003;14: 1803-7.
41. Bongers RM, Kyberd PJ, Bouwsema H, Kenney LP, Plettenburg DH, Van Der Sluis CK. Bernstein's levels of construction of movements applied to upper limb prosthetics. J Prosthet Orthot 2012;24:67-76.
42. Haverkate L, Smit G, Plettenburg DH. Assessment of body-powered upper limb prostheses by able-bodied subjects, using the Box and Blocks Test and the Nine-Hole Peg Test. Prosthet Orthot Int 2016;40: 109-16.
43. Resnik L, Borgia M, Latlief G, Sasson N, Smurr-Walters L. Self-reported and performance-based outcomes using DEKA Arm. J Rehabil Res Dev 2014;51:351-62.
44. Markovic M, Schweisfurth MA, Engels LF, et al. The clinical relevance of advanced artificial feedback in the control of a multi-functional myoelectric prosthesis. J Neuroeng Rehabil 2018;15:28.
45. Metcalf C, Adams J, Burridge J, Yule V, Chappell P. A review of clinical upper limb assessments within the framework of the WHO ICF. Musculoskeletal Care 2007;5:160-73.
46. Vujaklija I, Roche AD, Hasenoehrl T, et al. Translating research on myoelectric control into clinics—are the performance assessment methods adequate? Front Neurorobot 2017;11:7.
47. Chadwell A, Kenney L, Thies S, Galpin A, Head J. The reality of myoelectric prostheses: understanding what makes these devices difficult for some users to control. Front Neurorobot 2016;10:7.