Assessing the Effect of DESC-Feedback on Cognitive Load, Gaze Behavior, and Motor Performance During Manipulation Tasks Performed With Hand Prosthesis

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***Abstract*— Individuals with upper limb amputation often reported functionality limitations due to poor confidence in myoelectric hand prosthesis control and the lack of tactile and proprioceptive feedback. This is typically associated with increased cognitive demands and compensatory reliance on vision to perform activities of daily living. Such limitations can contribute to user frustration and device abandonment. Providing sensory feedback has the potential to reduce these limitations, but its implementation must be intuitive to avoid adding further cognitive demand on the user. The Discrete Event-driven Sensory feedback Control (DESC) model offers a promising strategy, delivering brief, event-based stimuli that mimic natural sensory encoding. While DESC feedback has been shown to improve motor performance, its cognitive demand and role in modulating visual reliance have not yet been investigated. In this study, we aimed to assess the cognitive load associated with DESC feedback, its effect on visual attention and motor performance during manipulation tasks. To this goal, healthy participants with no prior experience in prosthesis control, performed motor tasks in three conditions: with their intact dominant hand, with a simulated prosthesis with and without DESC feedback. Then the findings obtained from the healthy participants were validated in an experienced prosthesis user. Our results suggest that DESC feedback can enhance prosthesis usability by supporting performance without impacting cognitive load. Conversely, feedback did not consistently reduce participants' reliance on vision during task execution; further investigation is needed to determine whether extended exposure may yield attentional benefits not observable in the short term.**

***Index Terms*— Upperlimb amputation, prosthesis, sensory feedback, sensory substitution, cognitive load.**

Received 10 November 2025; revised 16 April 2026 and 19 June 2026; accepted 13 July 2026. Date of publication 3 August 2026; date of current version 14 August 2026. Associate Editor: Erkan Kaplanoglu. This work was supported in part by Italian Ministry of University and Research, through the Complementary Actions to the Piano Nazionale di Ripresa e Resilienza (PNRR), project "Fit4MedRob—Fit for Medical Robotics" under Grant PNC0000007; in part by the Young Researchers 2024 program (PNRR), project HAND2; and in part by Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro (INAIL), within the Framework of the NoProblem Project under Grant PR23-CR-P3. *(Corresponding author: Christian Cipriani.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Local Ethical Committee of the Scuola Superiore Sant'Anna, Pisa, Italy, under Application No. 10/2023, and performed in line with the Declaration of Helsinki.

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This article has supplementary downloadable material available at https://doi.org/10.1109/TNSRE.2026.3719427, provided by the authors.

Digital Object Identifier 10.1109/TNSRE.2026.3719427

I. Introduction

THE complex activities we perform with our hands arise from the seamless interplay of feedforward motor commands and sensory feedback pathways, which guide and refine movement execution. Here, vision plays an important role in achieving hand-arm coordination [1]. Vision supports motor planning by providing information about the environment. Typically, individuals briefly fixate on an object before grasping it, and then visual attention is directed to the object's final destination [2], [3].

The loss of an upper limb can significantly disrupt natural behaviours, forcing individuals to rely on unintuitive interactions with prosthetic devices. Prostheses users often reported functionality limitations, with difficulty in grasping and manipulating objects successfully [4], [5]. To compensate for the poor confidence in prosthesis control and the complete lack of tactile and proprioceptive feedback, a higher amount of cognitive resources and visual attention are typically required [6], [7]. In particular, during object manipulation tasks, prosthetic users focus the visual attention more on the prosthetic hand and less towards the actual target [8], [9], [10]. Such limitations—ineffective motor control, high cognitive load, lack of sensory feedback—are associated with a poor tech-embodiment experience, user dissatisfaction and ultimately high abandonment rates [7], [11], [12].

In recent years, several approaches to provide sensory feedback and close the sensory-motor control loop have been proposed, including invasive and non-invasive strategies [13], [14]. The typical approach is based on a continuous modulation of the feedback stimuli (vibration, electrical current, mechanical pressure) to proportionally infer the grip force applied by the robotics fingertips [15], [16], [17], [18]. Alternatively, Benoni et al. proposed a discrete (i.e., non-continuous) feedback modality based on the Discrete Event-driven Sensory feedback Control (DESC) model, a neuroscientific theory of sensorimotor control [19], [20]. The DESC model resembles the activation of fast adapting peripheral neural fibers, leveraging on the idea that the central nervous system learns and encodes dexterous tasks by segmenting them via discrete sensory events [21]. For this, brief and event-driven vibrotactile stimuli (DESC-Feedback) are delivered at key manipulation events—such as first contact, release, or lift-off. Feedback delivered according to the DESC theory was demonstrated to be incorporated into the sensorimotor control loop [19], to improve motor coordination during a pick-and-lift task [22], and to show enhanced performance in manipulating fragile objects [23].

While the DESC feedback modality has demonstrated improvements in motor performance and grasping functionality, no studies have yet explored whether this improvement is accompanied by a reduced reliance on vision**.** Further, its impact on cognitive load has not been objectively quantified.Indeed **,** previous findings only inferred a minimal cognitive cost based only on preserved task execution time [23] and improved performance in a dual task (i.e cognitive task added to a motor task) [24]. Moreover, only few studies have investigated the relationship between sensory feedback restoration and gaze behaviour. Notably, Marasco et al. [25] argued that the combination of prosthesis kinesthetic and touch feedback (rather than touch feedback alone) in amputees treated with targeted skin reinnervation resulted in a reduced reliance on vision compared to no feedback in functional transfer tasks. However, here touch feedback was provided through pressure tactors at contact events as well as proportionally to the force applied, thus no specific conclusion can be drawn about DESC feedback.

This study aims to assess the cognitive load associated with DESC feedback. Additionally, we aim to examine its effects on visual attention demand and explore whether changes in these variables are associated with motor performance in tasks inspired by everyday activities. Prior studies in human-machine interaction reported several subjective and objective metrics to quantify users' cognitive workload [7], [26]. Among subjective measures, the NASA-TLX survey [27] was one of the most used as quick and simple to administer; however, it suffers from recall bias and large inter-individual variability [28]. Objective measures include heart rate variability (HRV), electrodermal activity (EDA) [29], functional near infrared spectroscopy (fNIRS) [30], [31] and electroencephalography (EEG) [32]. However, their application in the prosthetic field presents several challenges: HRV and EDA are also sensitive to physical load [26], while brain signals are susceptible to motion artefacts and require extensive preprocessing [26], [33]. To address these limitations, recent studies have proposed eye-tracking metrics as viable alternatives [34], already validated in domains such as driving and arithmetic tasks [35], [36]. Specifically, larger pupil diameter has been associated to increase mental effort, attention and task difficulty in prosthesis use [33], [37], [38]. Saccadic movements represent another ocular metric sensitive to cognitive load [35], [39], [40], [41]. When the amount of information to be processed within the visual field exceeds the limits of the working memory, saccades occur within a narrowed visual field. This is reflected in a shortened amplitude [42], [43]. Recently, Hill and Linder [44] effectively introduced saccade amplitude as a proxy for cognitive load in the prosthetic field. This metric was preferred over pupil size since the latter is affected by lightning conditions [45], [46]. However, saccadic movements may also reflect changes in visual search strategies [47]. Therefore, considering the potential advantages and limitations, we decided here to perform a multi-modal assessment of the cognitive load by combining NASA-TLX, changes in pupil size (i.e. pupil dilation), and saccade amplitude. We hypothesised that DESC feedback, being event-driven and intuitively perceived, would not aggravate the cognitive load required to operate a prosthesis without any tactile feedback, even with minimal training. Moreover, we expected that DESC would improve motor performance and that its integration into the sensorimotor loop can help prosthesis users to reduce their dependence on visual feedback during task execution.

To test these hypotheses, we conducted an experiment in which participants performed manipulation tasks while wearing an eye-tracking system. The tasks were inspired by activities of daily living, involving objects of different shapes and difficulty levels, chosen to reflect functional, real-world actions. This setup allowed us to explore the interplay between sensory feedback, cognitive demand, visual attention, and motor effectiveness in a realistic and functional context and represents a preliminary step toward future longitudinal clinical validation. Our findings, although collected from healthy individuals and one prosthesis user in short-term experiments, suggest that DESC feedback is a promising strategy to enhance prosthesis usability by supporting performance without impacting cognitive load.

Conversely, DESC feedback did not consistently reduce participants' dependence on vision during task execution. These results support the use of this feedback modality without exacerbating cognitive burden, despite its effect on visual attention demand may be limited.

II. Methods

A. Participants

Six healthy participants (4 female, 27.66 $\pm$ 3 y/o) with no upper limb pathology or history of neurological or musculoskeletal impairment and one individual with right-sided transradial traumatic amputation (male, 62 y/o) were recruited for this study. All participants were right-handed and had little to no experience with controlling a prosthetic hand. Participants with prescribed contact lenses were asked to wear them during the experiments. All participants provided written informed consent to participate in the study, according to the Declaration of Helsinki. The study was approved by the local ethical committee of the Scuola Superiore Sant'Anna, Pisa, Italy (ref. 10/2023).

B. Experimental Setup

The experimental setup consisted of eye tracking glasses, a prosthesis bypass, a vibrotactile actuator, a synchronization module, a PC and a table hosting the objects and the tasks scene.

A wearable eye tracking system (Tobii Pro Glasses 3, Tobii AB, Sweden) was used. Two eye cameras for each lens acquired gaze positions on the x- and y-axes at a sampling rate of 100 Hz, while a third camera placed over the nose recorded the scene with a 1920 × 1080 px resolution at 25 frames per second.

A multi-articulated hand prosthesis (MIA Hand, Prensilia, Italy) was attached to a 3D-printed bypass and secured to the right forearm of the participant, simulating transradial amputation. The hand allowed to perform cylindrical, pinch and lateral grasps, and included a load cell on the thumb to measure the grip force. The opening and closing of the hand prosthesis were controlled through a custom embedded system via proportional EMG-to-speed mapping [48]. For this, two pairs of differential EMG electrodes were placed respectively along the wrist extensor and flexor muscles, for opening and closing, respectively. Additionally, a single reference electrode was placed on the olecranon bone [48]. EMG Signals were acquired with a sampling frequency of 1000 Hz and segmented in 200ms sliding time windows (150ms overlapping). Data were filtered with a digital second-order Butterworth 20 Hz high-pass IIR filter and a 50 Hz notch filter. Mean absolute value was extracted for each time window and channel, and the resulting values were then compared against subject-specific activation thresholds, triggering, if needed, the EMG-to-speed mapping. Moreover, a custom tactor based on a miniature vibration motor (*Precision Microdrivers, UK*) was applied over the skin in a myoelectric neutral area of the forearm to provide discrete vibrotactile sensory feedback each time a contact or release event was detected by the hand load cell. The vibrotactile stimulation had a frequency of 210 Hz and an amplitude of 3N.

An infrared sensor placed over a 10 × 15 cm rectangle support (home position) was used to enable a smooth synchronization of participants' movements with the eye tracking data. Participants were asked to place their hand on the infrared sensor while not executing any tasks. Data from the sensor were recorded with an Arduino Nano 33 Ble at a frequency of 20 Hz. A height-adjustable table, placed in front of a white wall, was used to host the objects and task scene. A whiteboard was placed over the table with lines drawn to clearly define areas where the objects should be placed during the tasks. The home position was placed on the bottom right corner of the table (Fig. 1).

C. Experimental Procedure

The experimental procedure consisted of three phases: first the device calibration, then the familiarization with prosthesis, feedback and motor tasks, and finally testing. Tests were executed in three conditions: prosthesis and feedback on (ON), prosthesis and feedback off (OFF), and with the natural dominant hand, hereafter as bare hand (BH). The order of conditions was randomized across participants.

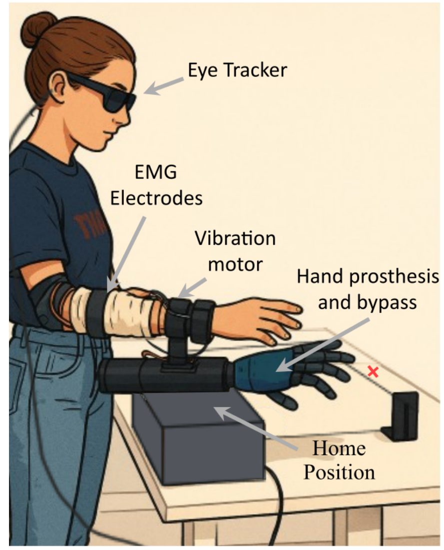

Fig. 1. Experimental Setup: the participant is standing in front of a table hosting the tasks scene, wearing eye tracking glasses and a myoelectric prosthesis bypass. The elbow is flexed at 90°, with the bypass in the home position.

The calibration phase concerned the eye tracking glasses as well as the EMG-based hand prosthesis control, the vibrotactile feedback and the table height. For the eye tracking calibration, participants were asked to comfortably wear the Tobii Pro glasses with the appropriate nose pad, and to fixate the centre of a calibration card placed at a distance between 0.5 m and 1 m. This fast automatic procedure was repeated at the beginning of each test condition. For the EMG-based control, participants were asked to perform alternating wrist extensions and flexions so to identify subject-specific activation thresholds for closing and opening the prosthesis. The duration of the vibrotactile stimulation was adjusted for each participant. To this aim, participants were provided with a series of stimulations with increasing duration ranging from 50 to 200 ms. The subject-specific duration was fixed at a value that was clearly perceived by participants, as verbally reported. Lastly, the table height was adjusted for each participant, aiming to roughly match the height of their pelvis. This height was deemed appropriate to allow the elbow to rest at 90° while in the home position, and to easily hover the hand prosthesis on the task scene.

In the familiarization phase the experimenter provided instructions for the execution of each task, and the participant had a chance to test them. At first, participants were requested to keep an idle position, resting the hand prosthesis steady in the home position in between trials. At the beginning and end of each task, participants were also asked to fixate a red cross placed in a neutral position in the top-centre of the table.

Then, the experimenter demonstrated how to perform the 7 motor tasks (Fig. 2). These tasks were directly inspired from ADLs and included:

1) 4 simple tasks: pick, lift and replace a banana; pick, lift and replace a bottle; pick and transfer a banana; pick

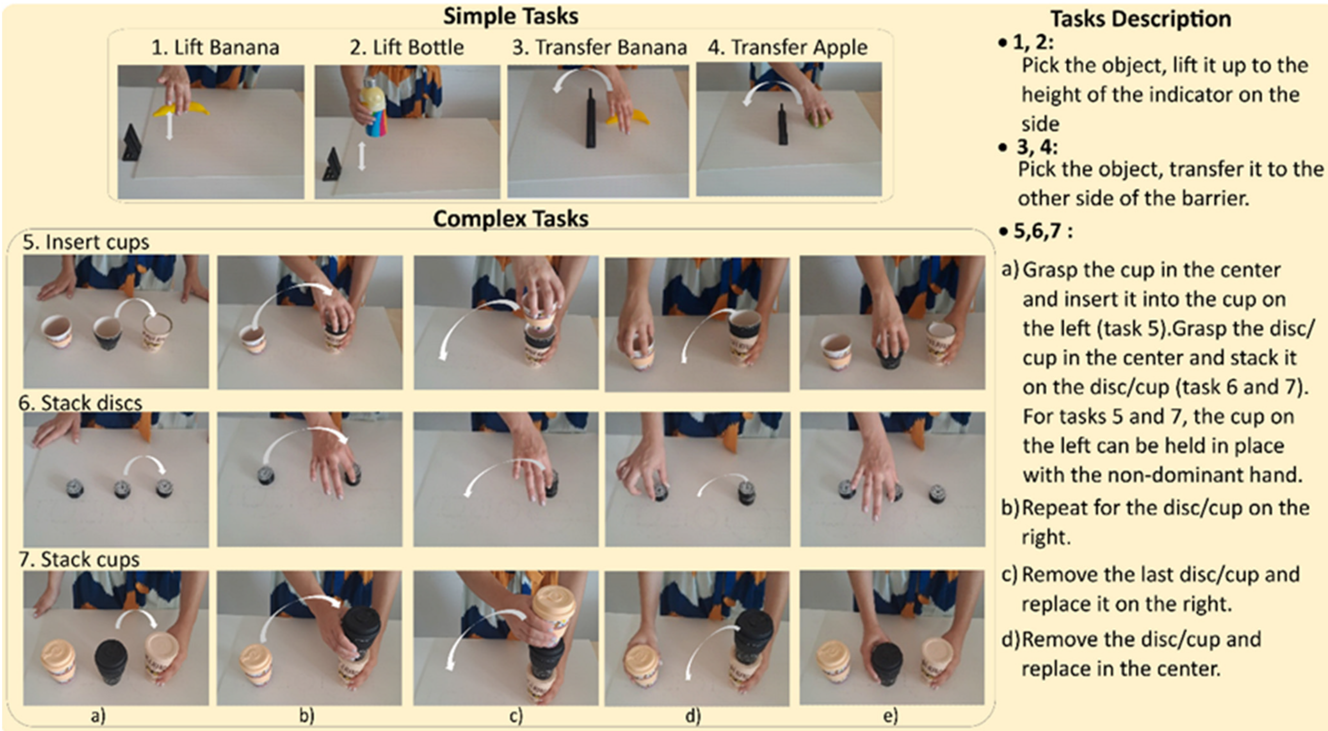

Fig. 2. Overview of the experimental tasks execution. When tasks were executed with the prosthesis a lateral cylindric grasp was used in tasks 2 and 7, while tasks 1,3,4,5 and 6 were performed with a cylindric grasp from top.

and transfer an apple. 10 repetitions were requested for each task

2) 3 complex tasks: insert 3 cups; stack 3 little discs; stack 3 cups. Each task consisted of four distinct phases, involving two assembly actions (insertion or stacking) and two disassembly actions in which the objects were returned to their initial positions.

All tasks were performed while standing in front of the table and controlling the hand prosthesis in a cylindrical grasp (i.e., no grasp switching was allowed). The wrist of the prosthesis was oriented before each task to perform side or top grips (Fig. 2). Each trial started and ended in the idle position (i.e., hand in the home position). Participants were encouraged to practise and familiarize with the myoelectric control of the prosthesis. For this, they were asked to rehearse each task at least once and until the execution was correct and they felt confident with the task sequence, prosthesis control, and sensory feedback.

During the testing phase, participants were asked to perform the motor tasks in the three conditions as fast as possible while avoiding unstable grasps and multiple attempts. To mitigate the risks of tactile perception suppression due to arm movements or due to hardware faults, participants were instructed to stop the experiment if no stimulation was perceived. Moreover, perception was also verified at the beginning and end of each trial. The simple tasks were always performed before the complex ones, but the order of the tasks in each category was randomized. Moreover, the order of the conditions was randomized between participants. After the execution of all the tasks in each testing condition, NASA-TLX was administered. Breaks were always provided after each test condition and between tasks if necessary. The findings obtained from the non-disabled participants were then validated in an experienced prosthesis user. Due to the participant's time availability, the pick-and-lift tasks were not performed. Tests were performed in the following sequence: BH (non-dominant hand), ON, OFF, with the same task order across conditions (4,3,6,5,7).

D. Data Analysis

The eye tracker data were pre-processed in the Tobii Pro Lab software (Tobii AB, Sweden) and segmented extracting Times of Interest (TOI, i.e. start and end of each task and of each trial) based on synchronization events. Gaze data were filtered with a moving median filter (5 samples window) and missing data (max gap length 80 ms) were corrected through interpolation. In addition, gaze data were discarded if information from at least one eye was marked as invalid by the Tobii Pro Lab algorithm. On average, about 8% of gaze data was discarded. Data about pupil size and position, saccade amplitude and fixation duration (detection threshold 100°/s) were extracted for each trial of each motor task and subsequently analyzed using Python 3.

The average saccade amplitude and pupil dilation were used as cognitive load metrics. The saccade amplitude is the angular distance travelled by the eye between two fixation points, and it increases as task difficulty or cognitive load decrease [39]. On the contrary, the pupil diameter increases as cognitive load increases [49]. To compute the variation in pupil size (i.e. pupil dilation), baseline correction was applied by subtracting the baseline measurement from the pupil diameter measured during task execution [50], [51]. The baseline pupil diameter was defined as the average pupil diameter computed over a 5-second time window during the rest period preceding the onset of each test condition. The reliance on visual feedback during a motor task was assessed by measuring the percentage of fixation on areas of interests (AOIs), i.e., the Object, the Hand (or both when moving together), and the Target, defined as the movement destination. A fixation was defined as a period in which the gaze remained at a specific location for a minimum of 100 ms [40].

An object detection algorithm (yolo11l-seg [52]) was used to identify objects (hand and the object to be manipulated) in frames extracted from each fixation. Then AOIs were attributed to fixations by comparing the object's bounding box with gaze coordinates. Then, through visual inspection, automatic classifications were checked and targets were assigned to the related fixations.

For each trial, the percentage of fixation time to each AOI was computed as shown in (1).

$$AOI\ Fixation\% = \frac{\sum_{i=1}^{n} Fixation_i Duration}{Trial\ Execution\ Time} * 100\% \quad (1)$$

A fixation was considered only if it was completely included within the temporal boundaries of the trial (i.e. it both began and ended during the trial). Additionally, the fixation immediately preceding movement onset, and ended after it was included as gaze typically precedes motor action [2], [3]. Lastly, data from all trials were averaged.

Execution time of each trial was computed as the time difference, in seconds, between the hand leaving and returning to the home position (i.e., the time in seconds to complete an entire trial). For complex tasks, as subphases were not identical, the execution time consisted of the sum of the four subphases durations.

To quantify the performance of task execution, a scoring protocol, detailed in Table I, was adopted. Each task was divided into 3 subphases: the grasp phase, the lift/transfer phase, and the replace phase. In addition, for complex tasks, an extra subphase was identified representing the key action of assembly/disassembly. The execution of the three subphases common to all tasks (i.e grasp, lift/transfer, replace), was assessed by checking a total of eight statements. For each one, when the statement was verified, a score of 1 was given; otherwise, the score was 0. The execution of the assembly/disassembly subphase of the complex tasks was assessed considering the number of attempts made (i.e Attempts) to complete it and the errors made in the successful attempt (i.e Errors). Both parameters were assessed by assigning a score from 0 to 3. The final subphase score was computed using (2) resulting in a value between 0 and 12; see Table I for more details. Then, the score of the single trial was obtained by summing all subphase scores (ranging from 0 to 8 for each simple task trial and from 0 to 20 for each of the four complex task phases). The final score for each task was computed by summing the scores from each trial and therefore ranged from 0 to 80 points. The total score was given by the sum of the single task scores and expressed as a percentage. The higher the total score, the better the performance. Scores were attributed by analyzing the video acquired with the eye tracker (two independent evaluators analyzed the video).

$$Score = (Attempts * Errors) + Attempts \quad (2)$$

E. Statistical Analysis

The NASA-TLX questionnaires administered at the end of each test condition, were analyzed to compute the overall score and the score of each subdomain: mental demand, physical demand, temporal demand, performance, effort, and frustration.

For each participant, the outcome metrics extracted from gaze data and execution time were summarised using the average value across trials for each task of each control condition. The distribution and homogeneity of variances of the data were evaluated using the Shapiro–Wilk and Levene test, respectively. Since the dataset exhibited non-normal distributions, the Friedman test was used, followed by post-hoc pairwise comparison (Wilcoxon signed rank test). Statistical analysis was conducted in Python 3 to assess whether performing a task with a hand prosthesis equipped with tactile feedback resulted in comparable workload, reduced visual attention and enhanced motor performance compared to no feedback. A p-value < 0.05 was considered statistically significant. Results are presented as median and interquartile range (IQR) using the format median (IQR).

III. Results

All participants successfully completed the experimental protocol in a single session lasting up to 1 hour; each test condition and the familiarization phase lasted approximately 10 minutes.

A. Cognitive Load

As expected, both saccade amplitude and pupil dilation indicate that the cognitive load was lower when performing the tasks with the bare hand (Fig. 3.a, 3.b; Table II), albeit the Friedman test proved not significant in all the tasks (Table II)

In non-disabled participants, no significant differences were observed when comparing saccades amplitude and pupil dilation between ON and OFF conditions across all tasks (Fig. 3.a, 3.b). This would indicate that providing tactile feedback according to DESC policy while using a simulated prosthesis device did not increase cognitive load. Interestingly, with feedback ON, a trend towards larger saccade amplitude was noted on simple tasks (task 1, 3 and 4) and when stacking discs (Fig. 3, Table II). For these tasks, the difference in the pupil dilation between ON and OFF conditions was lower than 0.08mm, suggesting a similar mental load. In contrast, an opposite trend was observed in task 5 with respect to both saccade amplitude and pupil dilation and in task 7 only with respect to saccade amplitude. (Fig. 3, Table II).

The results from the amputee participant proved consistent with non-disabled participants showing similar cognitive load between feedback and without feedback conditions. The only exception was task 5, in which, even if not significant, there was a greater difference in favour of ON condition for saccade amplitude (BH:19.05 (5.90), ON:14.71 (12.10), OFF:7.29

TABLE I

SCORING CRITERIA USED TO ASSESS MOTOR PERFORMANCE IN EACH TASK PHASE. IN COMPLEX TASKS, "ASSEMBLY" CORRESPOND TO THE PHASES A) AND B) SHOWN IN FIG. 2. THEIR ASSESSMENT IS CARRIED OUT SEPARATELY BUT USING THE SAME SCORE CRITERIA (I.E GIVING A SCORE BETWEEN 0 AND 3). SIMILARLY, THIS WAS DONE FOR "DISASSEMBLY" SUBPHASE THAT CORRESPONDS TO THE KEY ACTION OF PHASES C) AND D), AS DESCRIBED IN FIG. 2

Task	Sub-phase	Score
Simple and Complex tasks	Grasp	a. Only one grasping attempt made: score 1, otherwise 0 b. Object grasped with correct grip: score 1, non-optimal grip: score 0
	Lift/ Transfer	c. The object does not slip: score 1, otherwise 0 d. The object does not fall: score 1, otherwise 0
	Replace	e. During the replacement of the object, it does not slip: score 1, otherwise 0 f. During the replacement of the object, it does not fall: score 1, otherwise 0 g. There is no difficulty in repositioning the object correctly: score 1, otherwise (object is wobbling, positioned outside the designated area, needs to be repositioned): score 0 h. There is no uncertainty/more attempts in opening the hand after repositioning the object: score 1, otherwise 0
Complex tasks	Number of attempts score: 1, score: 3 2, score 2 3, score 1 Unable, score 0	
Insert cups	Assembly	a. No errors, score 3 b. The cup oscillates during insertion into the other cup, score 2 c. The cup bumps into the other cup during insertion, score 1 d. Unable/the other cups falls, score 0
	Disassembly	a. No errors, score 3 b. The cup inserted in the other, it oscillates as it is removed/ uncertainty when placing, score 2 c. The cup hits the other one while being taken out, score 1 d. Unable/the other cups falls, score 0
Stack discs	Assembly	a. No errors, score 3 b. The disc is not positioned in the center of the other (partial overlapping of discs), score 2 c. Disc repositioning required, score 1 d. Unable/the other disc falls, score 0
	Disassembly	a. No errors, score 3 b. Uncertainty/oscillations while removing the disc, score 2 c. The position of the disc on top of the other is changed in the removal, score 1 d. Unable/the other disc falls, score 0
Stack cups	Assembly	a. No errors, score 3 b. The cup is not positioned in the center of the other (partial overlapping of cups), score 2 c. Cup repositioning required, score 1 d. Unable/the other cup falls, score 0
	Disassembly	a. No errors, score 3 b. Uncertainty/oscillations while removing the cup, score 2 c. The position of the cup on top of the other is changed in the removal, score 1 d. Unable/the other cup falls, score 0

(5.61), BH vs OFF p = 0.02; Fig. 3.a). In bare hand condition, the participant showed lower cognitive load compared to prosthesis conditions, except for the first two tasks carried out (tasks 4 and 3), in which the pupil dilation was higher (Fig. 3 b). Overall, the prosthesis user exhibited lower cognitive load than non-disabled participants, as indicated by saccade amplitude and pupil dilation, perhaps reflecting his 40 + years' experience with myoelectric prostheses.

B. Perceived Workload

NASA-TLX scores indicated that when using the prosthesis, both without and with feedback, participants experienced higher mental demand (BH vs ON $p = 0.03$, BH vs OFF $p = 0.03$), physical demand (BH vs ON $p = 0.03$, BH vs OFF $p = 0.03$), effort (BH vs ON $p = 0.03$, BH vs OFF $p = 0.03$) and frustration (BH vs ON $p = 0.03$, BH vs OFF $p = 0.03$) and perceived a lower performance (higher values indicates poorer performance, BH vs ON $p = 0.04$,

BH vs OFF $p = 0.04$) with respect to the bare hand control condition (Fig. 3.c). As concerns the temporal demand, no differences were found across the three conditions ($p = 0.07$). Compared to no feedback, the ON condition resulted in significantly lower mental demand (ON: 11 (9), OFF: 14.5 (2); $p = 0.04$). When analysing the total workload score, it proved lower in the ON condition with respect to OFF, even if not statistically significant (*p = 0.06; ON: 8 (2.17); OFF: 10.92 (2.5)*). As concerns the amputee participant, he showed higher perceived cognitive and physical load with the feedback ON and higher perceived effort without feedback. The perceived temporal demand was higher in the initial condition (BH), and then it progressively decreased following the order of execution of the conditions.

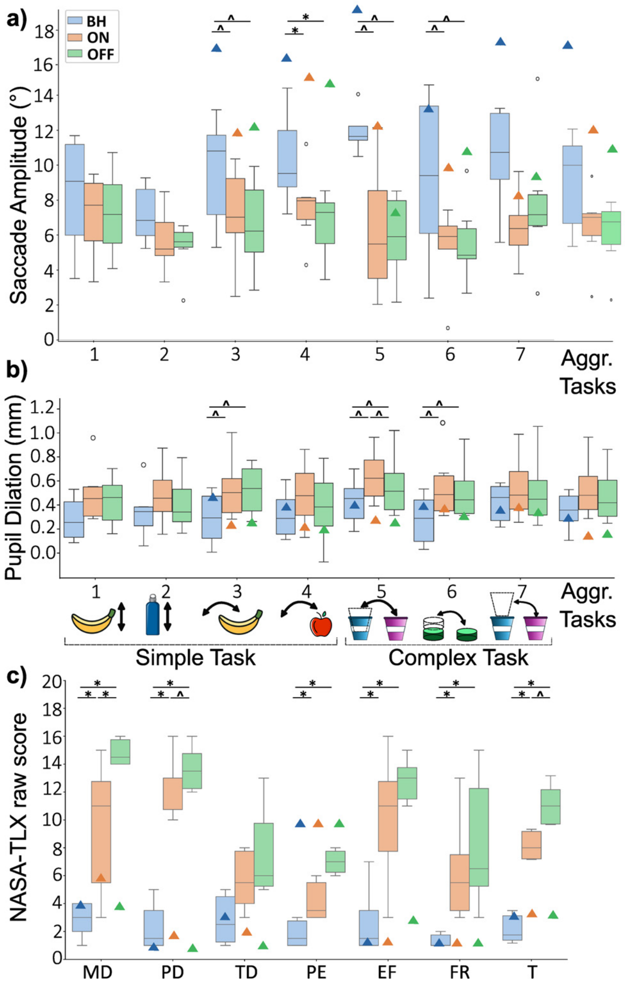

Fig. 3. Results of Workload outcome metrics in each test condition (blue for Bare Hand, orange Feedback ON, green Feedback OFF, Amputee results shown as Triangles). a) Saccade Amplitude for each task; b) Saccade Amplitude for all task aggregated; c) NASA-TLX questionnaire scores, MD= Mental Demand, PD=Physical Demand, TD=Temporal Demand, PE=Performance, EF=Effort, FR=frustration, T=total score. (* indicates $p < 0.05$, ^$p < 0.1$).

C. Visual Attention

Across all tasks, non-disabled participants in the BH condition exhibited a consistent pattern of visual attention: compared to prosthesis-use conditions, they showed a lower percentage of fixations on the Object and the Hand, and a higher percentage on the Target (i.e., the location in which the object has to be replaced) (Fig. 4). A similar pattern was observed in the amputee participant, with fewer fixations on the hand in the BH condition. However, in transferring apple and stacking discs, the amputee adopted a different gaze strategy, showing fewer fixations on the target in the BH condition compared to prosthesis-use conditions.

When evaluating the effect of feedback on visual attention in intact-limb individuals, it resulted in no significant difference with respect to the OFF condition; only a weak difference was observed in terms of fixation percentage on the target in task 1 ($p = 0.06$, ON: 6.48 (7.60); OFF: 2.62 (3.56)). However, with feedback, participants showed slightly more fixations on the target (tasks 2, 4 and 6) and a reduced visual attention on the object and hand (tasks 3 and 5, Fig. 4 and Table II)

Considering the fixations aggregated from all tasks, a tendency towards a more natural gaze behaviour was found (i.e., more fixations on the target) when non-disabled participants received the feedback (BH vs ON $p = 0.03$, BH vs OFF $p = 0.03$, ON vs OFF $p = 0.09$; *BH: 25.74 (14.42); ON: 20.50 (11.22); OFF: 17.67 (12.61)*). This result was also confirmed by the fixation percentages on the object and hand (BH: 58.09 (19.72); ON: 63.10 (28.62); OFF: 69.61 (33.96)), even though not significant. Consistently, the prosthesis user showed no significant differences in visual attention when comparing ON and OFF conditions. The same trend towards fewer hand fixations was found with the feedback in tasks 4 and 7. Overall, the amputee required less visual monitoring of the hand during prosthesis use, as indicated by fewer fixations on the hand, which is consistent with greater experience in myoelectric control.

D. Motor Performance

In terms of execution time, both healthy participants and the amputee were significantly faster in the BH control condition (Fig. 5.a; 5.b). When using the prosthesis, healthy participants showed a non-significant trend of shorter execution time between ON and OFF conditions, in all the tasks with the exception of stacking discs (Table III). Regarding the amputee participant, no differences were found in terms of execution time except for task 3, in which the ON condition resulted in slower performance (ON: 4.07s, OFF:3.90s, Fig 3.a). As for non-disabled participants, tasks 5 and 7 showed a similar trend toward longer execution time when using the prosthesis without feedback (task 5: ON:18.30s, OFF: 19.72s, task 7: ON: 22.03s, OFF: 22.80s). Compared to the non-disabled participants, the prosthesis user was faster while using the prosthesis in all the tasks (Fig. 5 b).

Non-disabled participants successfully completed all the tasks with maximum score in the BH control condition (Fig. 5.c). As expected, the performances were poorer with the simulated prosthetic hand and, overall, the sensory feedback improved the performance and reduced mistakes (Table III); more in detail, the DESC feedback significantly higher scores were obtained in 3 tasks with respect to the OFF condition (task 1: $p = 0.03$, task 2: $p = 0.03$; task 3: $p = 0.04$). The amputee participant proved superior motor performance with feedback, consistently with what observed with non-disabled participants. Specifically, he showed an improved performance in transfer banana (task 3: ON:79, OFF:70), insert cups (task 5: ON: 79, OFF: 70) and stack cups (task 7 ON: 79, OFF: 67), and comparable performance in the remaining tasks.

IV. Discussion

This study aimed to investigate whether the use of a robotic hand equipped with vibrotactile feedback—providing short vibrations at object contact and release—would influence cognitive load, visual attention, and motor performance when used for the first time by non-disabled participants through a bypass socket and by an experienced prosthesis user. To explore this, the performance obtained with feedback was compared with normative data (Bare Hand condition) and with

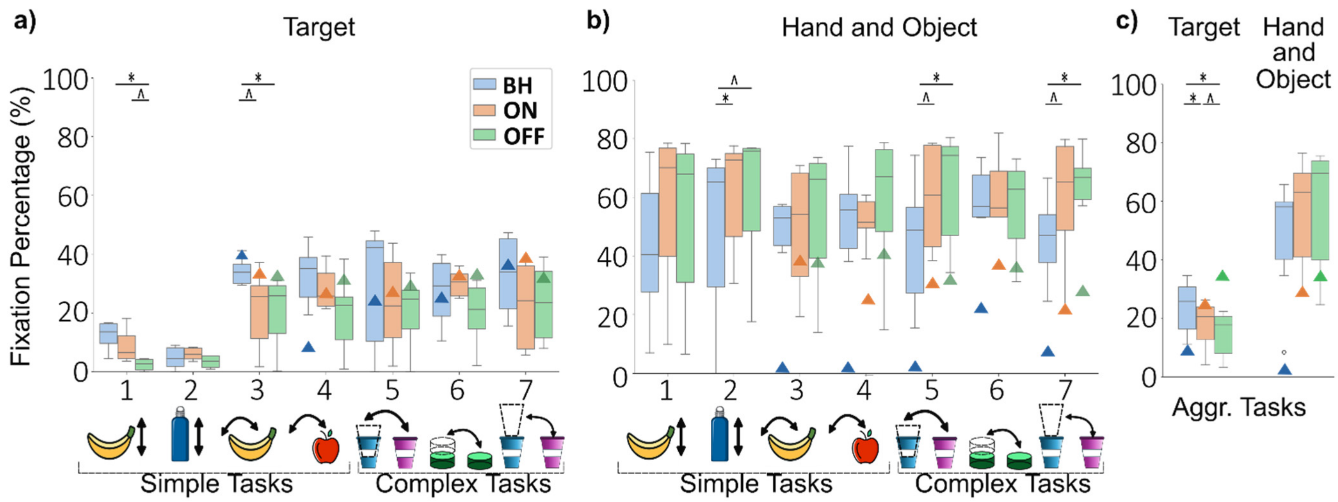

Fig. 4. Visual Attention results expressed in terms of fixation percentage on the Target (i.e. the final location of the object) and on the Hand and Object respectively in a) and b) for each task, and in c) for all tasks aggregated. Amputee results shown as Triangles (* indicates $p < 0.05$, ˆ$p < 0.1$).

TABLE II
Cognitive Load and Visual Attention Results for Each Task (Columns) and Each Condition (rows). Results are Reported as Median (IQR). For Each Metric, the Corresponding P-Value (p) From the Friedman Test is Reported: * Indicates $p < 0.05$, ** $p < 0.001$

		1	2	3	4	5	6	7
Saccade Amplitude	BH	9.08 (5.19)	6.84 (2.64)	10.81 (4.54)	9.53 (3.22)	11.64 (0.80)	10.43 (5.99)	10.73 (3.77)
	ON	7.71 (3.28)	5.20 (1.90)	7.46 (3.84)	7.96 (1.25)	5.46 (2.58)	5.92 (1.32)	6.51 (1.09)
	OFF	7.18 (3.34)	5.62 (0.84)	7.09 (4.15)	7.30 (2.32)	6.78 (3.35)	5.05 (2.15)	7.62 (1.82)
	p	n.s.	n.s.	*	**	*	*	n.s.
Pupil Dilation	BH	0.25 (0.29)	0.35 (0.15)	0.3 (0.35)	0.29 (0.31)	0.45 (0.25)	0.29 (0.34)	0.48 (0.29)
	ON	0.45 (0.22)	0.45 (0.26)	0.5 (0.28)	0.47 (0.35)	0.61 (0.28)	0.49 (0.28)	0.49 (0.3)
	OFF	0.46 (0.29)	0.35 (0.26)	0.53 (0.34)	0.39 (0.37)	0.53 (0.32)	0.35 (0.27)	0.49 (0.3)
	p	*	n.s.	**	n.s.	*	*	n.s.
Fixation Target	BH	13.55 (6.6)	4.54 (6.29)	33.84 (6.47)	35.14 (13.45)	42.20 (34.19)	29.32 (17.91)	34.02 (23.82)
	ON	6.48 (7.60)	5.89 (3.58)	22.54 (17.96)	25.73 (11.24)	22.41 (25.55)	30.54 (7.47)	24.21 (28.19)
	OFF	2.62 (3.56)	3.59 (3.88)	25.79 (16.28)	22.65 (14.52)	24.72 (13.17)	21.24 (13.85)	23.43 (22.61)
	p	*	n.s.	*	n.s.	n.s.	n.s.	n.s.
Fixation Hand + Object	BH	40.40 (33.56)	65.25 (40.67)	52.93 (13.39)	55.66 (18.49)	48.77 (29.25)	56.84 (14.32)	47.09 (16.38)
	ON	70.15 (36.85)	72.79 (28.34)	54.27 (35.34)	51.43 (8.95)	60.81 (34.58)	56.38 (15.73)	65.32 (28.65)
	OFF	67.93 (43.72)	75.81 (28.22)	66.19 (32.40)	67.11 (27.96)	74.33 (30.36)	62.73 (22.96)	66.84 (10.58)
	p	n.s.	*	n.s.	n.s.	*	n.s.	*

the use of the prosthesis without feedback. Such an experiment could be susceptible to tactile stimuli suppression due to the task-related movement of the arm or residual limb [53], [54]. Through our verification protocol, the participants did not report this phenomenon and declared they clearly perceived the stimuli throughout the entire experiment. We argue that this outcome was due to the event-driven nature of the stimuli, that ensured perceptual redundancy and salience [19], [21].

Overall, our findings indicate that receiving event-related feedback did not negatively affect cognitive load, as assessed through both subjective and objective measures. This is in line with our initial hypothesis and consistent with previous work suggesting that DESC feedback, delivering information naturally used in the motor control loop, can be easily integrated into it [19], [23].

Specifically, in non-disabled participants, lower perceived mental load in NASA-TLX questionnaire and comparable cognitive load (i.e. similar saccade and pupil dilation) were observed in simple tasks under the feedback condition (Fig. 3). Furthermore, in simple tasks, the feedback ON condition was associated with fewer errors than OFF condition (Fig. 5.c). However, these feedback benefits were less evident in complex tasks that were less repetitive and required more focus to execute the sequence of motor actions correctly. Particularly in tasks involving cup manipulation, we observed a slight trend toward higher cognitive load in the feedback condition, accompanied by greater variability in motor performance, even if not deteriorated with respect to the OFF condition. Interestingly, in the discs-stacking task, the cognitive load was comparable between feedback ON and OFF conditions, but the execution time was slightly longer when feedback was provided. Arguably, in participants with no experience in myoelectric prosthesis control and feedback, when task demands exceed the available cognitive capacity, processing the feedback may be less immediate, and its advantages might be masked by the overall challenge of task planning and execution. In such situations, participants may either prioritize error avoidance rather than the feedback processing (i.e., tasks 5 and 7), or, alternatively, feedback integration may

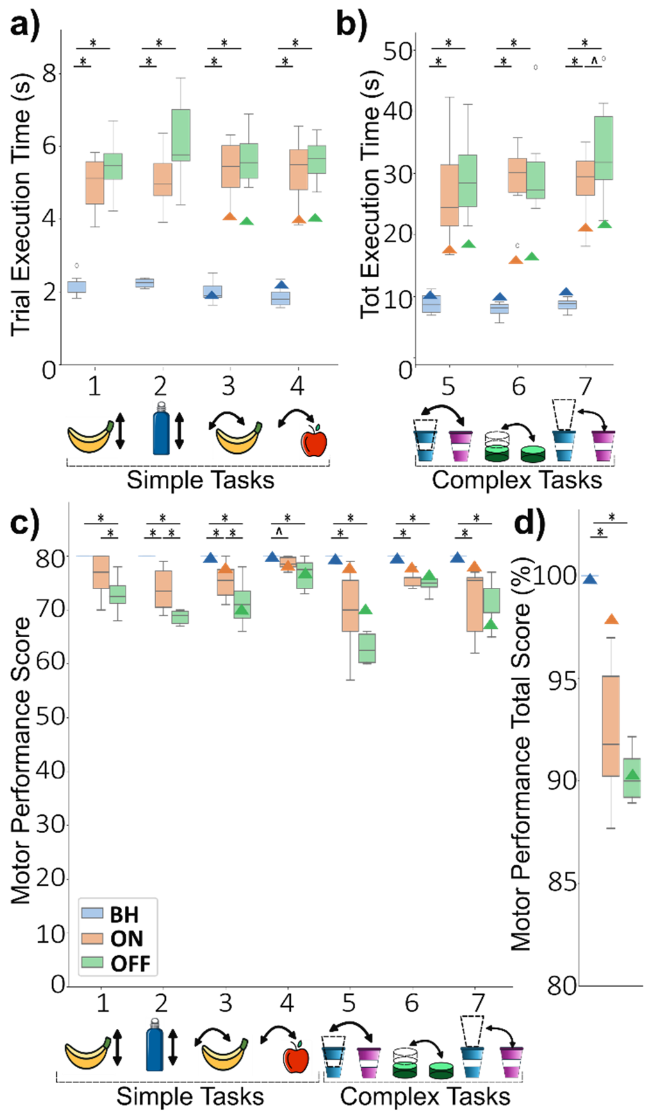

Fig. 5. Motor Performance results. a) Execution Time averaged on trials of simple tasks. b) Total Execution time of complex tasks. On the right: Motor Execution Quality Score for each task c) and total score of all tasks d). Amputee results shown as Triangles. (* indicates p < 0.05, ˆp< 0.1).

occur without adding cognitive load but at the cost of longer execution time (task 6).

A direct comparison between the non-disabled participants and the prosthesis user is partially limited by the fact that the two pick-and-lift tasks were not performed by the amputee due to time constraints. Nevertheless, the amputee participant exhibited a behaviour similar to the non-disabled participants, with saccade amplitude and pupil dilation indicating comparable cognitive load with and without feedback. The prosthesis user showed a slight reduction in saccade amplitude while transferring banana and stacking discs with feedback ON (Fig. 3). This behaviour is unlikely to reflect feedback-driven cognitive load, given the small difference relative to the saccade baseline and similar pupil dilation to OFF condition. It is more likely that a different visual search strategy is required when manipulating small objects during the first task execution (ON condition). Regarding execution time, the amputee, highly

TABLE III
MOTOR PERFORMANCE RESULTS FOR EACH TASK AND EACH CONDITION

Outcome	Task	BH	ON	OFF
Execution Time (s)	1	2.00 (0.30)	5.13 (1.16)	5.47(0.70)
	2	2.25 (0.21)	4.96 (0.89)	5.77 (1.40)
	3	1.89 (0.32)	5.46 (1.15)	5.56 (0.95)
	4	1.80 (0.36)	5.50 (1.10)	5.67 (0.75)
	5	8.65 (2.66)	24.47 (9.91)	28.45 (8.42)
	6	8.15, (1.47)	30.10 (5.52)	27.32 (5.93)
	7	8.82 (1.25	29.47 (5.57)	31.77 (10.24)
Score	1	80.00 (0.00)	77.00 (6.00)	72.50 (3.25)
	2	80.00 (0.00)	73.50 (6.75)	69.00 (2.25)
	3	80.00 (0.00)	75.50 (4.75)	71.00, (5.00)
	4	80.00 (0.00)	78.50 (1.75)	77.50 (4.75)
	5	80.00 (0.00)	70.00 (9.50)	62.50 (5.25)
	6	80.00 (0.00)	76.00 (1.50)	75.00 (1.50)
	7	80.00 (0.00)	75.50 (10.00)	74.00 (4.50)

proficient in prosthesis use, showed no substantial differences between conditions, likely due to a ceiling effect in his baseline performance compared to healthy participants. However, the improvements observed in terms of motor performance scores suggest that feedback may be more effective during the most challenging tasks.

Overall, the tendency found in ON condition, towards faster and improved performance in comparison to the absence of feedback, further supports the effectiveness of DESC feedback in functional tasks that are different from those previously investigated [19], [22], [23], [24].

As concerns the effect of feedback on restoring normal gaze behaviour, comparison with previous results is limited by the fact that these studies were focused on other feedback strategies. Raveh et al. [55], [56] found that adding grip-force proportional vibrotactile feedback had no effect on the gaze behaviour of prosthesis users performing a dual-task paradigm that required visual attention. However, the authors hypothesized that this testing paradigm may not have been appropriate for identifying the effects of feedback suggesting that the secondary task may not have adequately challenged the user. In addition, visual attention was only required at the beginning and end of the motor task. Considering that information could be processed through peripheral vision, gaze location may not be an effective indicator of attentional demand in a dual task.

In another study by Marasco et al. [25], sensory feedback has demonstrated the potential to restore typical visuomotor patterns in two amputees who underwent targeted motor and sensory reinnervation. The authors compared gaze behaviour in a cup and pasta box transfer task (Gaze and Movement Assessment, i.e. GaMA protocol) across three conditions: no feedback, tactile feedback and the combination of tactile and kinesthetic feedback. Stimuli were provided through tactors respectively at contact events, with a pressure proportional to the grip force (tactile) and through vibration in correspondence with hand closing (kinesthetic). Compared to no feedback, when both sensory information was provided, visual fixations towards the hand were reduced when reaching and transporting objects, and one participant also exhibited increased visual fixations to the next target location. When only tactile feedback was provided, no significant benefits were found in terms of visual attention.

Unlike the GaMA protocol aforementioned [2], [25], [57] we did not use a motion capture system to segment the movement into distinct phases (i.e., reaching and transport) and to analyze visual attention separately. To address our research question, we deemed a less detailed visual behaviour analysis to be sufficient. This assumption is based on the idea that providing feedback concurrent with object contact and release is unlikely to affect the need for gaze-based control of the prosthesis during the reaching phase—a phenomenon that is likely to be more pronounced when kinesthetic feedback is provided, as in their study.

Comparison with the results reported by Marasco et al. [25] supports our idea that analyzing visual attention over the entire task can still yield meaningful information. In their study, the percentages of fixations on the object during the reaching phase and on the hand + object during the transport phase fall within the range of our fixation values for hand + object. While our fixations on the target are lower, they remained consistent with their transport phases if considering that their percentages are calculated over a shorter time interval (transport phase), rather than over the total task duration, as in our case. In addition, we obtained a lower percentage of fixation on the target in tasks 1 and 2, which is consistent with the nature of the lifting task that requires only replacing the object in the starting position.

Overall, similar to the results obtained by Marasco et al. [25] about touch feedback condition, we did not find a significant reduction of visual attention towards the hand and object across all tasks (Fig. 4.b). Considering that increased reliance on vision to monitor prosthesis status has been attributed to grip insecurity and unreliability of myoelectric control [58], [59], [60] it is plausible that tactile information alone, as we investigated in our study, is insufficient to provide full confidence in grip stability and that kinesthetic information is needed to effectively reduce visual monitoring of the hand. However, further analyses are needed to directly compare the effects of different feedback modalities. Nonetheless, a modest pattern emerged suggesting the potential of DESC feedback in promoting a shift of visual attention toward the target compared with no-feedback conditions (Fig. 4.a).

Similar to healthy participants, the amputee showed comparable visual attention across ON and OFF conditions in most of the tasks. Interestingly, in the first executed task (i.e. Transfer Apple), the participant showed less need to fixate both hand + object and target when feedback was provided. Upon the removal of feedback, there was an immediate increase in visual reliance despite the greater participants' experience. However, visual attention decreased in the following tasks, reaching levels similar to those in the feedback condition. This indicates adaptation to the absence of feedback up to the final task executed. Specifically, when stacking cups without feedback, the participant showed increased visual attention on the hand + object and less on the target. Notably, this was accompanied by a decline in motor performance and longer execution time compared to the ON condition. This suggests that feedback was effectively exploited during complex manipulations, and that once removed, compensatory strategies become insufficient to maintain optimal gaze patterns and functional efficiency.

The absence of a consistent difference in terms of visual attention between ON and OFF conditions could be explained considering that the participants in our study were introduced to the feedback for the first time. The short familiarization phase could limit the possibility to fully incorporated the DESC feedback in the sensorimotor control. Similarly, longer training could be needed to significantly reduce the cognitive load [23]. This hypothesis is supported by previous studies on different feedback modalities, showing that multiple training sessions are sometimes required to observe positive effects on motor performance [61], [62].

In addition to the limited exposure to the feedback, another explanation for the limited evidence and variability observed across participants is the limited sample size and the possible role of unreliable myoelectric control experienced, especially by naïve users [63], [64], [65]. To limit the potential confounding effect of unpredictable control, in addition to a familiarisation phase, we sought to minimize factors that could increase its complexity: grasp type and wrist position were fixed before each task, and a simple EMG-to-speed control mapping modality was adopted. Nevertheless, we cannot exclude the possibility that different control strategies might yield different effects in terms of feedback benefits. Indeed, the idea that early difficulties in motor control may mask feedback advantages is consistent with previous findings, demonstrating that, in some tasks, the benefits of feedback become evident only once prosthesis control improves [61]. In addition, previous studies have reported reduced cognitive load [44] and changes in gaze behavior [66], [67] as participants progressively learned to control a prosthesis, even in the absence of explicit feedback. This is further supported by the fact that, regardless of the condition, the skilled prosthesis user, showed a reduced cognitive load and a reduced need to visually monitor the prosthesis compared to healthy participants (Fig. 3 and Fig. 4). Hence, expanding this analysis introducing feedback in participants with prior experience in myoelectric control could provide clearer insights into its contribution by minimizing the confounding variability introduced by difficulties in prosthesis control itself. On the other hand, the presence of effective, well-established compensatory strategies that result in few internal model errors may reduce the need for integrating new information and updating the model. Moreover, expanding this analysis to experienced prosthesis users should help in discerning the relative role of motor control proficiency and sensory on cognitive load, gaze strategies, and task performance; moreover, a longitudinal study design can help in obtaining more insight about how they change in relation to feedback learning.

The key role that feedback, cognitive demand and visual burden may have in prosthesis and device abandonment and dissatisfaction [11], [68] highlights the importance of further investigation in this direction. The setup and methodology proposed was proven suitable for obtaining information not only on motor performance but also on cognitive load and visual attention, which can add relevant information in understanding how sensory feedback is integrated in sensorimotor control. In addition, since our protocol is based on everyday-life tasks, it can be applied not only in the prosthetic field but also to deeply investigate the effects of sensory feedback in rehabilitation.

Finally, unlike other physiological measures, the use of eye tracking provides information on both cognitive and visual attention domains. It also allows for a lighter setup and faster processing, while being less affected by body movements [7], [26], [38]. Such advantages come at the cost of some cautions on light condition [69] and inclusion criteria (e.g., it cannot be employed in individuals who underwent eye surgery).In conclusion, the trends observed towards positive effects on motor performance, coupled with the minimal cognitive demand, support the use of this feedback strategy as a promising approach for prosthesis control.

Author Contributions

Virna Marliani and Tommaso Mori performed experiments. Virna Marliani analyzed data and wrote the first draft of the manuscript. All the authors contributed in the study design, reviewed, and approved the submitted manuscript.

Competing Interests

Christian Cipriani holds shares in Prensilia S.r.l.

Acknowledgment

The authors would like to thank all who participated in the experiments.

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