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Continuous tongue robot mapping for paralyzed individuals improves the functional performance of tongue-based robotic assistance

Mostafa Mohammadi, Hendrik Knoche, Lotte N. S. Andreasen Struijk

***Abstract*—Individuals with tetraplegia have a challenging life due to a lack of independence and autonomy. Assistive robots have the potential to assist with the activities of daily living and thus improve the quality of life. However, an efficient and reliable control interface for severely disabled individuals is still missing. An intraoral tongue-computer interface (ITCI) for people with tetraplegia has previously been introduced and tested for controlling a robotic manipulator in a study deploying discrete tongue robot mapping. To improve the efficiency of the interface, the current study proposed the use of virtual buttons based on the ITCI and evaluated them in combination with a joystick-like control implementation, enabling continuous control commands. Twelve able-bodied volunteers participated in a three-day experiment. They controlled an assistive robotic manipulator through the tongue to perform two tasks: Pouring water in a cup (PW) and picking up a roll of tape (PUT). Four different tongue-robot mapping methods were compared. The results showed that using continuous commands reduced the task completion time by 16% and the number of commands of the PUT test by 20% compared with discrete commands. The highest success rate for completing the tasks was 77.8% for the PUT test and 100% for the PW test, both achieved by the control methods with continuous commands. Thus, the study demonstrated that incorporating continuous commands can improve the performance of the ITCI system for controlling robotic manipulators.**

***Index Terms*—Tongue-computer interface, robot control, rehabilitation robotics, human-robot interaction, disabled individuals, assistive devices, tetraplegia.**

I. Introduction

APPROXIMATELY 1.5 million individuals live with spinal cord injury (SCI) in the United States, of which 72% are younger than 65 years [1]. One-third of them are reported to suffer from tetraplegia [2], i.e. partial or complete paralysis of both legs and arms. The mean age for the incidence of SCI is 33 years [2], and it has been predicted that the median survival time of individuals who have sustained an SCI between the ages of 25-34 years is 38 years after the injury [3]. Individuals suffering from complete tetraplegia are reliant on 24-hour assistance from a caregiver to help them with activities of daily living (ADL). Thus, any assistive technology that can increase autonomy and independence may greatly impact their quality of life.

Assistive robotic manipulators (ARM) have shown the potential to help individuals with tetraplegia to perform ADL and improve the quality of life [4]. So far, JACO (Kinova Co., Canada) and iARM (Exact Dynamics, Netherlands) are the only commercially available ARMs with comparable mobility to the human arm. The JACO's standard interface is a joystick and for the iARM a keypad. These both require a level of dexterity and voluntary control of the fingers and of the hand to control the 6-7 degrees of freedom (DOF) which cannot be achieved with complete tetraplegia.

Therefore, several control schemes have been investigated to enable individuals with tetraplegia to control ARMs with their remaining capabilities. These interfaces have tried several input modalities: head and mouth movement [5], brain signals [6], eye movement [7], tongue movement [8][9], and voice commands [10]. However, the available solutions pose several challenges, one of the major being the number of continuous control commands that these interfaces can provide in robustly undisturbed by the ever-changing environment of a user as manually controlling an ARM with seven DOF requires 14 commands. Furthermore, most ADL require some degree of fine manipulation of the end-effector, which is a gripper for ARMs, and most of the assistive interfaces cannot provide this. Some interfaces are limited to a fixed and isolated setup and cannot be used outside the laboratory or the home. Another limiting factor is how the interface affects the appearance and social identity of the user. For example, systems requiring attachment of visible objects to or nearby the face and head reduce user acceptance. Some control schemes also have inherent problems. Using brain signals for controlling ARMs is widely investigated and reported in the literature [11]. It has great potential for users who have no other options, as it may be the case in late-stage Amyotrophic lateral sclerosis (ALS) [12]. A recent study demonstrated a noninvasive brain-robot interface for a two-dimensional continuous target tracking task [13]. However, using brain signals has faced many challenges such as time-consuming training and calibration procedures, low information transfer rate, inherent noise, and complexity of the signal [14]. Eye trackers engage the gaze in the control and may compromise the monitoring of the robot motions and regular interaction with other people and with the environment.

A solution to some of these challenges is to use automation

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based on computer vision to assist the user with controlling the ARMs and provide the control with less number of inputs. The computer vision uses perception sensors to sense the environment and help with the grasping and avoiding a collision. In most cases, the computer vision detects available objects and allows the user to select from a list of graspable objects [15]. Previous studies have shown that this can decrease the user effort and the required time for a grasping task [16][17]. However, a study has shown that the user may prefer more manual and interactive control [16]. In addition, most of the proposed computer vision methods for autonomous grasping can only identify a limited set of objects [17].

The tongue functionality usually remains intact after an SCI even in high level (C1-C4) cases. The tongue musculature has a large representation in the motor cortex, comparable to that of the hand [18]. A study investigating the tip of the tongue pointing and motor learning showed that the tongue movement is supported by a remarkable motor learning potential [19]. These facts led to the development of tongue-based interfaces for ARMs such as the tongue-drive system (TDS) [15] and the intraoral tongue-computer interface (ITCI) [8]. The TDS has less than the desirable 14 dedicated command signals for a 6-7 DOF arm whereas the ITCI has 18 available individual sensors.

The ITCI system was first presented in [20], and has appeared applicable for hands-off interfacing of several devices, such as personal computers [21], wheelchairs [22] and drones [23]. A study in 2017 [8] demonstrated the ability of an individual with tetraplegia to control a seven DOF ARM with the ITCI. Several studies have investigated different aspects of using the ITCI for controlling ARMs [8][24], including the use of computer vision and using the interface in a remote mobile robot setup. However, all of them used the inductive sensors of the ITCI as switches that can issue a discrete command; that is a command that can have only "On" or "Off" states similar to the control commands from a push button or a switch.

To improve the performance of the ITCI for controlling ARMs, we have recently developed a high-resolution, two-dimensional control method based on sensor interpolation algorithms for the ITCI [25] with which the position of the tongue could be estimated. This allows for definition of virtual buttons of different sizes and positions on the ITCI as well as exploiting continuous joystick like commands. In the case of controlling an object in two dimensions with the ITCI, discrete control allows for motions in fixed directions with a fixed velocity. On the contrary, continuous control provides a continuous adjustment of velocity and direction, which may improve the robot control.

This study is the first to explore robot control interfaces based on tongue-operated virtual buttons in two different sizes. Additionally, continuous two-dimensional inputs were introduced in which two different methods for emulating a joystick were tested for controlling a robot and navigating it in a 3D space. The continuous control schemes were compared with control schemes based on discrete commands.

II. Methods

A. System overview

The ITCI system was used to control a JACO ARM (Fig. 1). The ITCI consists of a mouthpiece unit (MPU, Fig. 1,A) which is mounted intraorally at the hard palate. It contains 18 inductive sensors on two printed circuit boards (PCB) that can be activated by a ferromagnetic activation unit (AU, Fig. 1,B) fixed to the tongue using tissue adhesives or as a piercing. The variation of voltage over each sensor is measured, amplified, rectified, and low-pass filtered [26] and then transmitted through wireless communication to a central unit (CU, Fig. 1,C) that processes the data and sends them to a computer or another electronic device to be controlled by the user. Fig. 2 shows the raw transmitted signal of the 18 sensors when the AU moved over the four neighbor sensors (Fig. 2, the white arrow in the left photo). To track the position of the AU on the sensor PCBs, we used the Mean Average of Neighbor Sensors method [25], which provided an accuracy of 1 mm in a test setup outside the mouth. The JACO had six DOF for navigating and one DOF for opening/closing the two fingers (gripper). The standard joystick of the JACO was used as the baseline for comparison with other studies.

The control interface was implemented based on the Robot Operating System (ROS kinetic) and the Python programming language. ROS handled the communication between the ITCI and JACO, during which the ITCI sent the data at a frequency of 30 Hz and the control commands were up-sampled to 100 Hz for a smooth motion of the JACO. The maximum linear velocity of the JACO was set to the factory default value (20 cm/s) for controlling it with the joystick and to 7 cm/s for controlling it with ITCI system. We chose a lower velocity for controlling JACO with the ITCI to account for the participants

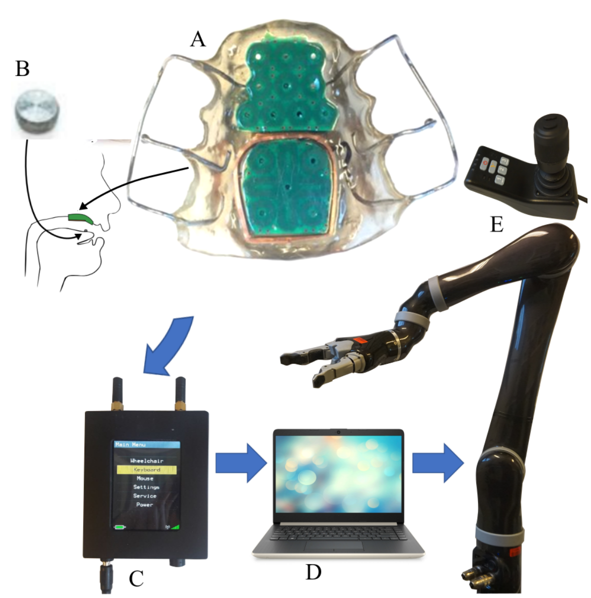

Fig. 1. System overview for using the ITCI system for control of the JACO ARM. A: The mouthpiece unit with two sensor PCBs carrying 10 sensors in the front and 8 in the back. B: The activation unit. C: The central unit. D: A visual feedback was presented on a screen. E: The JACO ARM and its joystick

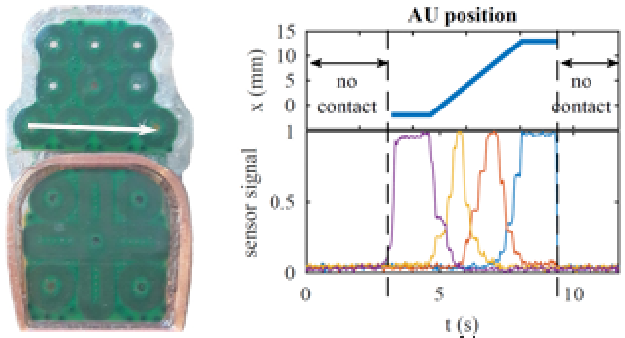

Fig. 2. An example of how the inductive sensors measure the contact of the AU. Right: The 18 sensor signals. The sensor voltage is measured in mV and then normalized to the range of variation. Left: The white arrow shows the path of AU. Top: The corresponding AU position.

low experience with the ITCI and the lower resolution of the ITCI joystick in comparison with the JACO joystick. However, we expect that the best performance of the ITCI and the JACO joystick will be achieved by the specified velocities.

B. Control layouts

We developed four different control layouts to compare several arrangement of buttons, i.e. mapping the position of the AU to the robot controls. Each layout provided full control of the seven DOF of the robot, which required 14 inputs (two per DOF). These commands were issued through virtual buttons on the ITCI PCBs by placing the AU in the area that was assigned to the button (Fig.3). A control command was sent to the robot with a delay of 0.5 second after pointing to a button and the robot immediately stopped after lifting the AU. This dwelling time was set to avoid unintended commands [27].

To study the effect of the size of the buttons on the control layout, we designed two layouts with discrete commands (Fig.3,B & C). The first one (B) included all the 14 buttons in one mode (discrete, one mode: D1M) and the second one (C) had bigger buttons, but in two modes (discrete, two modes: D2M). The design enabled switching between modes by rapidly touching the sensor PCB with the AU twice (double click) on the front part of the layout. We designed the buttons in the D2M layout such that the surface area of each button is approximately 100% (88% - 205%) bigger than the same button in D1M.

Another layout was designed containing a joystick-like control that provided continuous commands in two modes (C2M). Similar to D2M, we used a double click on the front PCB for switching between the two modes and the dwelling time of 0.5 seconds prevented activation of the joystick during mode switching. As the joystick could control only two DOF, they were mapped to linear motion in the X and Y axes of a Cartesian frame fixed to the table (Fig. 4,C) in the Motion mode and rotation around the same axes in the Orientation mode. Two different methods for emulating a joystick with the ITCI system were previously introduced for a pointing task on a screen [25]. One of them maps the position of the AU relative to a fixed origin to a velocity command (position to velocity mapping: PV). The length and direction of the vector from the origin point in the center of the layout to the contact point specifies the magnitude and direction of the velocity command. The other one maps the displacement of the AU to a velocity command (displacement to velocity mapping: DV). There is no fixed origin in this method. Instead, making a contact and dragging a vector will specify the direction and magnitude of the velocity command. The two methods were tested on the same layout (Fig.3,D). We put the joystick button on the front PCB to achieve a high-performance joystick, taking into account the higher throughput [19] and resolution [25] of the front PCB compared to the lower. Because the joystick was the only button on the front PCB, no boundary line was applied on this PCB in the C2M layouts and only horizontal lines between the two PCBs were used for defining it as a button.

In order to map the AU position to the virtual buttons on a layout, we developed a method based on boundary lines (e.g. Fig. 3,A). Each layout was defined by *n* boundary lines and could contain *m* buttons. A line (l_i) was defined by the three elements a_i, b_i and c_i in the the XY space of the touchpads (Fig. 3,A):

$$l_i(x, y) : a_i x + b_i y + c_i = 0 \tag{1}$$

For example, l_1 in Fig. 3,A is defined as $1 \times x + 0 \times y - 5 = 0$. Matrix *L* contains the *n* lines of the layout:

$$L = \begin{bmatrix} a_1 & b_1 & c_1 \\ \vdots & \vdots & \vdots \\ a_n & b_n & c_n \end{bmatrix}_{n\times 3} \tag{2}$$

Another matrix (*B*) specified the position of the buttons with respect to the lines. The rows of *B* were the unique codes for each button. Elements of *B* could only be -1, 1 or 0. The first two defined at which side of the line a button was located and zero meant that the line was not used for defining the button's area. For example, considering l_1 in Fig. 3,A (boundary lines for "Motion" mode of D2M layout in Fig. 3,C), the code for the "left" button was -1, for the "right" it was +1 and for "forward" it was 0. *B* had *m* rows and *n* columns. The position of each button was defined exactly with respect to five lines (minimum number of lines that are required to define all the buttons uniquely) and had zero code for the rest of the lines.

$$B = \begin{bmatrix} 0 & -1 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix}_{m\times n} \tag{3}$$

When a contact point in *p=(x,y)* was identified, it was multiplied by matrix *L* (the index shows the size of the matrix):

$$C_{n\times 1} = L_{n\times 3} \cdot \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{4}$$

The sign of elements of *C* represented at which side of the line the point was located and it was zero when the point was on the line itself. If the five nonzero values of one of the rows in *B* matched those of *C*, the point was located on the button that was specified by the row in *B*. To check this, matrix *D* was calculated by:

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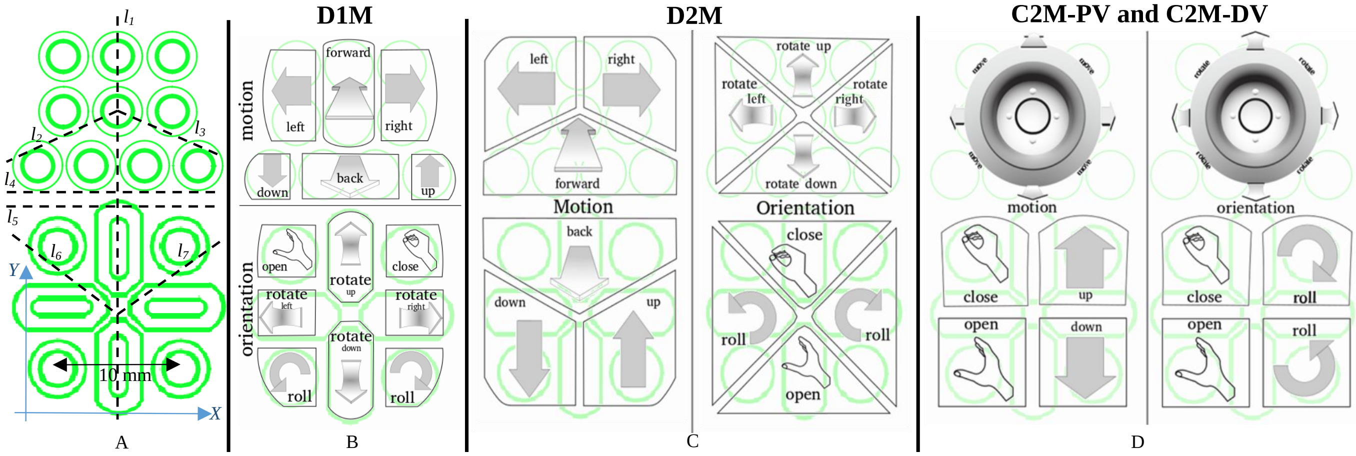

Fig. 3. A: Layout of inductive sensors on the MPU; the dash-lines are an example of the boundary lines for the left mode of D2M. B: Control layout with discrete commands in one mode. C: Control layout with discrete commands in two modes. D: Control layout with continuous commands in two modes.

$$D_{m\times 1} = B_{m\times n} \cdot sign(C) \tag{5}$$

D was an array with m elements and just one of them was equal to five. If the i_{th} element was equal to five, it meant that button i was selected.

C. Participants

Twelve able-bodied volunteers participated in this study (mean age 30, range 26-38, 1 female). Eight of them had prior experience in using the ITCI system: Five participants had one hour, two had three hours and one had 40 hours of prior experience. The participants signed a written informed consent before the experiment. The study had been approved by the local ethical committee.

D. Experimental setup

To the best of our knowledge, no standard and common evaluation method exists for the interface of assistive robots. A review article [4] reported different tasks that had been used for assessing assistive robot interfaces and illustrated the lack of standard outcome measures and evaluation tools. Most studies included performing ADLs [28][29][30] to simulate a real scenario of the assistive applications. Drinking is one of the ADLs that was rated with high importance by interviewed people with tetraplegia, their family members, and the care-givers [31][32][29]. Thus, we used a pouring water (PW) task for the evaluation, similar to [29] and [33].

Similar to what was conducted in [8], another task was to pick up a roll of tape (PUT) from a mount as this task required a higher degree of precision than grasping a bottle. This task was conducted to evaluate two fundamental tasks that could be part of any grasping task [34]: gross motion and fine adjustment of the arm. Gross motion includes moving the robot end-effector from one point to the vicinity of another point in the 3D space. Fine motion requires precise control of the position and orientation of the end-effector and is differentiated from gross motion by the shorter displacement and the higher accuracy required.

The process of accomplishing the tasks is depicted in Fig. 4. The participants sat at a table in front of a screen (Dell, 22 inches, 1680x1050 resolution). Visual feedback from the contact position of the AU on the control layout was presented on the screen. The JACO ARM was mounted on another table next to the participant (Fig. 4,C). A plexiglass screen was used to avoid collision between the participant and the JACO.

The PW task started when the JACO was in its default home position (Fig. 4, A.1). The first step was to pick up a 500 ml bottle filled with 250 ml water, and move it towards a cup. Then the bottle was rotated around the wrist joint (Fig. 4, A.3) to pour water in the cup. Finally, the bottle was replaced on the table. A hole in the bottle lid was made instead of removing it to prevent the table and the participant from getting wet in case the bottle was dropped. The relative distance in Cartesian coordinates ([X,Y,Z]) of the JACO end-effector in the initial position to the position of the bottle on the table was [15,25,-50] cm, and to the position of the cup was [35,-5,-50] cm. Using this notation, the X axis was parallel to the width, the Y axis to the depth, and the Z axis was parallel to the height of the table (Fig.4, C). The trial was considered failed if the bottle fell on the table or if water was not poured into the cup. Spilling was allowed.

The PUT task required picking up a roll of tape (diameter: 63 mm; height: 19 mm) placed and centered on a mount (a circle of 32 mm diameter). The relative position of the JACO end-effector to the center of the tape was [20,20,-30] cm. A displacement of more than 5 mm caused a drop of the tape and failure of the trial. Similar to the PW task, the PUT task started with the JACO in the home position.

E. Study protocol

The study consisted of three sessions on consecutive days. The participants received the information about the experiment prior to the first day and they signed informed consent before participating. A custom MPU was made for each participant. At the beginning of each session, the AU was glued on the tongue of the participant approximately 1 cm posterior to the tip of the tongue using Histoacryl® (B.Braun Surgical S.A.,

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ES). The AU consisted of a cylindrical titanium unit with a diameter of 5 mm and a height of 3 mm. The AU, MPU and the tools for gluing the AU were sterilized before each session for each participant based on a standard procedure.

The purpose of the first session (Fig. 5) was to train the participants and familiarize them with the ITCI, the different control layouts, and the tasks. Because of the individual variability of the experience in controlling ARMs, the participants trained each task with each layout until they could complete the task successfully. This session lasted approximately one hour. But it varied between the participants based on how fast they learned the tasks and the layouts.

The second session consisted of four parts. In each part one of the control layouts was used to perform three trials of the PUT task followed by three trials of the PW task. In total, 24 trials (3 repetitions x 2 tasks x 4 layouts) were recorded from each participant on the second day. The order of testing the layouts was counterbalanced across the participants such that the layouts placed in different positions of the sequence of testing equally.

The purpose of the third session was to evaluate the performance of the tongue-based robot interface and compare it with the standard joystick of the JACO (Fig. 1,E). The participants performed the PUT and PW tasks five times each using three different control methods: (1) using the joystick; (2) using the

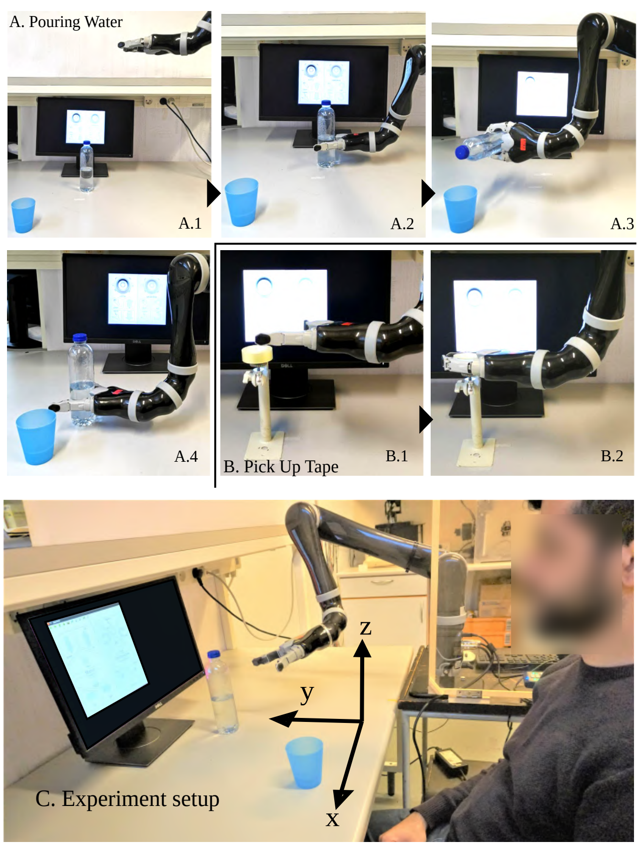

Fig. 4. A: Pouring water task steps. A.1: home position. A.2: grasping the bottle. A.3: pouring water in the cup. A.4: Putting the bottle back on the table. B: Pick up roll of tape task. B.1: reaching the vicinity of the tape. B.2: Fine positioning the fingers to align with the tape. C. Experiment setup

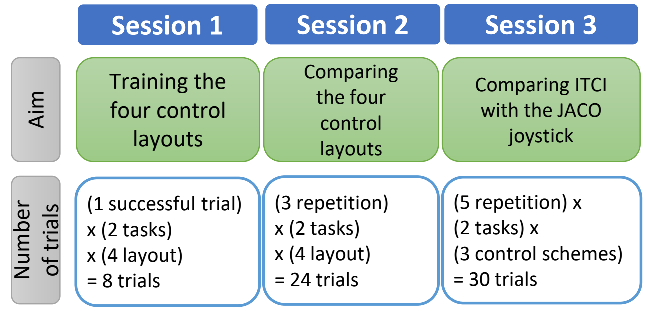

Fig. 5. The three experimental sessions, the aim and number of trials. The tasks were to pick up a roll of tape (PUT) and to pick up a bottle of water and pour water in a cup (PW). In the first session, participants trained each layout until they completed both tasks successfully.

ITCI while keeping it in one hand and moving the AU with the other hand, and (3) using the ITCI system in the mouth (5 repetitions x 2 tasks x 3 control schemes = 30 trials). We tested the ITCI in hand to assess the capability of the system while reducing the effect of the longer learning time of using it with the tongue, which is more challenging than using it with the hand during which the vision can be used for guidance. Participants used the same layout for controlling by hand and by the tongue. As holding the ITCI in hand inversed the left and right compared to having it in the mouth, we adopted the control such that the position of buttons match the direction of ARM movement. The order of testing the three control schemes was counterbalanced. Each participant only used the control layout that had the lowest mean task completion time on the second day. This was to compare the best performance of the ITCI for each participant with the JACO joystick that is already optimized by the manufacturer.

F. Outcome measures

We used *task completion time* as the main performance outcome to evaluate and compare the layouts. For the PW task, we measured the time from the first command to the robot, until the instance when an *open finger* command for releasing the bottle was issued. For the PUT task, the task completion time was measured from the first command to the robot until the instance when a *move up* command was issued after grasping the tape.

In order to obtain further performance measures and analyze the characteristics of the layouts, the *number of issued commands* and the duration for which the robot was moving (*moving time*) were recorded.

The *trajectory length* was measured by summing up the distance of consecutive points of the end-effector trajectory, which were obtained with 100 Hz (based on the joint angles and forward kinematic of the robot). Finally, two outcome measures were calculated specifically for the PUT task: the interval from the beginning of the trial to the instance that the end-effector reached the vicinity of 10 cm to the tape center was considered as the *gross motion time* and the rest until the end of the trial as the *fine motion time*.

To evaluate the time cost of mode switching, we measured the interval between releasing a button on one of the PCBs

(Fig. 1,A) and then selecting a button from the same PCB in two cases; one case with a mode switch between selecting the two consecutive buttons and one without a mode switch. The difference between the duration of these two variables was an estimation of the mode switch duration.

G. Statistical Analysis

Shapiro-Wilk test was used to determine whether the data were normally distributed. In that case, one-way repeated ANOVA was used to test for significant differences between layouts and control schemes. If data were not normally distributed, a log transformation was applied followed by a new normality test. In the case that even the log-transformed data were not normally distributed, we used related-samples Friedman's analysis of variance by Ranks. Post hoc comparisons were conducted using Bonferroni correction for multiple comparisons. The statistical significance was defined as $p<0.05$. The analyses were conducted using SPSS (version 26).

H. Task load index questionnaire

To analyze the subjective perception of the participants from performing the tasks with the ITCI, the participants filled in the National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire [35] after using each of the three control schemes on the third day. They scored the six subscales including mental, physical and temporal demands, own performance, effort and frustration level from 0 to 100 in an online version of the questionnaire [36]. High scores represent high task loads. In order to illustrate the effect of the control scheme and remove the effect of confounding factors on the task load, such as performing the task with the robot arm and inter-rater variability, we considered JACO joystick condition as a baseline and thus examined the difference in TLX scores between the JACO joystick condition and the two other conditions. We used the One-sample t-test for each score to determine whether the mean score of the condition is statistically different from their baseline.

III. Results

A. Comparing control layouts

All participants attended the three experiment days and finished all the tasks. The functional difference between the layouts was investigated on the second day of the experiment using different outcome measures (Table I).

The task completion time data of the four layouts for both tasks were positively skewed (Fig. 6). Thus, a log transformation was applied to make them normal and remove the outliers. The transformed data were normally distributed as assessed by Shapiro-Wilk's test ($p > 0.05$).

Considering all the trials, the one-way repeated measures ANOVA of the task completion time of the PUT task over the four layouts showed a significant difference ($F(3, 105)=3.105$, $p=0.03$). The assumption of sphericity was met as assessed by Mauchly's test of sphericity. Pairwise comparisons with a Bonferroni correction revealed that the layout with continuous command and displacement to velocity mapping (C2M-DV) had a significantly lower ($p=0.047$) task completion time (37.9 s on average) than the D2M layout (45.0 s) of 15.8% (Table I). No statistically significant difference appeared between the other pairs of layouts. The same statistical analysis of the task completion time of the PW task showed a statistically significant difference ($F(3,105)=6.31$, $p=0.001$). Pairwise comparison tests illustrated that the task completion time was significantly lower for the C2M-PV layout (87.4 s) than the D2M (97.7 s, $p=0.006$) and the C2M-DV (101.4 s, $p=0.002$), but not lower than the D1M (92.5 s) (Table I).

The participants completed the tasks the fastest by means of the layouts with continuous commands. The minimum task completion time was 18.9 seconds for the PUT task with the C2M-DV and 56.0 seconds for the PW task with the C2M-PV (Table I). The mean gross motion time for all the layouts were similar with no significant difference. However, the layouts differed in performance of fine motion of the end-effector for grasping the tape (Fig. 7, top). The C2M-DV had significantly lower ($p=0.006$) fine motion time (median of 20.3 s) than the D2M (26.0 s) of 21.9% (Friedman's test with Bonferroni adjustment). The moving time was similar within the continuous (C2M-PV and C2M-DV) and discrete layouts (D1M and D2M), but it was different between them (Fig. 7). The continuous layouts had a lower moving time in the PUT test (an average of 21.5 s compared with 26.0 s, Table I) with a significant difference between both of the continuous layouts and the D2M ($p<0.05$) as assessed by the Friedman's test. For the PW test, Friedman's test showed that only the C2M-PV had a significantly lower ($p=0.028$) moving time (median of 56.0 s) than the D2M (69.9 s). The average number of commands for completing the PUT task was significantly lower (ANOVA: $p<0.005$) for the continuous layouts than the discrete layouts (8 compared with 10 and 13; c.f. Table I). The C2M-PV required a significantly lower number of commands for completing the PW task (ANOVA: $p<0.05$) than all of

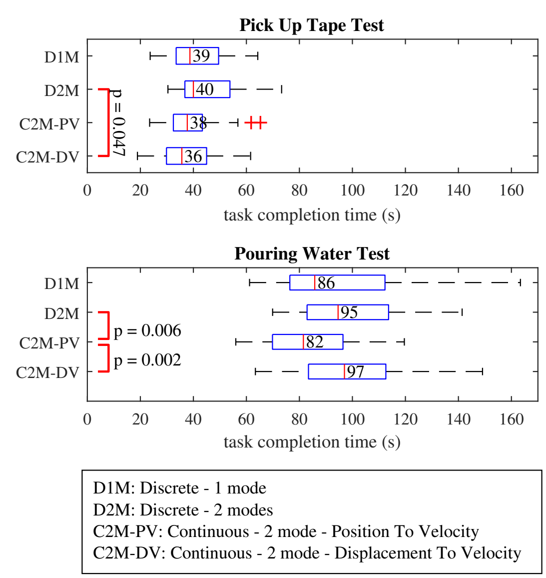

Fig. 6. Box plot of task completion time for the PUT and PW tasks over the four control layouts. The median of each layout is printed inside the box. The plot is based in the data of all trials. The "+" symbol shows an outlier.

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TABLE I
PERFORMANCE MEASURES OF THE CONTROL LAYOUTS FOR PUT AND PW TASKS ON THE SECOND SESSION OF THE EXPERIMENT, MEAN VALUE AND STANDARD DEVIATION IN PARENTHESIS OVER 36 TRIALS

Task	Layout	Task completion time (s)	Minimum task completion time (s)	Gross motion (s)	Fine motion (s)	Moving time (s)	Failed trials (%)	Trajectory length (cm)	Number of commands
Pick Up Tape	D1M	41.7 (12.0)	23.7	14.2 (4.6)	27.5 (11.7)	26.3 (8.8)	25.0	85.5 (13.1)	13 (4.3)
	D2M	45.0 (11.7)	30.4	15.9 (4.3)	29.1 (10.2)	25.7 (8.1)	27.8	87.9 (7.4)	10 (3.5)
	C2M-PV	39.2 (13.5)	23.5	14.6 (4.4)	24.6 (8.8)	21.9 (5.2)	30.6	76.8 (8.1)	8 (3.6)
	C2M-DV	37.9 (10.1)	18.9	15.6 (3.1)	22.2 (9.9)	22.1 (4.0)	22.2	80.4 (13.7)	8 (2.7)
Pouring Water	D1M	92.5 (23.3)	61.2	-	-	65.1 (11.7)	2.8	151.6 (21.3)	24 (8.5)
	D2M	97.7 (18.5)	69.9	-	-	65.2 (12.0)	11.1	143.2 (16.3)	18 (5.7)
	C2M-PV	87.4 (29.0)	56.0	-	-	57.2 (12.6)	0.0	132.9 (25.8)	13 (6.3)
	C2M-DV	101.4 (23.9)	63.4	-	-	62.9 (11.1)	8.3	151.9 (27.3)	18 (7.0)

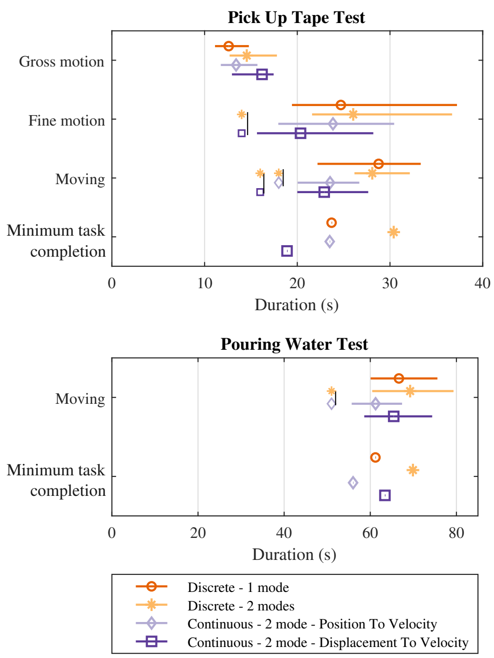

Fig. 7. The median, and the first and third quartiles of the Gross motion, the Fine motion, and the Moving time of the control layouts for the PUT task and the Moving time of the PW task in the second session of the experiment. The minimum task completion time over all trials is also presented. The vertical black lines with the markers on the two ends shows a significant difference of $p < 0.05$

the other layouts (Table I)). The C2M-DV had a significantly lower (p=0.034) number of commands for the PW test only compared with the D1M. Friedman's test did not show any significant difference between the trajectory length of the layouts for the PUT test. For the PW test, the robot moved in a significantly shorter trajectory with the C2M-PV than the other three layouts (p<0.05) and no significant difference was found between the other three layouts (Friedman's test with Bonferroni adjustment).

The number of participants that used each layout on the third day (the layout with the best performance for the individual participant on the second day) was 4 for D1M, 6 for C2M-PV and 2 for C2M-DV. D2M was not used in the third session. The mean task completion time for both tasks was similar for all the layouts on the third day without any significant difference. The mean task completion time was 33.3 s (D1M), 31.7 s (C2M-PV) and 31.6 s (C2M-DV) for the PUT task and 77.1 s (D1M), 68.9 s (C2M-PV) and 76.4 s (C2M-DV) for the PW task.

B. Mode switching

The average time interval between releasing a button and selecting a button on the same sensitive area (the PCBs) was 3.8 s when a mode switch was conducted between the commands and 1.7 s when no mode switch was conducted. These values were equal for both PCBs. Thus, the average time for the mode switch command was 2.1 s, which is obtained by subtracting 1.7 from 3.8.

C. Comparing ITCI with a standard joystick

In the third sessions, the overall performance of the ITCI system was tested and compared with the standard joystick of the JACO ARM. The statistical difference of task completion time with the joystick and the ITCI was investigated. The data were positively skewed and even a log transformation did not make them normally distributed. Thus, we used the related-samples Friedman's analysis of variance by ranks. The post hoc test with the Bonferroni correction showed a significant difference in the task completion time of the joystick compared with the ITCI, both by hand (p=0.024) and by tongue (p<0.001). No significant difference was detected between ITCI by hand and by tongue. The results were similar for the PUT and the PW tasks (Fig. 8). On average, it took the participants 17.3 s to complete the PUT task with the joystick. It took 60.1% longer with the ITCI by hand and 98.0% longer with the ITCI by tongue (Table II). The mean time for grasping a bottle of water, pouring water in a cup and replacing the bottle on the table was 36.7 s with the joystick followed by 62.0 s using ITCI by hand and 73.0 s using ITCI by tongue; i.e. 68.8% and 95.6% of the joystick respectively (Table II). We observed a statistically significant difference (p<0.005) between the three control schemes for the trajectory length (Friedman's test with Bonferroni adjustment) in both tasks. For the PUT task, controlling the ARM with the joystick led

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TABLE II
PERFORMANCE MEASURES OF THE JOYSTICK AND ITCI SYSTEM BY HAND AND BY TONGUE FOR THE PUT AND PW TASKS IN THE THIRD SESSION OF THE EXPERIMENT, MEAN VALUE AND STANDARD DEVIATION IN PARENTHESIS OVER 60 TRIALS.

Task	Control Scheme	Task completion time (s)	Increase over Joystick[a](%)	Minimum task completion time (s)	Gross motion (s)	Fine motion (s)	Moving time (s)	Trajectory length (cm)	Failed trials (%)
Pick Up Tape	Joystick	17.3 (6.0)	-	8.2	4.9 (2.1)	11.9 (4.9)	10.9 (3.1)	57.9 (7.8)	8.3
	ITCI by hand	27.8 (7.1)	60.1	17.1	9.8 (5.6)	15.7 (6.1)	17.9 (3.2)	68.3 (2.8)	18.3
	ITCI by tongue	32.7 (9.3)	98.0	17.6	9.1 (6.9)	18.5 (6.7)	19.4 (4.5)	73.8 (6.8)	30.0
Pouring Water	Joystick	36.5 (10.0)	-	22.9	-	-	25.6 (4.5)	100.6 (9.0)	0
	ITCI by hand	61.6 (9.9)	68.8	48.0	-	-	46.7 (6.4)	115.6 (8.7)	3.3
	ITCI by tongue	71.4 (13.7)	95.6	53.4	-	-	50.8 (8.1)	125.2 (6.8)	3.3

[a] Difference of mean task completion time (ITCI -Joystick)/Joystick

to the mean trajectory length of 57.9 cm, followed by ITCI by hand with 18.0% and ITCI by tongue with 27.5% longer trajectories (Table II). Similarly for the PW task, the shortest trajectory was achieved by the joystick (100.6 cm) followed by ITCI by hand with 14.9% and ITCI by tongue with 24.4% longer trajectories (Table II).

D. Learning

We investigated the improvement in the performance of the layouts between the three days. The D2M layout was not used by any of the participants in the third session. We tested the decrease in task completion time from the first day to the second day and from the second day to the third day for each layout (except D2M) and each task using a paired-samples t-test and a Bonferroni correction of the significance level. A significant difference appeared between the first day and the second day ($p < 0.025$) for all the layouts and in both of the tasks with an average decrease of task completion time of 33.6% from the first day to the second day. However, we did not find enough evidence to show any significant difference between the second and third sessions due to the low number of samples for each layout in the third session (Fig. 9, top).

No significant learning was taking place; neither within a day (over trials), for the four layouts in the second session nor for the three control schemes in the third session (ANOVA).

E. Trajectory planning

The different available control commands on the robot interfaces led to different strategies for planning the trajectory. The control layouts with discrete commands only provide linear motion along or rotating around a single Cartesian axis. Therefore, participants had to move along the three axes sequentially (fig. 10, A & B). As the Left and Forward buttons were adjacent in the discrete layouts, some participants used a zigzag motion in the horizontal plane to move diagonally

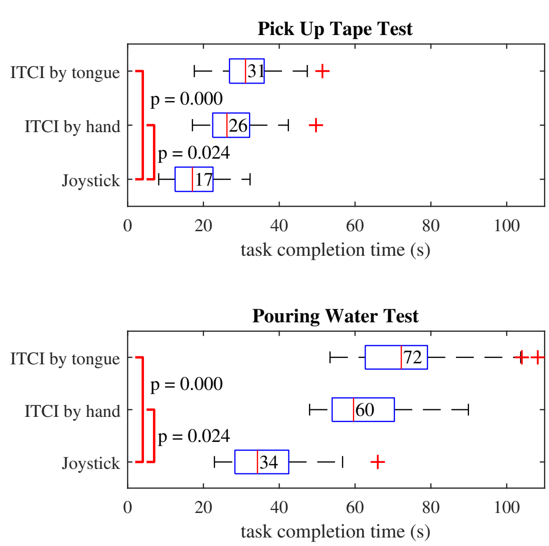

Fig. 8. Box plot of task completion time for the PUT and PW tasks with joystick, ITCI by hand and ITCI by tongue. The median of each layout is printed inside the box. The "+" mark shows an outlier

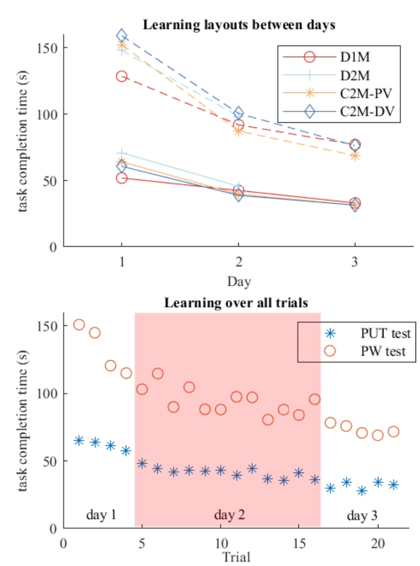

Fig. 9. Top: Learning curves between the three experiment days. Solid lines show the PUT task and dashed lines show the PW task. Bottom: Learning curves over all the trials regardless of the layout

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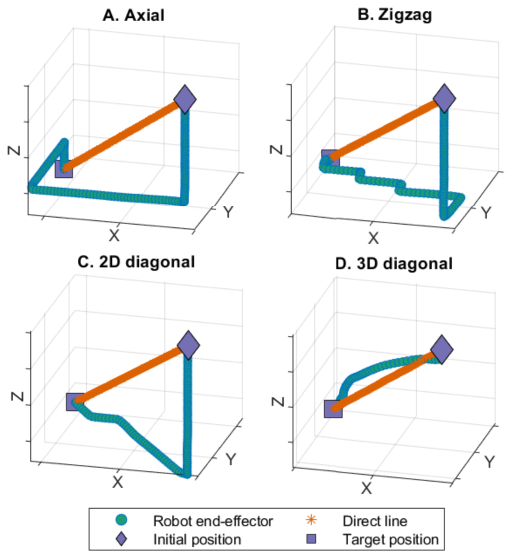

Fig. 10. Different trajectory strategies for reaching the tape roll from the home position in PUT task. A and B are examples of trials with discrete commands. C is an example of a trial with continuous commands. D shows a trial with the JACO joystick

towards the target (fig. 10, B). However, the length of a zigzag trajectory is similar to the axial approach. Through the joysticks-like buttons on the continuous layouts, it was possible to move diagonally in the horizontal plane and have shorter trajectories (fig. 10, C). The fastest way to reach the tape from the home position was to move along the line that connects these two points. This requires simultaneous control of the three Cartesian axes and it can be done by the JACO joystick (fig. 10, D). The differences in the controls are also reflected in the trajectory length values. For the PUT task, the average trajectory length with the joystick was 57.9 cm comparing to 68.3 cm and 73.8 cm for the control schemes with the ITCI by hand and by the tongue respectively (table II).

F. NASA TLX scores

We considered the results from the six participants that were not a member of the research group of the authors to avoid any bias in the analysis. The One-sample t-test showed that the NASA TLX mean scores of the ITCI by hand condition are not statistically different ($p>0.05$) from zero (the JACO joystick). For the ITCI by tongue condition, we obtained a statistically significant difference from the baseline for the physical demand ($t=3.169$, $p=0.025$) and the effort ($t=4.444$, $p=0.007$). The mean value and the confidence interval of the relative scores (difference with the JACO joystick condition) are presented in Fig. 11.

IV. Discussion

The objective of this study was to evaluate the effect of using continuous commands in comparison with discrete commands and a mode switching method on controlling an ARM with a tongue-based robot interface. We compared the performance of a control layout with discrete commands and a single mode with another layout with the same commands in a two mode configuration and approximately 100% bigger buttons than the single mode layout to investigate the trade-off between larger buttons and mode switching. The statistical tests on the task completion time for the PUT and PW tasks showed no significant difference between larger buttons that required mode switching and smaller buttons that did not.

The contribution of the continuous command to the performance of the interface was investigated by comparing the layout with discrete commands in two modes (D2M) with the layouts with the continuous command in two modes (C2M-PV and C2M-DV). We compared D2M with the continuous layouts because they differed only based on the type of control (continuous/discrete), and the number of modes was similar. For both tasks, the task completion time of D2M was significantly higher than one of the control layouts with continuous command. This may be due to lower moving time (Fig. 7) of the layouts with continuous command which is due to the shorter trajectory (Table I and Fig. 10). The moving time reflects the efficiency of the available control commands, regardless how much time was required for activating them when the robot was not moving. Furthermore, the number of commands for completing the tasks was lower for the layouts with the continuous command (Table I) which means less effort by the user. The participants chose different strategies for moving from the home position to the target object. Thus, we could not identify the participant's desired commands and we were not able to measure the accuracy and the required time for activating the commands in different layouts. This question will be addressed in our future study.

The two layouts with the continuous command yielded different performances in the different tasks. The method that mapped position to velocity (C2M-PV) yielded faster completion of the PW task than the method with displacement to velocity mapping (C2M-DV), but slower completion of the PUT task (Fig. 7). According to the results (Table I) C2M-PV had a lower mean gross motion time (14.6 s vs. 15.6 s) and C2M-DV had a lower mean fine motion time (22.2 s vs.

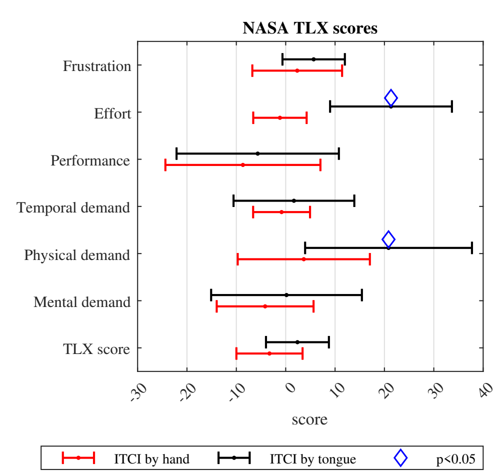

Fig. 11. NASA TLX scores of performing the tasks with the ITCI system by hand and by tongue relative to performing it with the JACO joystick. The data from lab-member participants were excluded. Error bars show the confidence interval. A diamond marker above the mean value signifies that the mean is statistically different from zero

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24.6 s). This difference may explain the different performances in the two tasks as pouring water does not require the same fine motion as picking up the roll of tape.

In a proof-of-concept study [8] after 30 min of training, one participant with tetraplegia completed the PUT task with the ITCI in 70.1 s on average. In that study, each sensor of the ITCI was mapped to one discrete command. We used an interpolating method to obtain a higher resolution interface. This approach led to a mean task completion time of 32.7 s in the third session; i.e. 53% lower than the previous method [8]. The position of the tape and the criteria for measuring the task completion time were similar between the two studies. However, in the current study the cohort was different (16 able-bodied participants) and the training lasted longer (two hours of the experiment in the first and second day sessions). Comparing the performance of ARM interfaces between studies requires a common standard test protocol. We did not find any study that evaluates a hands-free full control of a seven-DOF ARM and uses a standard performance measure to compare it with the results of this study. We reported the details of our test setup and used the standard JACO joystick to enable comparison with other future studies.

As expected, the JACO joystick had a higher performance than the ITCI system (Table II). One of the reasons for its higher performance is the possibility to control three DOF simultaneously that led to shorter trajectories (Table II and Fig. 10). Another reason is the higher maximum speed for the joystick control scheme (20 cm/s vs. 7 cm/s for the ITCI) which was convenient for controlling the ARM due to the high resolution of the joystick. We assumed that increasing the velocity of the ITCI would not decrease the task completion time. This hypothesis should be tested in another study. However, the performance of the ITCI system was comparable with the joystick (only 60.1% higher mean task completion time for the PUT task while it was controlled by the hand).

Performing the tasks with the ITCI and the control layouts did not impose higher mental load comparing to the JACO joystick when used in hand. However, the participants rated the effort and the physical demand of the intraoral use of the ITCI higher than the JACO joystick (Fig. 11). A plausible explanation of the higher physical demand is that low proficiency of the participants in using the ITCI led to pushing the AU to the touchpads more than required. The higher effort of intra-oral use was expected, due to the indirect visual feedback of the contact between the AU and the touchpads and the difficulty in pointing to the button of interest with the tongue.

This study further showed that the task completion time decreased significantly over time with an average of 33.8% of task completion time from the first session to the second session, and it may improve even more with more training as the learning curves did not reach a plateau. In fact, the learning was not clear over a few consecutive trials due to the low slope of the learning curve (Fig. 9). However, it is evident that over long intervals such as days the performance improves.

A limitation of this study was that we recruited able-bodied individuals to simulate the use case of individuals with tetraplegia using the ITCI for controlling the JACO ARM. A previous study in which both individuals with tetraplegia and able-bodied participants were recruited suggested that the rate of typing correct characters per minute with the ITCI was comparable between the two groups [37]. A study evaluated another tongue interface [9] in a wheelchair driving task and showed that the task completion time for a group of participants with SCI was only 2.9% lower than the able-bodied group (253.2 s vs. 260.7 s in the first session) [9]. The tongue functionality usually remains intact after a spinal cord injury and performs similar to the tongue of able-bodied individuals. Thus, we expect that similar results may be achieved from a cohort of individuals with tetraplegia and this may be validated in a future study.

Although the participants had different levels of experience, it may not compromise the comparison between the layouts because their proficiency contributed equally to all of the conditions. However, the different proficiency increased the variability of the data and decreased the power of our statistical analysis. Thus, participants without prior experience with the ITCI system may be recruited in our future study.

The ITCI provides continuous and full control of a seven DOF robot for individuals with complete tetraplegia. It can be used for a short time by gluing the AU to the tongue. However, it requires a tongue piercing for long-term use. A study showed that from 25 individuals with spinal cord injury, 19 agreed to have a tongue piercing to test the ITCI [38]. Another study investigated the interference of speaking on the control of a wheelchair with the ITCI and showed that a dwelling time 0.5 second prohibits unintended activation of buttons while speaking [27].

V. Conclusion

This study showed that a novel tongue-based robotic interface with continuous input can provide individuals with severe disabilities, such as tetraplegia, the possibility to efficiently control an assistive robot manipulator and perform activities of daily life. The study demonstrated the ability to improve the performance of a tongue-based robot interface by incorporating virtual buttons and continuous commands. This enabled simultaneous control of two DOF and fine control of the velocity and the direction, improving the task completion time of the pouring water task by 10.5 percent.

In future, the use of virtual buttons and continuous commands may allow for dynamic and highly personalized tongue–robot interfaces.

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