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Published in:
I E E E Transactions on Biomedical Engineering

DOI (link to publication from Publisher):
10.1109/TBME.2021.3052065

Publication date:
2021

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Johansen, D., Popovic, D., Dosen, S., & Struijk, L. N. S. A. (2021). Hybrid Tongue-Myoelectric Control Improves Functional Use of a Robotic Hand Prosthesis. *I E E E Transactions on Biomedical Engineering*, *68*(6), 2011-2020. [9325542]. https://doi.org/10.1109/TBME.2021.3052065

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TBME.2021.3052065, IEEE Transactions on Biomedical Engineering

Hybrid Tongue - Myoelectric Control Improves Functional Use of a Robotic Hand Prosthesis

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***Abstract*— *Objective:* This study aims at investigating the functional performance of a novel prosthesis control scheme integrating an inductive tongue interface and myoelectric control. The tongue interface allowed direct selection of the desired grasp while myoelectric signals were used to open and close the robotic hand. *Methods:* The novel method was compared to a conventional sequential on/off myoelectric control scheme using functional tasks defined by Assistive Hand Assessment protocol. Ten able-bodied participants were fitted with the SmartHand on their left forearm. They used both the conventional myoelectric control and the Tongue and Myoelectric Hybrid interface (TMH) to accomplish two activities of daily living (i.e., preparing a sandwich and gift wrapping). Sessions were video recorded and the outcome measure was the completion time for the subtasks as well as the full tasks. *Results:* The sandwich task was completed significantly faster, with 19% decrease in the completion time, using the TMH when compared to the conventional sequential on/off myoelectric control scheme ($p < 0.05$). *Conclusion:* The results indicate that the TMH control scheme facilitates the active use of the prosthetic device by simplifying grasp selection, leading thereby to faster completion of challenging and relevant tasks involving bimanual activities.**

***Index Terms*— Functional Assessment, Hand Prosthetics, Robotic Hands, Control Schemes, Tongue Control, Myoelectric Control.**

I. Introduction

IN the last two decades many novel prosthetic arms and hands have been introduced into the field of upper limb prosthetics. The appearance, movements and the supported grasp types in these systems increasingly resemble those present in the natural hand. [1]

Several of the novel prosthetic hands have been successfully commercialised, but the control schemes implemented at the clinics and used by amputees have not improved according to the advances in the prosthesis control made in academia.

As concluded by Vujaklija et al. [3] most of the commercially available devices still rely on EMG based myoelectric control schemes developed decades ago. Most commonly, two channels of EMG placed on an antagonistic muscle pair (e.g., hand flexors and extensors) are used to drive two directions of a single degree of freedom (DoF) of a prosthetic hand (e.g., closing and opening). This enables direct and proportional control of a simple gripper. Control of the multiple DoFs that are supported by the new prosthetic hands is typically implemented using a state machine to provide sequential control of the available DoFs [2]. This approach utilises co-contractions or other specific muscle activation patterns, to allow the user to cycle through the functions (e.g., switch between grasp types or between grasp and wrist control).

In line with Vujaklija et al. [3], Jiang et al. [4] also refers to a gap between the industry and academic achievements in terms of prosthesis control. Unsatisfactory control is the current bottleneck in achieving an increased clinical impact with the myoelectric upper limb prostheses [3],[4]. The prosthesis users demand systems that can effectively perform different grasping actions (e.g., power, pinch, lateral, neutral grasps and finger pointing) and simple manipulation tasks enabling the execution of ADLs. [5]

An approach for providing enhanced prosthesis control, that has been the subject of extensive research, is pattern classification of myoelectric signals [6]-[8]. In this scheme, machine learning is used to recognize user motor intention from the muscle activation patterns recorded using multichannel EMG. Therefore, the user can select desired function directly without the need for sequential switching. Pattern classification is a promising approach, and two solutions are now commercially available (i.e., Coapt [9] and MyoPlus [10]), but they still have to prove their clinical effectiveness and usability.

Pattern classification methods do not allow for simultaneous and proportional control of prosthesis functions. For this, regression methods can be used but they are typically limited to controlling at most 2-3 DoFs [6]. Furthermore, the classification algorithms do not adapt to the changes occurring in the EMG signals during use e.g. due to sweat, electrode shifting, muscle fatigue, and therefore they lack robustness.

Different approaches have been tested so far to address the limitations of myoelectric control. For example, some studies

Manuscript received June 19th, 2020. This work was supported in part by Bevica Innovation A/S, The Danish Agency for Science, Technology and Innovation and Sahva A/S.

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proposed the integration of other sensor modalities into the control scheme (e.g. inertial sensing [11] force myography [12], computer vision [13] and ultrasound [14]). In Carrozza et al. [15], foot switches were used to select different grasping patterns in a dexterous hand, while in [16], foot commands detected using inertial measurements units were employed to control a full prosthetic arm. Another solution for the control of a dexterous prosthesis (i-Limb Quantum) is grasp selection based on proximity and gesture detection. The latter uses inertial measurement units to detect specific movement patterns that activate associated grasps, while in the former, target object is tagged by a compact wireless unit (Grip Chip) that activates predefined grasp(s) when the prosthesis approaches the object [17].

A novel approach to the control of robotic hands has recently been proposed by Johansen et al. [17]-[20]. This scheme combines an inductive tongue control system with EMG control signals. The proposed Tongue and Myoelectric Hybrid control scheme (TMH) allows direct activation of grasps using the tongue interface, and proportional control of opening and closing using two EMG signals.

Previous results showed that the TMH outperformed a conventional EMG (cEMG) control scheme in an abstract task that required dexterous multi DoF control [18]. The subjects were asked to activate the desired grasp indicated on a computer screen. However, the effectiveness of the proposed control scheme in terms of functional performance when operating a dexterous hand prosthesis during activities of daily living (ADL) still needs to be addressed.

The objective of the present study was therefore to evaluate the TMH presented by Johansen et al. [18] from a functional performance perspective in an ADL context and compare this novel approach to cEMG control used in commercial prostheses. This evaluation was based on the functional tasks defined by the Assisting Hand Assessment for adults with upper limb Prosthesis, Amputations and Deficiencies (AHA-PAD) [21], [22]. The tests focuses on the completion of the ADL tasks characterised by bimanual activities, which are particularly challenging for prostheses users. The inclusion of bimanual activities in the AHA test is especially important because these are rarely considered in prosthesis assessment [23],[24], despite being common and important for accomplishing daily life tasks.

II. Materials & Methods

A. System Overview

An overview of the system components, connections and data types sent between the components, is presented in Fig. 1.

The subjects wore a dexterous prosthetic hand. The EMG signals recorded using two electrodes as well as sensor data from the prosthesis were acquired by a microcontroller based central unit (CU) and then sent to a laptop for logging.

The CU received the data from the tongue control interface that was comprised of a mouthpiece and an external electronic unit. Based on the EMG and tongue data as well as the current control condition, the CU sent the control commands to the prosthetic hands. The individual components of the overall setup and the control conditions are described in the following sections.

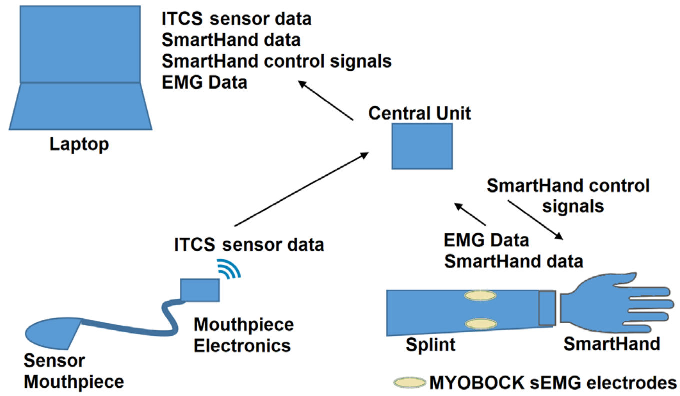

Fig. 1. System overview of components and data types sent between the components. See text for explanation.

B. The Prosthesis Prototype

A left-hand SmartHand (Prensilia S.r.l., Italy) robotic hand was used in this study (Fig. 2.A). The SmartHand weighs approximately 530 g, and is a human sized, self-contained multi-grasp hand. It is underactuated and has four motors driving 16 DoFs using tendons [25]. We have selected this hand due to the ease of reconfiguring, the available grasps and the speed and force of grasping. The following grasps/pinches were available to the subjects in the current study: precision/bi-digit pinch, lateral/key pinch, diagonal volar grasp, transversal volar grasp and a tripod pinch. According to Sollerman & Ejeskär [26] these grasps are the five most often used in ADL activities.

The robotic hand was mounted onto the left arm of able-bodied subjects using a custom-made splint (Fig. 2.B) manufactured by Sahva A/S. The prosthetic splint was designed to enable concentric contractions of both wrist flexors and extensors. Therefore, the subject movements (prosthesis commands) could be visually identified by analysing video recordings of the trial sessions.

Fig. 2. (A) The SmarHand robotic hand used in this study. (B) The robotic hand mounted in front of the left hand using a custom-made splint (manufactured by Sahva A/S).

C. The Hybrid Tongue Myoelectric control system

A wired version of the Inductive Tongue Control System (ITCS) introduced by Struijk et al. in [27], [28] was placed intra-orally at the upper palate and the interface provided the functionality of a wireless keyboard (Fig. 3). A commercial wireless version of this system (Itongue®), in which the electronics is integrated into the mouthpiece, is available from the company TKS Technologies [29].

The system used in this study was a version suitable for research and previously used for prosthetic control in other studies [18]. This system included a mouthpiece unit (MU), a ferromagnetic activation unit, which was glued to the tongue,

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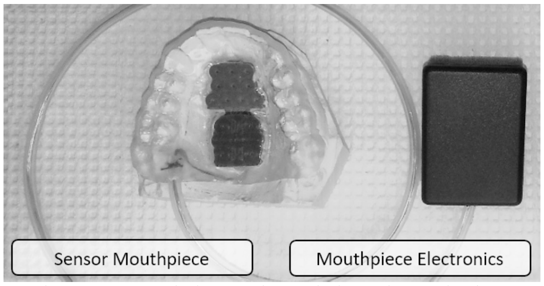

Fig. 3. The sensor mouthpiece and mouthpiece electronics box comprising the Mouthpiece Unit (MU).

and an external CU comprised by a wireless receiver and a microcontroller (MSP430 from TI inc.).

The MU included mouthpiece electronics placed outside the mouth and 18 coil sensors encapsulated in a sensor mouthpiece customised for each subject and built from a dental imprint of the upper palate. The sensors were connected to the electronic circuit through a silicone rubber tube, exiting at the corner of the mouth (Fig. 3). The electronic circuit handled sampling of the 18 sensors at 30 Hz and the transmission of sensor values to the CU.

Each sensor was activated using a ferromagnetic activation unit glued to the tip of the tongue using tissue glue (Histoacryl ® from B|Braun). Active sensors were identified in the CU by comparing the received sensor values to the predetermined activation thresholds [30]. Furthermore, the EMG electrodes were connected to the CU of the ITCS, which handled sampling and comparison of the EMG amplitude to predefined activation thresholds, and the communication with the SmartHand

The EMG was recorded from wrist and hand flexor and extensor muscles using 13E200 MYOBOCK surface electrodes (Otto Bock). The output from the 13E200 MYOBOCK was an amplified, filtered, rectified, and enveloped analogue representation of the EMG.

The CU was connected to a laptop, and all data concerning the EMG, the ITCS and the commands sent to the SmartHand hand were stored.

D. The TMH & cEMG Prosthesis Control Schemes

The TMH and the cEMG control scheme both used EMG signals recorded from wrist/finger extensor and flexor muscles for the opening and closing of the grasps, respectively.

The cEMG control scheme implemented the sequential control employing co-contractions for switching to the next grasp, whereas the TMH used the 10 anterior sensors on the ITCS mouthpiece for direct activation of the desired grasps (Fig. 4).

Based on studies on the use of grasps in ADL [26], the five grasps available were mapped onto 10 sensors. Pairing of adjacent sensors into five activation areas and the allocation of grasps (Fig. 4) was based on the accessibility of the ITCS sensors [31]. The most used grasps were allocated to the sensors that were most easily activated.

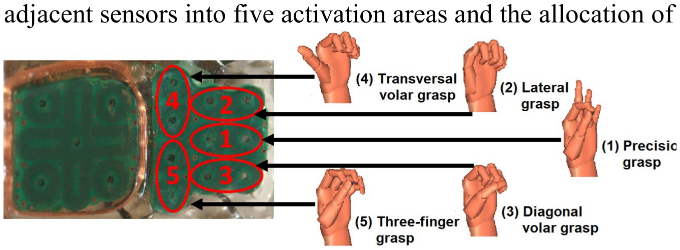

Fig. 4. Layout of the five sensorpairs usede for the activation of the five grasps in the TMH control scheme; 1. Precision pinch, 2. Lateral pinch, 3. Diagonal volar grasp, 4. Transversal volar grasp, 5. Tripod pinch.

In both control schemes, an activation of a grasp resulted in the robotic hand preshaping into the initial open position associated with the activated grasp.

E. The Assistive Hand Assessment Protocol

The Assistive Hand Assessment for adults comprises two functional activities; “Gift wrapping” and “Sandwich making”. Both tasks involve several bimanual activities during which the subject was seated in front of a desk with predefined materials (depending on task) within reach.

Gift wrapping consisted of the following six subtasks:
1. Reading gift card: Opening the envelope and reading the gift card inside
2. Unwrapping: Unwrapping the gift and taking out the piece of chocolate placed inside the cardboard box
3. Replacing chocolate: Opening the glass jar with chocolate and replacing the piece of chocolate taken from the box
4. Wrapping: Cutting wrapping paper and rewrapping the box applying sticky tape where needed
5. Gift ribbon: Cutting and tying the gift ribbon onto the wrapped box
6. Writing gift card: Retrieving pencil (with lid) from pencil case and writing new note. Folding the paper placing it inside an envelope and closing it.

Sandwich making consisted of the following eight subtasks:
1. Bread: Cutting two slices of bread from a loaf of white bread
2. Butter: Spreading butter on both slices of white bread
3. Ham: Taking a piece of ham from a plastic box placing it on one of the slices of white bread
4. Cheese: Using a cheese plane to cut a piece of cheese placing it on one of the slices of white bread
5. Cucumber: Using a knife to cut slices of cucumber placing them on one of the slices of white bread
6. Tomato: Using a knife to cut slices of tomato placing them on one of the slices of white bread
7. VitaWrap: Building the sandwich and wrapping it in VitaWrap/clingfilm
8. Bag: Placing the wrapped sandwich in a zip bag

For both tasks, the materials needed were placed at a distance encouraging the subject to reach and grab. No specific way of handling the objects was defined. The subjects were free to choose when and how to use the robotic hand during the subtasks (e.g., holding the bread or knife while cutting bread). The AHA sets no restrictions on the use of the dominant (non-prosthetic) hand. Only the task completion time was evaluated and not the manner in which the functional task was performed or the quality of the end result (e.g. how nicely the gift was wrapped). Assisting a subject was permitted if the subject could not complete a subtask on his/her own.

F. Participants

The study was approved by the North Denmark Region Committee on Health Research Ethics. Ten healthy adults (3 males), aged 27.7 ± 1.2 years (mean ± standard deviation),

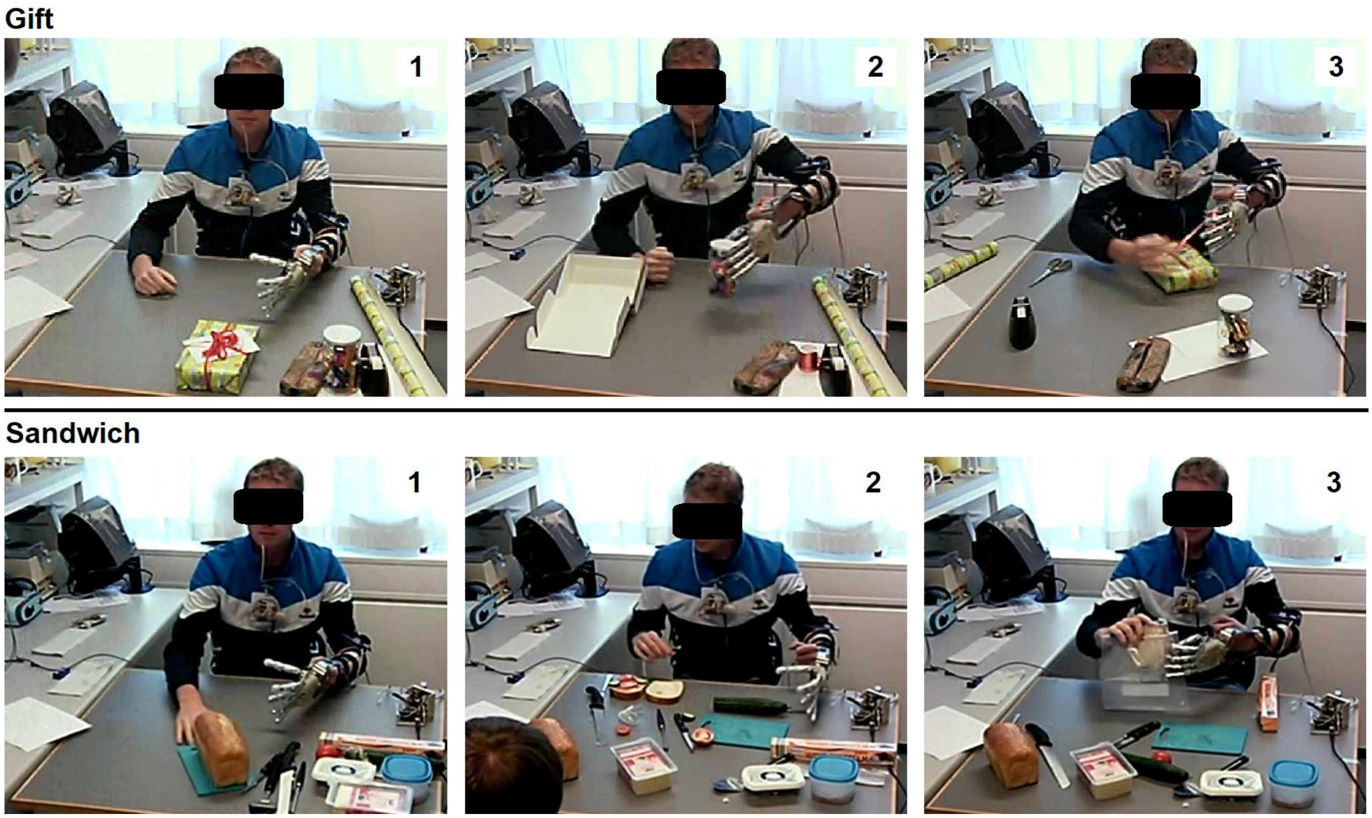

Fig. 5. Screenshots from experimental sessions of both the "Gift Wrapping" and "Sandwich Making" tasks. Screenshots are presented in chronological order from left to right. **Gift:** 1: Read gift card 2: Replacing chocolate 3: Gift ribbon. **Sandwich** 1: Cut bread 2: Cucumber 3: Bag

participated in the study. All participants gave voluntary, written and informed consent to their participation.

The subjects were recruited from outside the university, but all subjects had been part of prior technical implementation and assessment studies involving both of the two control schemes [18],[20]. Therefore, all subjects had two hours of training experience with each of the control schemes used in the current study.

A left-hand SmartHand was used in the present study. In order to ensure e all recruited subjects were right-handed.

The performance of each subject and task was video recorded for analysis. Screenshots of the tasks' progress can be seen in Fig. 5.

G. Experimental Design, Setup & Protocol

The number of sessions was selected based on our previous work. The study by Johansen et al. [18] showed that completing three experimental sessions across three consecutive days produced a significant difference in grasp activation times between the cEMG and TMH control schemes.

The subjects were randomly assigned to one of two groups of equal size. To prevent acclimatization bias a cross-over design was used. The first group completed three sessions using the cEMG control scheme, one session per day on three consecutive days, and then three sessions using the TMH, again one session per day on three consecutive days. No more than 14 days were allowed between the cEMG and the TMH sessions. The second group followed a similar protocol, the only change being the order of the control schemes used. Thus, the second group started using the TMH and ended using the cEMG control scheme.

Each session included completion of both of the functional tasks defined by the AHA protocol, starting with the Gift wrapping and then the Sandwich making task. The tasks were always performed in the same order, first Gift and then Sandwich task, and therefore, we assume that this did not have an impact on the comparison between the same tasks across the two control conditions.

At the beginning of a training session, two EMG electrodes would be fitted on the left forearm of the subject. Skin preparation and adjustment of amplification levels for each electrode were conducted according to Otto Bock instructions [32]. The subjects were instructed to perform a maximum voluntary contraction (MVC) and amplification levels of the MYOBOCK electrodes were then adjusted so that the MVC corresponded to the maximal output of the electrodes.

When a session involved TMH, the activation unit was glued to the tip of the tongue of the subject, and the subject then placed the MU of the ITCS at the upper palate. The external MU electronics were fixed to the shoulder of the subject. An image of the mapping between the sensors and the grasps was placed in front of the subject.

The splint and the robotic hand was strapped to the left forearm (Fig. 2B). The subject was seated in front of a desk and materials for the functional task were then readied at the desk according to the AHA guidelines. Before the start of the functional tasks, the robotic hand was calibrated, using the built-in calibration feature, and subjects were instructed to ensure that all grasps could be activated, closed and opened.

A digital video camera was positioned at a high level in front of and to the left of the subject, providing an overview of the desk, the materials and the subject performing the functional tasks. For both functional tasks, a verbal "go" cue was given to indicate to the subject to start performing the task.

The primary outcome measure in the present study was the completion time of the full task. The secondary measure was the individual completion time of each of the involved subtasks. We have also counted the number of active and passive uses of the prosthetic hand. An active use defined as actively using the prosthetic hand to grasp, hold and manipulate an object. A passive use defined as pressing or pushing objects with the splint or the prosthetic hand. Opening of a grasp in use (active use) or removing the splint or the prosthetic hand from the object (passive use) would make the next active or passive use count as a new use, thus incrementing the number of active or passive uses.

H. Data Acquisition and Analysis

Each functional task was video recorded and the recordings were stored on a laptop. Data from the ITCS sensors and EMG electrodes were sampled at 30 Hz. The videos were analysed manually to measure the completion time (CT) of the tasks and of the subtasks involved, and to count the number of active and passive uses of the prosthetic hand during completion of the tasks.

We have considered the subtasks because the tasks in AHA represent complex actions where individual phases require rather different manipulations (e.g., in Sandwich task, Cheese involves cutting while Bag requires placing).

Time to complete a subtask was measured from the "go" cue or from the completion of the previous subtask until completion of the actual subtask. For example for the Reading Gift Card subtask this would be when the subject puts down/pushes aside the card with the next action being reaching for the wrapped gift in order to start unwrapping. Thus, no time pause existed between the subtasks.

For both control schemes, the measured completion times were grouped according to the session numbers. Matlab ® and the statistical software, SPSS © were used for the statistical analyses. As the purpose of this study was to compare the performance of the TMH to that of a cEMG control scheme, rather than studying the effect of training, only data from the third sessions were included in the data analysis.

The CT for all subtasks and for the entire functional tasks were grouped and outliers were removed from the datasets. The normality of the data was tested using the Lilliefors test. With the exception of the Sandwich-Ham subtask, all groups of data proved to be normally distributed. The mean completion times were computed and then an absolute and relative difference in these mean times were calculated using equation (1).

$$Diff\ (\%) = \frac{(TMH\ CT - cEMG\ CT)}{cEMG\ CT} \cdot 100 \quad (1)$$

Data for each full task and for each of the involved subtasks were analysed for statistical differences between the control schemes using a paired t-test, with the exception of the Sandwich-Ham subtask, for which the non-parametric Wilcoxon-test was used. The threshold for the statistically significant differences was set at $p < 0.05$. Furthermore, in case of a significant difference between the subtasks and/or task, the effect size was computed using Cohen's D.

In relation to the second outcome measure concerning active and passive uses of the prosthetic hand, data was grouped across subjects and according to the functional tasks. Outliers were removed from the data, and a Lilliefors test was performed to test for normality. The means of the number of both active and passive uses for the functional tasks Gift and Sandwich was computed for both the cEMG and the TMH control scheme, and a paired t-test was used to test for significant differences in the number of active and passive uses of the prosthetic hand across control schemes. In case of significant differences, the effect size was computed using Cohen's D.

III. Results

Tables I and II present the summary results of the group of subjects (mean ± standard error of the mean (SEM)) for the performance of the two control schemes during the gift wrapping (Table I) and the Sandwich making task (Table II).

TABLE I
GIFT WRAPPING SUBTASK COMPLETION TIME (CT) FOR CEMG AND TMH

Sub-task	N	cEMG CT (Mean ± SEM) [s]	TMH CT (Mean ± SEM) [s]	Diff. [s] (%)	Paired t-test p-values
1	8	39 ± 3	37 ± 4	-2 (5.2)	0.779
2	10	44 ± 4	53 ± 7	9 (20.5)	0.177
3	9	49 ± 4	42 ± 4	-7 (-14.3)	0.026*
4	10	141 ± 10	144 ± 9	3 (2.1)	0.698
5	9	187 ± 28	182 ± 19	-4 (2.1)	0.831
6	10	102 ± 7	103 ± 10	1 (1.0)	0.905
Comp. Task	9	569 ± 33	571 ± 41	2.00 (0.3)	0.939

Table I SEM = standard error of the mean. Subtask labels: 1: Read gift Card, 2: Unwrap gift, 3: Replace chocolate, 4: Wrap Gift, 5: Gift ribbon, 6: Write gift card. (*) Indicates a statistical significant difference ($p < 0.05$).

TABLE II
SANDWICH SUBTASK COMPLETION TIME (CT) FOR CEMG AND TMH

Sub-task	N	cEMG CT (Mean ± SEM) [s]	TMH CT (Mean ± SEM) [s]	Diff. [s] (%)	Paired t-test p-values
1	8	54 ± 6	45 ± 2	-9 (-16.7)	0.114
2	8	60 ± 5	49 ± 4	-11 (-18.3)	0.153
3	*8*	*18 ± 2*	*17 ± 2*	*-1 (-5.6)*	*0.940*
4	9	63 ± 4	51 ± 5	-12 (-19.0)	0.046*
5	10	47 ± 5	47 ± 6	0 (0)	0.976
6	10	68 ± 11	43 ± 4	-25 (-36.8)	0.043*
7	9	186 ± 13	172 ± 13	-14 (-7.5)	0.285
8	10	67 ± 8	51 ± 5	-16 (-23.9)	0.041*
Comp. Task	9	566 ± 41	458 ± 25	-108 (-19.1)	0.024*

Table II SEM = standard error of the mean. Subtask labels: 1: Cut bread, 2: Butter, 3:Ham, 4: Cheese, 5: Cucumber, 6: Tomato, 7: VitaWrap, 8: Bag. (*) Indicate a statistical significant difference in mean $p < 0.05$. *Italics: Non-parametric Wilcoxon-test.*

The tables also include the differences in the CT between the two control schemes. They are shown as absolute difference in seconds and as a relative difference in percent of change in CT with respect to the cEMG CT, calculated as shown in (1):

Negative value indicates the improvement in performance with TMH. Finally, the tables include the p-values of a paired t-test conducted on the full task, and on each of the subtasks.

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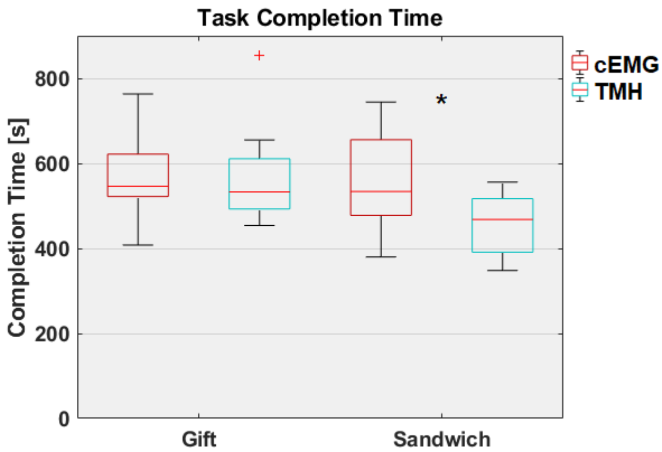

Fig. 6. Boxplot of completion time using the cEMG and TMH control schemes for two functional tasks; gift and sandwich. (*) Indicate a statistical significant difference in mean p < 0.05.

Fig. 6 shows the boxplots for the completion time of the full tasks for both control schemes. The completion time for the full task of Gift Wrapping was similar in the two control conditions (~ 570 s). For the full Sandwich task the mean CT was significantly lower for the TMH compared to the cEMG (p=0.024, Table II). This difference corresponds to 19% reduction in completion time (108 seconds). The corresponding effect size calculated as Cohen's D was 0.92.

Boxplots of subtask completion time for the six gift-subtasks in two control conditions are plotted in Fig. 7, and for the eight sandwich subtasks in Fig. 8.

Analysing the Gift Wrapping task, the only subtask in which the performance of the two methods was significantly different (p = 0.026, Table I) was the subtask of Replacing chocolate, with an effect size calculated as Cohen's D of 0.91. For all other subtasks, there were no significant differences in the CT between the two control schemes.

For the Sandwich task, all but the Cucumber subtask were performed faster using the TMH compared to the cEMG. The paired t-test yielded statistically significant differences for the

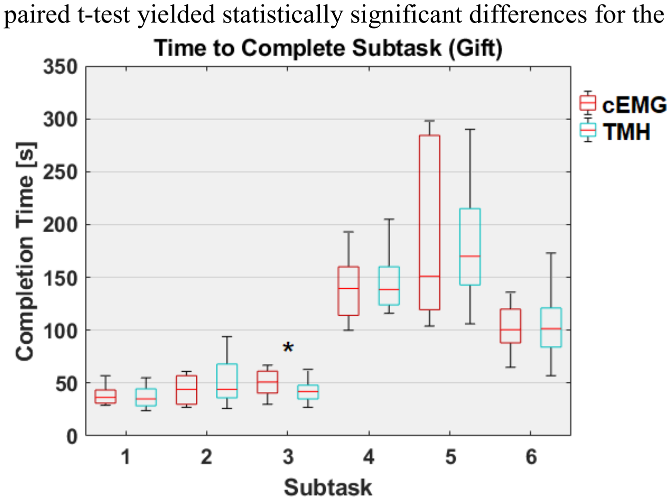

Fig. 7. Boxplots of the completion time using the cEMG and TMH control schemes for the six subtasks included in the gift task of the AHA. Subtask labels: 1: Read gift card, 2: Unwrap gift, 3:Replace chocolate, 4: Wrap gift, 5: Gift ribbon, 6: Write gift card. (*) indicates a statistical significant difference in mean p < 0.05.

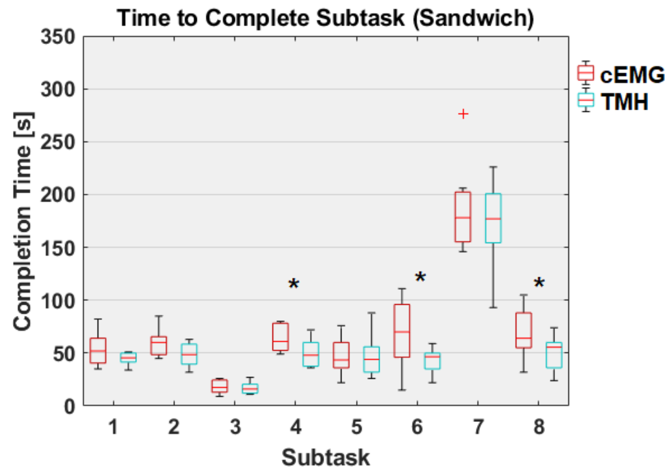

Fig. 8. Boxplot of completion time using the cEMG and TMH control schemes for the six subtasks included in the sandwich task of the AHA. Subtask labels: 1: Cut bread, 2: Butter, 3:Ham, 4: Cheese, 5: Cucumber, 6: Tomato, 7: VitaWrap, 8: Bag. (*) Indicate a statistical significant difference in mean p < 0.05.

three subtasks; Cheese, Tomato and Bag (p-values; 0.046; 0.043; 0.041) with effect sizes calculated as Cohen's D of 0.79; 0.75; 0.75, respectively.

The number of active and passive uses of the prosthetic hand when completing the Gift and Sandwich tasks are summarized (mean ± SEM) for both control schemes in table III.

TABLE III
ACTIVE AND PASSIVE USES OF THE PROSTHETIC HAND DURING COMPLETION OF FUNCTIONAL TASKS

Task	N	Use Type	# Uses cEMG (Mean ± SEM)	# Uses TMH (Mean ± SEM)	Paired t-test p-values
Gift	9	Active	7.1 ±1.0	8.8 ±0.5	0.105
Gift	8	Passive	19.6 ±1.9	24.4 ±2.0	0.095
SW	9	Active	12.0 ±3.0	10.7 ±1.0	0.581
SW	10	Passive	13.9 ±2.5	12.6 ±1.3	0.601

Table III SEM = standard error of the mean.

IV. DISCUSSION

The aim of the present study was to compare the performance of a novel hybrid control scheme, combining tongue and myoelectric interface, to that of commercial myoelectric control during relevant tasks of daily living. The assessment was based on a standard clinical test focusing on bimanual activities, which can be particularly difficult to perform using a prosthetic hand. The results have shown that the two control schemes performed similarly in the gift wrapping task, but the hybrid approach was substantially faster in the sandwich-making task. Therefore, the novel method can be regarded as a promising approach that can significantly improve the control of a dexterous prosthesis.

The TMH approach allows direct selection of the desired grasp while in the myoelectric control condition the subjects used co-contractions to switch sequentially through the available grasp types. The present study demonstrated that the grasp selection using tongue has the potential to be an effective method, which the subjects could utilize successfully after only a short training.

The difference in the results between the two tasks (Gift wrapping versus Sandwich making) may partly relate to differences in the degree of bimanual manipulation required in the tasks. When analysing the videos of the experimental sessions, it became evident that the Gift wrapping task did not require as high a degree of active grasping of objects as the Sandwich making. For example, when unwrapping or wrapping a box, even as an able-bodied person, the typical strategy is to press the box against the table, thus using the non-dominant hand or prosthesis as a passive device. Therefore, although the Gift wrapping subtasks are still bimanual in nature, they do not necessarily require active grasping. On the contrary, the Sandwich task required active grasping, and therefore, the subjects were prompted to select the grasp type more often. Since this could be done faster and more reliably with TMH, the hybrid method decreased the total time needed to accomplish the task.

Across both functional tasks, the completion time showed a significant decrease in four subtasks (Gift wrapping; Replacing chocolate – Sandwich making; Cheese, Tomato, Bag). These subtasks are all characterised by the fact that active grasping can facilitate the performance. The subtask Replacing chocolate involves unscrewing the cap of a jar. Thus, grasping the jar makes completion of this subtask faster compared with e.g. using the prosthesis to press it against the chest in order to fixate it for unscrewing the cap. In the Cheese subtask, the cheese needs to be grasped and firmly held in order to use the cheese plane effectively. Similarly, the tomato is sliced most effectively when held using an active grasp compared to pressing the tomato against the table. Keeping the bag open with one hand using an active grasp while putting in the sandwich with the other hand also proved the most efficient way of completing this subtask. Another less efficient strategy would be to press the bag against the table using the prosthesis hand while trying to open the bag and slide the sandwich inside using only one hand.

No significant differences was found in the number of active and passive uses of the prosthesis for subjects completing the functional tasks. This could possibly indicate that the ease of activating or changing specific grasps and the faster activation times when using the TMH are the possible causes for the faster completion times in these subtask. However, this would need to further investigated in order to be confirmed.

No subjective usability measures were included in this study, and therefore it is not known if there is a difference in the cognitive load of using the TMH and the cEMG control scheme.

Two tasks have been assessed in the present study. It could be argued that the functional task Gift wrapping is not truly an ADL since wrapping gifts does not normally occur in everyday life. However, the specific subtasks and the bimanual activities involved are actually relevant for many ADL. The Sandwich making task, however, is commonly performed in daily life, and therefore, improved performance in this task can increase the quality of life by promoting the sense of being self-sufficient and independent. Overall, we assume that making the completion of comprehensive ADL tasks faster and facilitating more active use of the prosthetic hand will be linked to increased functional performance.

The ITCS used in the present study was a prototype version, where the electronics was placed outside of the mouth while the sensors were connected to the electronics via a silicone rubber tube. This could have negatively affected the performance of the TMH control scheme.

Another limitation is the fitting of the prosthetic hand. The able-bodied subjects used a splint resulting in unnatural positioning of the prosthetic hand in front of the actual hand. This led to a mismatch of visual and proprioceptive inputs that may affect the ability to naturally grasp and manipulate objects using the prosthetic hand.

The results presented were based only on able-bodied subjects with no prior experience in using a prosthetic device to complete functional tasks, and future work should be carried out in order to evaluate the TMH used by actual amputees.

However, the TMH implement very simple use of EMG control signals, and amputees would have similar motor control of the tongue compared to able-bodied subjects. Therefore, the present results may reflect the performance of amputees that do not have substantial prior experience in controlling a myoelectric prosthesis (novice users), but this has to be tested in a dedicated experimental study. Also, the completion times for the tasks and subtasks are likely to be affected by the strategy used, and not just the control schemes. An experienced prosthetics user could complete the functional tasks by employing strategies that take the limitations of the prosthesis into consideration. Therefore, an experienced prosthetics user would be expected to outperform able-bodied subjects and novice users of upper limb prosthetics, using both the TMH and cEMG control scheme.

It was also observed that the subjects often used a suboptimal strategy for activation of desired grasps when using TMH control scheme. Namely, the subjects used the posterior/medial sensor (pad 1, Fig. 4) as a reference point. Instead of consulting the image illustrating the grasp layout and then activating the desired grasp directly, they often placed the activation unit at the pad 1, and then slid the unit to the side (grasp 2 or 3) or sideways and back (grasp 4 or 5), depending on the specific grasp that was desired. We assume that with training the suboptimal strategy would be replaced by the direct activation of the desired grasp, thereby potentially further improving the functional performance of the TMH control scheme by decreasing the grasp activation time

The present study further supports the results reported in [18] by demonstrating that the TMH seems to be a viable method to control dexterous hand prostheses during challenging and relevant functional tasks. The TMH offers an effective method for grasp selection plus a simplified and thus more robust use of the EMG control signals. In this scheme, the myoelectric signals are employed only to open and close the hand, and therefore, the control is less prone to be influenced by e.g. sweat, electrode shifting and muscle fatigue, which are reported factors affecting the use of EMG for grasp selection in pattern classification [4].

In this work, only 10 of the ITCS sensors were used. Thus, the TMH could easily support more grasps or DoFs, which makes the method easily scalable to accommodate systems that are more complex. For example, using the TMH for shoulder

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TBME.2021.3052065, IEEE Transactions on Biomedical Engineering

level amputees controlling a full arm prosthesis would be an evident future application. This is particularly relevant considering that in the case of a high-level amputation, there is a decreased number of viable EMG sources that could be used for control. However, exploring the full functionality of the unit could be challenging for the subjects since they would need to locate and select among 18 closely-spaced sensors. But, this can be addressed by training as demonstrated in our previous work [28], [33]. The optimal number of sensors for prosthesis control as well as mapping between the sensors and prosthesis functions is an important future goal.

Nonetheless, for high-level amputees the TMH could be considered an alternative option to e.g. TMR and Implantable Myoelectric Sensors (IMESs) [34]-[36]. The latter provide more intuitive control but also require a surgical intervention. Implantable electrodes is another alternative for providing enhanced control of prosthetic devices, such approaches eliminates the need for nerve-remapping [37]. However compared to the TMH they are still dependent on successful surgery and pattern recognition algorithms. The alternative (non-myoelectric) methods for grasp selection, such as TMH, also have specific pros and cons. The foot interface [16] cannot be used while walking and grip chips [17] provide grasp selection only for the objects that were tagged. The TMH is a general solution but it can be somewhat affected by speaking and eating [38]. The availability of all these different solutions is important since it allows users to choose according to personal preferences.

For the permanent use of the TMH, the activation unit would be fixed to the tongue through a tongue piercing. In a survey study, 61% of the responding individuals with tetraplegia would undergo a tongue piercing in order to use the ITCS [39], and a study on medical tongue piercings has shown that the perceived pain intensity during a tongue piercing was rated to be less than half of other injections in the oral cavity [40]. Furthermore, Lontis et al. [38] evaluated the degree of discomfort perceived by users during talking and drinking whilst having the mouthpiece unit inserted in the upper palate. On a scale from 1 to 10 (1 meaning no discomfort and 10 high discomfort) the reported discomfort was between 1 and 3. The level of reported discomfort was low but the study was conducted in patients with tetraplegia and not in amputees. Nevertheless, the current commercially available ITCS unit is already smaller than the one used in the study of Lontis et al. [38], and we expect that advances in technology will lead to even further miniaturization of the device. This in turn is likely to decrease the discomfort as well as the effect on speaking, eating and drinking. Nevertheless, the ITCS is still an intraoral device that requires an activation unit fixed on the tip of the tongue. The long-term effects of wearing an intraoral device like the ITCS is still to be investigated and the device could potentially cause added wear and abrasion of teeth. In addition, the tongue piercing could be possible reasons for rejection and/or abandonment.

Taken into consideration the user demand of being able to perform simple manipulation tasks enabling the execution of ADLs [5], the possible discomfort of wearing the ITCS is assumed to be of decreasing significance in relation to the level and degree of amputation. The exact turning point of this trade-off between perceived discomfort and increased functionality of prosthetics is yet to be investigated. However, it is assumed that e.g. bilateral amputees would have a meaningful and significant increased prosthetic functionality from using the proposed TMH control scheme.

Another highly desired improvement of prosthetic hands is the provision of sensory feedback [5]. Taking the sensitivity of the oral cavity and especially tongue and teeth into consideration, the ITCS could be adapted to provide somatosensory feedback to a prosthesis user via electrical or mechanical stimulation. For instance, low-intensity vibrations could be delivered to indicate grasping force or object slipping.

The TMH also offers possibilities of developing customised, user-oriented solutions e.g. user-specific layouts of grasps easily changed using e.g. an app, a switch or even directly from the ITCS. This would allow an amputee to activate specific layouts of the grasps for specific situations e.g. “At Work”, “At Home” etc. This could also include controlling and customising how ITCS sensors are grouped, thus if “At Work” only requires the use of three grasps, more sensors could be allocated to these grasps, thereby making the activation faster. Similar functionality is available in i-Limb, where the user can configure preferred grasps in different contexts (work, home and leisure). However, a unique feature of ITCS is that the configuration can include the sensor layouts in addition to the grasps, directly facilitating the selection (e.g., fewer grasps, larger sensor areas and hence easier selection).

In this study, the TMH was used for grasp selection, reflecting the mechanical design of the prosthesis, which did not have a wrist unit. However, the ITCS is a general interface that could include the selection of the wrist DoFs (or any other DoFs) as well. It can also emulate a joystick function and therefore provide simultaneous control, as in regression approach [6], but this is outside the scope of the present study

Further, the ITCS is more general as the same interface can be used to control other devices, such as wheelchair [30],[41], assistive robots [42] or consumer electronics (e.g., computer control [43]). Such functionality could be particularly relevant for bilateral amputees and for individuals with additional impairments.

V. Conclusion

The functional use of the TMH control scheme for multifunctional hands was evaluated and compared to the performance of an EMG based conventional sequential on/off control scheme. The comparisons were based on two functional tasks (Gift wrapping and preparing a Sandwich) defined by the Assisting Hand Assessment for adults with upper limb Prosthesis, Amputations and Deficiencies (AHA-PAD) protocol. The time to complete the two functional tasks and the involved subtasks was measured. No significant differences between the TMH and cEMG control schemes were found for the completion of the complete “Gift wrapping”. However, for the task of preparing a sandwich, the TMH outperformed the EMG based conventional sequential on/off control scheme ($p=0.024$). The task completion time was reduced by 108 seconds, corresponding to 19% improvement when using the TMH compared to EMG based conventional sequential on/off control scheme. It was concluded that the TMH control scheme could be a possible alternative for providing enhanced control of multifunctional prosthetic hands.

ACKNOWLEDGMENT

Bo Bentsen, Cand. Odont., Ph.D. is acknowledged for his part in the study, being clinically responsible for the protocol.

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