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A Dedicated Tool Frame Based Tongue Interface Layout Improves 2D Visual Guided Control of an Assistive Robotic Manipulator – a Design Parameter for Tele-applications

Ásgerður Arna Pálsdóttir*, Mostafa Mohammadi, Bo Bentsen and Lotte N. S. Andreasen Struijk

***Abstract*— It is crucial to increase the independence of severely disabled individuals. Assistive robotics can aid in the desired activities of daily living, including tasks requiring remote performance e.g. grasping remote objects, turning switches on/off, and opening/closing doors. The robot control is compromised by the lack of efficient interfaces for individuals with disabilities and the lack of depth perception. This paper addresses these challenges by presenting the development and evaluation of efficient tongue-based robot interfaces and low-level robot control schemes targeting tele-robotic control through a 2D display. Ten able-bodied participants were successful in completing ten rounds of controlling a JACO robot to perform a pouring water task, using five different control methods, under 2D or 3D visual feedback. The tool-frame based tongue interface layout, L2_TF (with emulated joystick, mode switch button and a "GO" button) improved the 2D visual guided control of the JACO robot compared with the other tongue control methods. The mean trajectory length of completing the task using L2_TF was 3% longer compared with the standard joystick when controlling through 2D. The trajectory length for reaching and grabbing a bottle was shortest for L2_TF compared with all other control methods, including the joystick. The iTongue control layouts performed well in gripping time, showing no significant difference between 2D and 3D. The transition from 2D to 3D resulted in a mean decrease of 27.7% for task completion time across all interfaces. L2_TF and the joystick had the strongest and most similar robustness to the transition between 3D and 2D.**

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

I. Introduction

INDIVIDUALS with severe tetraplegia are challenged by a radical loss of independence and often need day and night assistance in order to perform activities of daily living (ADL). According to WHO, between 250,000 and 500,000 individuals worldwide suffer a spinal cord injury (SCI) every year [1], with over one third resulting in tetraplegia [2], [3]. Other causes of partial or full paralysis include stroke, ALS, multiple sclerosis, etc. The level of independence, life satisfaction, and quality of life (QoL) are expected to decrease over time for individuals with traumatic SCI [4]. Furthermore, functional decline has been correlated with a sense of hopelessness in individuals with ALS, which has been shown to predict suicidal attempts and suicides [5]. Therefore, it is crucial to empower severely disabled individuals by finding solutions that increase their independency.

Assistive robotic (AR) users have identified some tasks that are most wanted when using AR such as daily hygiene, scratching, eating and drinking, and being able to grab/reach for objects when lying in bed or sitting in their wheelchair [6]–[8]. Chang et al. [7] interviewed and observed high level SCI patients for a duration of 6 months and identified 12 important tasks. The most important tasks were eating and drinking, but other task needed remote performance, e.g. picking up objects that were far away, turning switches on/off, and opening/closing doors [7]. Assistive robotic manipulators (ARMs), with 6 or 7 degrees of freedom (DOFs), such as the iARM (by Assistive Innovations, the Netherlands) [9] and the JACO (by Kinova, Canada) [10] have shown to facilitate some of the desirable ADLs within the personal and peripersonal space and have the potential to allow individuals with tetraplegia to be self-sufficient, even when lying in bed.

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When these robots are to be controlled by individuals with severe tetraplegia in tele- or remote settings, the robot control is compromised by the lack of efficient interfaces and the lack of depth perception. Therefore, two critical challenges must be addressed: 1) how to provide a paralyzed individual with an efficient robot interface for control through a 2D representation of the 3D remote workspace and 2) how to provide an efficient robot control scheme for 2D tele operation.

Even though some input solutions based on key-pads [11] exist, the standard control method for both of these ARMs requires the user to be able to manipulate the interfaces using the hands and arms, which generally is very difficult or impossible for individuals with tetraplegia. Consequently, researchers have put effort into finding alternative interface methods. The input can be based on various modalities, e.g. head-gestures [12], tongue control [13], [14], voice recognition [15], eye gaze [16] and brain computer interface [17]. Despite this effort, most interfaces suitable for individuals with tetraplegia are stuck in a laboratory setting and have yet to reach the general user, thus creating a significant lack in the potential use of ARMs. There is room for improvement in terms of reliability, ease of use, and acceptance of the interface [18]. Generally, a user will spend a considerable amount of time using the interface, to a degree that it becomes a part of the user's social identity. Thus, the aesthetical aspect is important in terms of acceptance of the system and the way in which other people will react to the individual using the interface [18], [19].

When controlling an ARM with seven DOFs (six in the ARM and one in the end effector), the minimum amount of required commands to fully control all DOFs is 14. If the control signals are not continuous, e.g. as in voice-based control schemes, safety issues may arise. Further, if the interface does not provide sufficient direct control signals (such as the standard joystick and most BCI systems), there is a need for methods to expand the control. There are mainly two ways to solve the lack of control signals: either by incorporating semi-automation [20] or by introducing different modes [11]. By implementing semi-automation, the user sets a goal for the robot and the robot performs the desired task with or without input from the user. This has been shown to decrease the cognitive load and the time it takes to complete a desired task but it also affects the satisfaction of the user in a negative manner as the user loses control [21]. Furthermore, it has been pointed out that the automation part usually works for a very well-defined and limited number of objects only and is unlikely to perform well outside of a fixed laboratory-like setting [20]. The second solution to this problem is to incorporate different modes. In this way, the user can control a subset of the DOFs and by switching the mode, gain control of a different subset of DOFs. As described by Herlant et al. [22], it can be difficult to keep track of mode in which the user is operating. This can make the control confusing and in particular make the control slow. Hence, in order to keep it as simple as possible, the amount of modes should be as low as possible.

Another factor to take into account when developing a new interface is that the standard joystick allows for control of the continual movement speed of the robot and two DOFs at the same time, which can be beneficial when doing fine manipulation versus gross motion, and this is thus desirable when using other input modalities as well. Recently, Mohammadi et al. [23] have developed a high-resolution tongue-based joystick for the tongue control interface first proposed in [24]. The tongue interface (an adapted version of the commercially available tongue control system, iTongue © [25]) contains 18 different inductive sensors [26] and thereby has the potential to control the robot without using different modes, as has been shown in [13], [25], and [26]. Mohammadi et al. have also shown that controlling an ARM using a joystick like tongue based command is more effective than using discrete buttons for control [29].

Yet another factor to look into when developing a human-machine interface (HMI) is the method used for low-level control. The reference frame for movement and rotation can be defined in many different ways; for example, the standard low-level reference frame for controlling the JACO in a Cartesian space with the accompanying joystick is the base frame for translation and tool frame for orientation. This means that the robot moves according to the base of the robot (usually fixed, either to a wheelchair or to a table) and rotates around an axis oriented according to the end-effector. In an attempt to develop a more intuitive low-level control scheme, Campeau-Lecours et al. [30] proposed orientation control, which is based on a newly defined adaptive reference frame. Another attempt to provide a better performance when low-level controlling an ARM is end-effector control in which both the robot translation and rotation are defined according to the orientation of the end-effector [28]. As indicated by these studies, other low-level control methods have the potential to make the robotic control even more intuitive for disabled users.

In order to perform one of the previously mentioned remote tasks and allow the user to control the robot to manipulate objects that are far away and potentially not in the user's field of vision, an efficient robot interface and robotic control are needed. Previous studies on teleoperation of ARMs focus on easing the operation for the user by incorporating automation [31]–[33], but often the interfacing method is not suitable for individuals with tetraplegia [32], [34], [35].

One example of a tele-operated system with a suitable interface is a prototype named "SAM" in which a JACO robotic arm is mounted on a RobuLAB10 (Robotsoft) mobile base [33]. The majority of the study participants reported the usage of the system as an interesting option for daily tasks. However, as mentioned the limitation factor to this system is that it is designed for picking up objects only; thus, performing other tasks such as opening/closing of doors is not possible at this stage [33]. A second study showed the feasibility of using the iTongue to tele-control a wheelchair-mounted robotic manipulator; however, with a very limited number of study participants [27].

By providing an efficient robot interface for control through a 2D representation of the 3D remote workspace, the independency and self-sufficiency of individuals with tetraplegia can be increased. As previously mentioned, the robot control is compromised by the lack of efficient interfaces and the lack of depth perception.

This paper addresses the two critical challenges by developing and evaluating an efficient robot interface targeting robotic tele-control through a 2D display and further explores the impact of different low-level robot control schemes on 2D

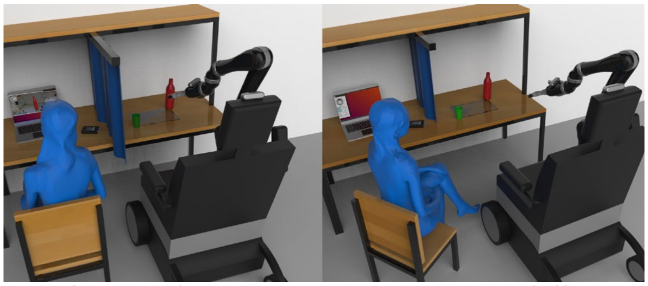

Fig. 1. Overview of the setup in the experiment in 2D (left) and 3D (right). The JACO ARM was mounted on a wheelchair and placed in front of a table. Next to the wheelchair, the participant sat on a chair in front of a computer screen which provided visual feedback. The study was perfomed in a local/wired setting, switching between direct 3D display and through 2D screen display.

visually guided 3D tele-operation of ARMs as compared with 3D visually guided operation.

II. Method

A. Technical/System Overview

The system developed in this study consisted of a tongue interface, a sensor-robot mapping software with visual feedback, a robot control software on a laptop, an ARM, a camera for providing 2D video of the workspace, and a visual display showing the workspace (Fig. 1).

The tongue interface deployed in this study was the inductive tongue control interface which was originally developed at Aalborg University in Denmark [24] but has since been commercialized by TKS A/S under the name iTongue [25]. In this study, we used an adapted version of the iTongue for control of the robot. The iTongue system consists of a mouthpiece unit (MPU), an activation unit (AU), and a control unit (CU) (Fig. 2) [36]. The MPU has 18 inductive sensors made of coils on a printed circuit board (PCB), a signal processing circuit (for amplification, rectifying and low-pass filtering [36]), and a wireless transmitter which sends the inductance signal to the CU through radio frequency. The MPU is encapsulated in epoxy and dental acrylic and made to fit the palate of the user in a custom-made dental retainer. In this study, the MPU was made to fit the palate of the study participants using a dental putty mold (ImpressA Putty, TopDent). The putty mold is made by mixing a base and a catalyst to make a stiff A-silicone impression that fit the palate of the participant. The AU is made from ferromagnetic material that is either pierced or glued to the tongue of the user (using Histoacryl® tissue glue) and when hovered over one of the sensors, the inductance in the coils changes which is interpreted as activation of the sensor. The CU connects to a computer or wheelchair using Bluetooth, USB or a joystick pin connector.

In this study, the CU was connected to a PC through a USB cable, which was further connected to a JACO2 robot from Kinova in Canada [10] with six DOFs and a three-finger gripper. The communication between iTongue, the PC, and the robot was implemented through a robotic operating system (ROS melodic) and Python programming language (Fig. 3). In the MPU, the raw iTongue signal was sampled and transmitted at 30 Hz [26] to the CU, which further transmitted it to the PC

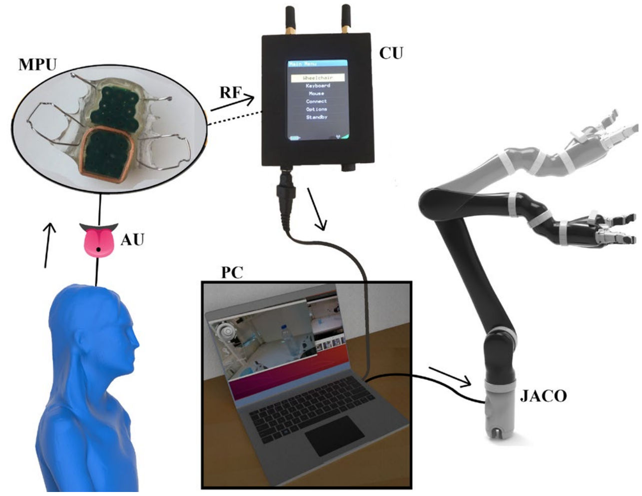

Fig. 2. Overview of the system. The study participant used iTongue in the mouth. The mouthpiece unit (MPU) communicated the sensor signal through radio frequency (RF) to the central unit (CU). The CU was connected to a PC, which translated the signal to commands for the JACO ARM.

via a USB cable, also at 30Hz. In the PC, the raw signal was read, processed, and interpreted to control commands for the JACO. The raw signal consisted of 18 hexadecimal numbers representing the voltage in each of the sensors, and to communicate with the robot, the iTongue data were mapped into a Cartesian linear velocity and published to a topic in a ROS package developed by Kinova [37]. The digital signal processing inside the robot looped every 10ms and in order to achieve the wanted velocity and not fill up a buffer in the robot, the publishing rate of the ROS topic was required to be 100Hz [37]. Therefore, the iTongue data were up-sampled and published at 100 Hz rate. The JACO2 robot came with a standard joystick (Joystick_BF), which was used for comparison in this study. The linear velocity was set to 0.07 m/s when controlling the JACO using both the iTongue system and the standard joystick.

B. Robot Control Schemes

Three different low-level reference frames (Fig. 4) were applied and assessed: 1) base frame (BF), as it is the most commonly used low level control, 2) tool frame (TF) to allow the user to be able to look around and easily direct the robot

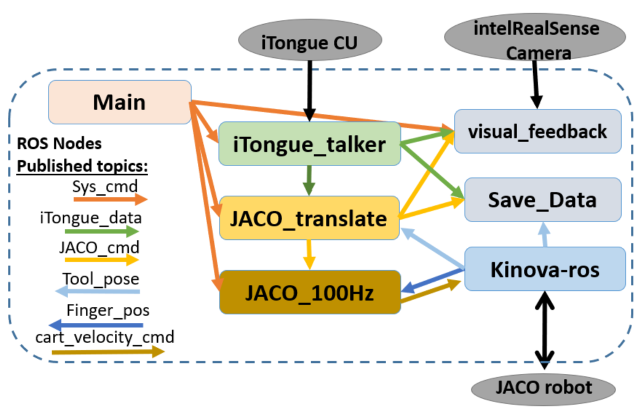

Fig. 3. Overview of the hardware (grey ovals) and software (colored squares) components. The dotten line represents the PC: containing the ROS nodes and messages published by each node.

towards an object, and 3) mixed frame (MF) for the same reason as TF but also to provide a reference frame that was easier to understand than TF. In an attempt to make the control more intuitive, three different high-level layout designs (Fig. 5) were designed, specifically targeting each of the low-level reference frame methods (Fig. 4).

The BF is the control scheme that is normally used with the robot; that is, when controlling the robot using the accompanying joystick. The end-effector moved according to the base, i.e., forward was always in x-direction (along the table/floor), no matter the orientation of the end-effector. When using the TF, the reference frame was rotated, depending on the orientation of the end-effector. If the end-effector was pointing upwards, the forward motion was rotated upwards. MF was a mix of the two. All commands except "GO" and "Retract" were according to the BF. When the "GO" and "Retract" commands were issued, the end-effector moved along the axis it was pointing to. If the end-effector pointed to the right, it moved to the right when issuing "GO" and left when issuing "Retract". Likewise, if the end-effector was pointing upwards, the end-effector moved upwards when activating "GO" and downwards when activating "Retract".

C. Mapping the iTongue Sensors to Commands

The raw signals from the MPU were converted to an x and y position on the PCBs using the weighted average of the neighbor sensor's method presented in [23]. This facilitated the design of the virtual buttons and joysticks within the area of the PCB plate for robot control (Fig 5).

In order to obtain the AU´s position, the activation ratio for each sensor was first calculated as

$$Activation = \frac{\max voltage - current\ voltage}{\max voltage - \min voltage} \quad (1)$$

where max and min voltage were the maximum and minimum voltage measured in the sensors. From that, the weights were calculated as the normalized activation for each of the neighboring sensors. That is, if sensor one was activated, the weight vector would contain a normalized activation ratio for sensor one and its neighboring sensors (sensors 2, 4 and 5) and zero for all other sensors (sensors 3, 6-18). When the weights or the normalized activation ratio were above a contact threshold (in this case set to 0.12), the sensor containing the maximum ratio was interpreted as being activated. From this, the x and y position of the AU on the touchpad could be calculated as the dot product of the weight vector and the center of the sensor positions:

$$XY_{Coordinates} = \frac{w \cdot sensor_{positions}}{sum(w)} \quad (2)$$

where $sensor_{positions}$ was an 18x2 matrix containing the center positions (x and y coordinates) of the 18 sensors and w was the weight vector. To overcome drifting in the baseline of the sensor signals, the minimum value for the sensor being activated, and the maximum value for all other sensors was updated during every iteration.

Using this information, the virtual tongue interface control layout could be designed in a desirable manner by using the x and y position as input for the control. In order to explore the best method for 2D visually guided control, four different high-level control layouts were implemented (Fig 5).

Mohammadi et al. [29] have previously shown that a continuous joystick-like control scheme can improve the functional performance as compared with a button based layout. The study was performed using only local setting, i.e., 3D. We wanted to build on this and study the effect of control in a tele-setting. Thus, the continuous control presented in [29] was implemented to be tested in a 2D vision condition (L1_BF). The mapping of the x, y coordinates in the top part of the MPU was conducted so it would emulate a traditional joystick in which the velocity increased as the AU moved further away from the middle. The emulated joystick controlled translation of the JACO2 in the horizontal plane.

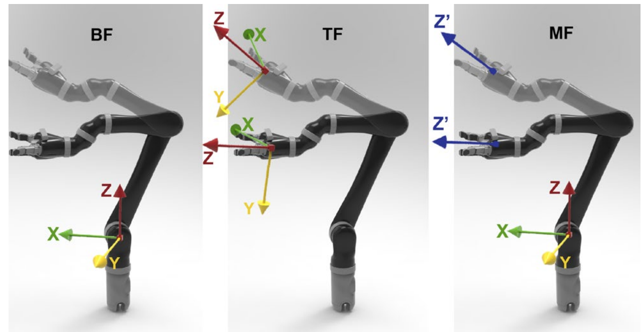

Fig. 4. **BF**: the standard method i.e., forward was always in x-direction along the table/floor. **TF**: the reference frame was rotated, depending on the orientation of the end-effector. Forward was always along the z-axis, pointing out from the end-effector. **MF**: a mix of the two. "GO" and "Retract" commands were based on the TF (movement along z') and other commands on the BF.

We thought that by allowing the user to "look" using a camera placed on the end-effector and move in the direction that the end-effector was "looking" would improve the control in a tele-setting. This could be achieved by using TF. Therefore, we decided to test the same layout in TF, i.e., L1_TF.

Subsequently, a new improved layout for control in TF was presented (L2_TF). A "GO!" button was introduced, which moved the robot along its tool-axis; that is, the participant could select a direction using the camera and make the robot translate in that direction using the "GO!" button. The emulated joystick was changed to control translation in the frontal plane and a new method for mode switch was introduced. Instead of switching modes using double click, the mode was switched by activating a specific sensor allocated to this for 0.5 seconds.

Lastly, as TF can be difficult to understand [30], the improved layout was adjusted for control in MF (L3_MF). In order to maintain control of all of the available DOF's, two DOF's were introduced as toggle buttons (forward/backward and roll+/roll-). The participants maintained the possibility to use the "GO!" button; that is, to choose a direction and make the robot move towards an object according to this direction.

D. Study Participants

This study was approved by the local ethical committee: The North Denmark Region Committee on Health Research Ethics. Ten abled-bodied individuals participated in this study (mean age 28.9 (SD 4.5), range 22-38, six females). None of the participants had prior experience using the iTongue interface. The participants were informed verbally and signed a written informed consent form before the start of the experiment.

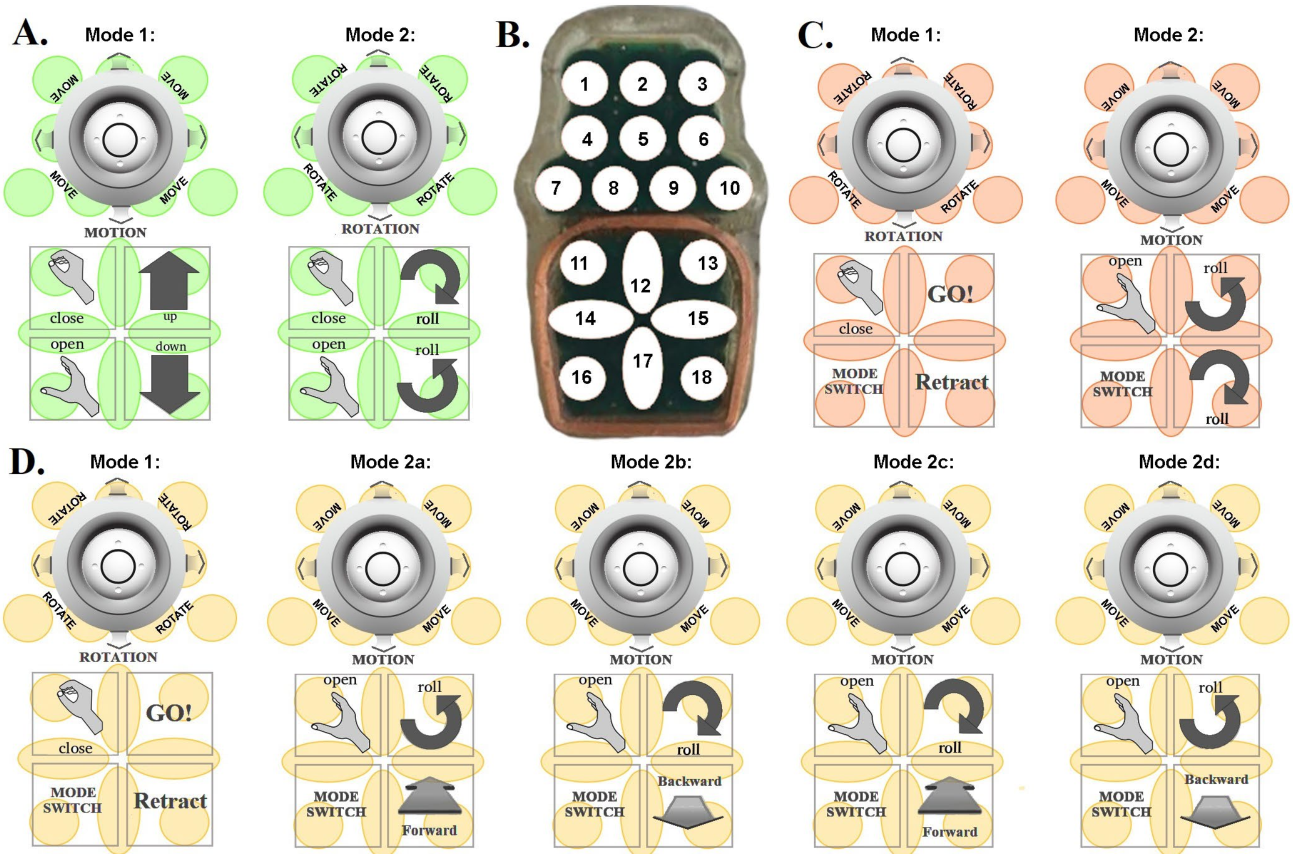

Fig. 5. Layout designs superimposed on the 18 sensors (green, red and yellow) of the MPU of the iTongue. The joystick on top is an emulated joystick. The signal from the sensors was processed to find an x and y position on the plate. If the x,y position was in the top left corner, the circular joystick (white part) moved towards that corner (similar to a top view of a regular joystick). **A.** Layout presented in [29] implemented for control in base-frame and tool-frame (L1_BF and L1_TF). The mode was changed by performing a double click anywhere on the touch plate **B.** The iTongue mouth piece unit and the 18 sensors. **C.** New improved layout (L2_TF) for control in TF with a "GO" button and a dedicated button for mode switching **D.** Layout adjusted for control in BF (L3_MF). Two DOF's were introduced as toggle buttons (forward/backward and roll+/roll-).

E. Experimental Setup

The participants performed tongue control of the JACO2 on three consecutive days for 2.5-4 hours per day. Studies have suggested that the users rate reaching, gripping, picking up objects, eating, and drinking as the most important tasks [38]. Previous studies have focused on an ADL task where water is poured from a bottle into a cup [13], [29]. As this involves several of the users' wishes, the same task was incorporated in this study.

The JACO2 robot was mounted on an electrical wheelchair, placed in front of a table. On the table, a bottle with water was placed 60 cm in front of the base of the robot. Furthermore, a cup was placed 35 cm diagonally from the bottle (Fig. 1). The relative position of the bottle from the end-effector in base frame was [-41cm, -6cm, -27cm] (Fig 4). The experimental task was to pick up the bottle of water, pour water in the cup and put the bottle down so that the cup was ready for picking up (although the cup was not picked up during this experiment). The trial was deemed unsuccessful and repeated if the bottle or the cup fell down. Otherwise, the trial was considered successful. Before starting each trial, the JACO2 was moved to its "home" position, a position that is pre-programmed in the Kinova ROS package and equivalent of holding down the "home" button on the accompanying joystick. The relative "home" position in the base frame was [-26cm, 21cm, 50cm] (Fig 4). Afterwards, the participants could start the trial when ready by moving the robot, and the trial ended when the bottle had been released on the table.

The participant was seated in a chair next to the wheelchair and in front of a computer screen (Dell, 22 inches) which provided visual feedback. The visual feedback was twofold. First, the participant controlled the robot looking directly at it and was provided with a graphical user interface (GUI) showing the area on the MPU being activated by the AU. Second, the line of sight from the participant to the robot was blocked and the robot was controlled through the 2D computer screen. As in the first part, the GUI showed where the AU was activating the touchpad but additionally it consisted of a video stream from the headrest of the wheelchair providing an overview of the scene and a video streamed from the end-effector of the JACO2 (Fig. 6).

F. Experimental Procedure

As has been shown in previous studies, the learning curve during the first days of an experiment using iTongue is steep but usually it plateaus around day three [39]. Therefore, this experiment ran over three days, with one experimental session per day that lasted between 2.5 and 4 hours. The length of each session was highly dependent on how easy it was for the participant to learn using the system and how well they could use the iTongue to control the robot (Table I).

TABLE I
EXPERIMENTAL PROCEDURE

Step	Day 1: session 1	Day 2: session 2	Day 3: session 3
1	Make Dental Putty [15-30 min]	Setup iTongue and AU [ca 5 min]	Setup iTongue and AU [ca 5 min]
2	Calibrate and learn how to activate sensors [ca 15 min]	Calibrate sensors [ca 5 min]	Calibrate sensors [ca 5 min]
3	3D Control: Learn how to use the first iTongue method and perform one repetition of the exp. task [30-45 min]	Control the robot with the iTongue. [ca 5 min]	Control the robot with the iTongue [ca 5 min]
4	3D Control: Learn how to, and perform one repetition of the exp. task [10-20 min per method]	2D or 3D Control: Perform 3 repetitions of the exp. task [10-30 min per method]	2D or 3D Control: Perform 3 repetitions of the exp. task [10-30 min per method]
5	**Break [10 min]**	**Break [10 min]**	**Break [10 min]**
6	2D Control: Learn how to, and perform one repetition of the exp. task [10-20 min per method]	2D (if it was 3D in step 4) or 3D (if it was 2D in step 4) Control: Perform 3 repetitions of the exp. task [10-30 min per method]	2D (if it was 3D in step 4) or 3D (if it was 2D in step 4) Control: Perform 3 repetitions of the exp. task [10-30 min per method]

Prior to the start of each session, all equipment and surfaces were cleaned and disinfected using 75% ethanol. Furthermore, the AU and dental equipment were sterilized in an autoclave and the iTongue system was disinfected using a >1000 ppm hypochlorite solution for at least 60 min.

At the beginning of the first experimental session, a custom dental putty mold was made that fitted the palate of the mouth of the participant and allowed the iTongue to stay in place. After the putty had set, the AU was glued to the tongue approximately one cm from the tip using Histoacryl® tissue glue. Then, the participant was seated in front of the computer screen and next to the wheelchair and the robot (Fig. 1).

The first session's goal was to familiarize the participants with the iTongue and controlling the robot. The participants started with calibrating the iTongue system by activating all of the sensors until the GUI showed that the activations were completely stable. This gave the participants an understanding of how the iTongue worked and where to place the activation unit to activate each of the sensors and commands. The robot was started and the participants were allowed to try controlling the robot with the iTongue. All participants started this day by controlling the robot using direct vision in one control method and completing one successful trial of the experimental task

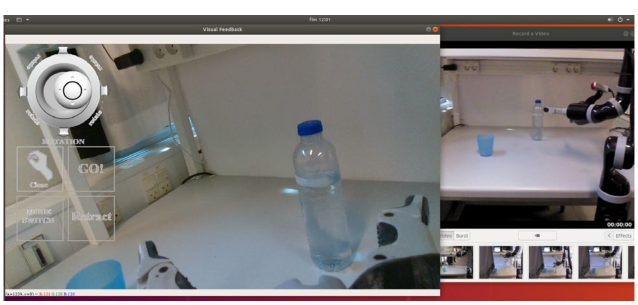

Fig. 6. The visual feedack given to the participant when controlling the JACO in a 2D setting. The visual feedback shows a live streams from cameras placed on the end-effector and on the headrest of the wheelchair.

before moving on to the next control method. After successfully completing one trial with all of the control methods, the participants went through the same process during which the line of sight to the robot was blocked and the control was conducted using the visual feedback that was provided. The control methods (L1_BF, L1_TF, L2_TF, L3_MF and Joystick_BF) were tested in random order. A trial was considered successful when the participant had poured water in the cup and placed the bottle on the table again. A trial had to be repeated if the bottle or the cup fell down.

Session 2 was meant to give the participants further training in using the iTongue to control the JACO2. During this session, the participants were only allowed to move the robot briefly before performing the experimental task. The participants were asked to perform three successful trials for each of the conditions, completing in total 30 successful trials. The third session was identical to the second session as the participants were allowed only to move the robot briefly before performing three successful trials for each condition.

At the end of each control method on day 1 and day 3, the participants qualitatively evaluated the system by filling out a NASA-TLX questionnaire. After completing day three, the participants were asked to rank the different methods from one to five where "one" was the method they preferred the most and "five" was the method they preferred the least.

G. Definition of Outcome Measures

- *Task completion time* (TCT) was defined from when the robot started moving until the last "open finger" command was sent using the iTongue system (L1_BF, L1_TF, L2_TF and L3_MF) or when the fingers stopped opening when controlling with the joystick (Joystick_BF).
- *Gripping time* (GT) was defined from when the robot first moved until the bottle had been grabbed; that is, until the last "close finger" command was sent using the iTongue or when the fingers did not close anymore when using the joystick
- *Movement time* (MT) was defined as the cumulative sum of time when the robot was moving.
- *Amount of used commands* (UsedCmd) was counted once each time a new command was sent to the JACO robot when using the iTongue. This was not counted when using the standard joystick.
- *The trajectory length* was measured as the cumulative Euclidean distance between the x, y, and z tool pose data points published by the robot.
- *The time it took to switch modes* was measured from when the last command was sent to the robot and until a new mode was published. This included thinking time, which was expected to increase if the mode switch method was troublesome. *Mode switch errors* were counted once each time the participant switched modes twice in a row without commanding the robot to move in between the two mode switches.
- *Successful Pouring* was a rate for successfully pouring the first drop of water into the cup (in order to assure a consistent task end point).
- *NASA-TLX Questionnaire* for evaluating the task load in different conditions.

TABLE II
PERCENT IMPROVEMENT BETWEEN DAYS AND MEAN TCT FOR EACH CONTROL METHOD

2D	Day 1 - Day 2	Day 2 - Day 3	Day 1 - Day 3	Mean TCT Day 3
L1_BF	18.2%	50.8%	78.3%	192.7 s
L1_TF	16.9%	26.8%	48.3%	196.5 s
L2_TF	65.5%	37.1%	126.9%	166.1 s
L3_MF	37.6%	60.1%	120.4%	182.0 s
Joystick_BF	50.1%	29.8%	94.8%	84.0 s
3D	Day 1 - Day 2	Day 2 - Day 3	Day 1 - Day 3	Mean TCT Day 3
L1_BF	119.6%	15.4%	153.3%	155.4 s
L1_TF	45.4%	36.1%	98.0%	154.0 s
L2_TF	79.8%	42.4%	156.0%	140.2 s
L3_MF	69.8%	64.0%	178.3%	148.0 s
Joystick_BF	41.5%	29.6%	83.4%	57.7 s

H. Outcome Measures & Statistical Analysis

During the three experimental days, each participant completed 70 trials which resulted in 700 trials in total for analysis, 300 of which were performed during the last day.

The analysis of the data was three-fold. First, the difference between controlling in 2D and 3D in terms of task completion time (TCT), gripping time (GT), amount of used commands (usedCmd), the trajectory length and MT (both for task completion and gripping the bottle) was analyzed. Then, the difference between the various control methods was analyzed by comparing TCT, GT, usedCmd, the trajectory length, and MT (both for task completion and gripping the bottle). Lastly, we looked at the form of mode switch by analyzing the time it took to switch mode (using either double click or button activation) and the amount of mode switch errors.

The statistical analysis was performed in SPSS Statistics (version 27.0.0.0) using a repeated measure ANOVA. The main effect comparisons were conducted using Bonferroni confidence interval correction. Mauchly's test of sphericity was used to test if the sphericity assumption had been violated. The significance level was defined at $p<0.05$.

TABLE III
MEAN OF ALL OUTCOME MEASURES

2D – Mean (SD) Day 3	L1_BF	L1_TF	L2_TF	L3_MF	Joystick_BF
Task Completion Time [s]	192.75 (77.5)	196.48 (81.6)	166.14 (54.3)	181.98 (67.5)	84.04 (23.3)
Movement Time [s]	67.30 (18.7)	70.11 (14.6)	61.56 (13.7)	71.32 (17.9)	49.53 (11.0)
ThinkPlanCmd [s]	125.44 (66.7)	126.36 (74.3)	104.58 (49.2)	110.66 (53.8)	34.51 (14.4)
Gripping Time [s]	83.43 (42.6)	70.72 (38.4)	63.05 (18.8)	76.47 (30.9)	40.44 (23.0)
Trajectory Length TCT [m]	1.72 (0.4)	1.81 (0.4)	1.55 (0.3)	1.82 (0.4)	1.50 (0.4)
Trajectory Length GT [m]	0.97 (0.2)	0.91 (0.1)	0.86 (0.1)	1.02 (0.3)	0.98 (0.4)
UsedCmd	21.27 (5.8)	24.00 (8.4)	19.93 (7.6)	28.17 (11.6)	N/A
Mode Switch Time [s]	3.27 (1.7)	2.95 (1.5)	3.01 (1.9)	2.75 (1.4)	N/A
Error Mode Switches	6.60 (9.1)	5.52 (8.3)	0.40 (0.8)	0.40 (0.7)	N/A
Successful Pouring [%]	70	63	73	73	63
3D – Mean (SD) Day 3	L1_BF	L1_TF	L2_TF	L3_MF	Joystick_BF
Task Completion Time [s]	155.42 (73.4)	154.00 (50.9)	140.22 (37.2)	148.04 (53.8)	57.71 (13.5)
Movement Time [s]	60.94 (10.7)	63.16 (10.7)	60.01 (8.5)	66.23 (12.6)	37.52 (7.9)
ThinkPlanCmd [s]	94.48 (64.7)	90.84 (43.6)	80.21 (34.2)	81.81 (44.4)	20.19 (7.9)
Gripping Time [s]	68.22 (30.1)	61.03 (20.4)	56.04 (12.9)	65.99 (25.1)	27.06 (13.4)
Trajectory Length TCT [m]	1.48 (0.2)	1.54 (0.3)	1.45 (0.3)	1.60 (0.3)	1.33 (0.4)
Trajectory Length GT [m]	0.91 (0.1)	0.88 (0.1)	0.83 (0.1)	0.93 (0.2)	0.85 (0.3)
UsedCmd	17.63 (4.6)	17.67 (4.1)	16.67 (4.3)	23.63 (8.6)	N/A
Mode Switch Time [s]	2.50 (0.8)	2.65 (0.7)	2.70 (1.7)	3.07 (1.9)	N/A
Error Mode Switches	5.03 (6.2)	4.40 (5.6)	0.23 (0.4)	0.37 (0.9)	N/A
Successful Pouring [%]	83	90	83	83	93

III. RESULTS

All 10 participants were able to complete the selected ADL for seven trials for each of the five control schemes in 2D and 3D representations. All participants showed up on three consecutive days except one who had the last day's trials postponed for three weeks due to illness. For all participants, TCT improved between all three days (Fig 7). The mean improvement between day one and day two was 54.4 ± 29.2% (Table II) and 39.2 ± 14.5% between day two and day three (calculated over 2D, 3D, and all control schemes). The main performance improvements appeared overnight between the

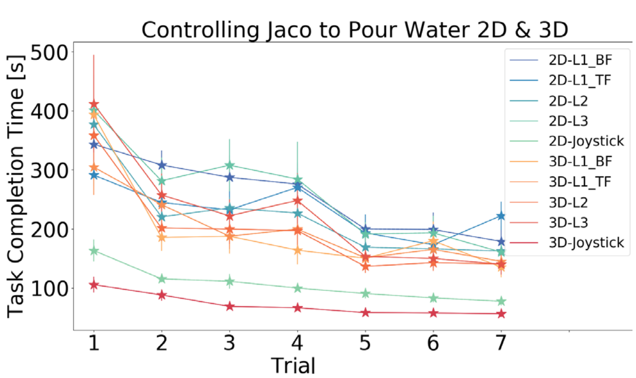

Fig. 7. Task Completion Time (TCT) for control in 2D and 3D. Trial 1 was performed on day one. Trials 2-4 were performed on day two and trials 5-7 on day three. The largest learning occurred overnight, between trials 1-2 and 4-5.

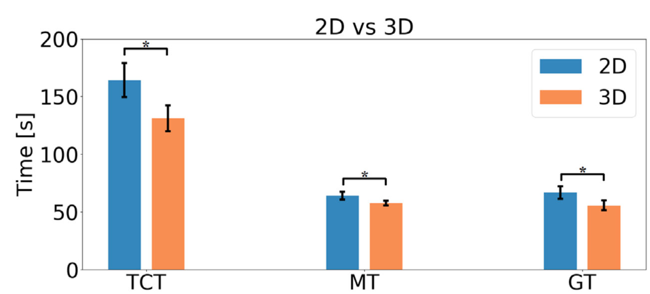

Fig. 8. Task completion time, movement time and gripping time for control in 2D and 3D. The performance was significantly better when controlling in 3D vs 2D (indicated by *).

experimental days, whereas the increase in performance during the sessions was lower (Fig 7). On the last experimental day, no outcome measure showed a statistical difference between trials 5, 6, and 7. Table III shows the mean of the last three trials (Day 3) over all participants for each of the outcome measures: TCT, GT, MT, Trajectory length, UsedCmd, mode switch time and error mode switches. When using the fastest of the iTongue layouts, L2_TF, the mean TCT on day three was 166.1s and 140.2s in 2D and 3D, respectively. The mean TCT when using the Joystick_BF was 84.0s and 57.7s in 2D and 3D, respectively.

A. Difference between Controlling in 2D and 3D Representation

There was a significant difference when controlling the ARM in 2D (where the line of sight was blocked) as compared with 3D (where the participant could see the robot) for all of the outcome measures (TCT: p=0.008, F=11.291; GT: p=0.042, F=5.595, MT: p=0.006, F=12.681). The participants used more commands (UsedCmd: p=0.009, F=10.836) to control the robot and longer paths (Trajectory Length: p=0.001, F=23.175). Therefore, the TCT increased when controlling the robot in 2D (Fig. 8). The mean TCT increased by 37.33s for the L1_BF, 42.48s for the L1_TF, 25.92s for the L2_TF, 33.94s for the L3_MF, and increased by 26.33s for the Joystick_BF (table III) suggesting that the L2_TF and the Joystick_BF had the strongest and most similar robustness to the transition between 3D and 2D. By subtracting the MT from the TCT, the remaining time can be defined as thinking, movement planning, and command activation time (ThinkPlanCmd, table III). The repeated measures ANOVA analysis of ThinkPlanCmd shows that there is a difference between 2D and 3D (p= 0.018, F=8.328) and thus that the participants did more thinking and movement planning when controlling the robot in 2D through the computer screen. By excluding the Joystick_BF and performing the repeated measures ANOVA using only the iTongue methods, there is no significant difference between 2D and 3D in GT; when reaching and grabbing the bottle (p=0.092, F=3.565). However, all other outcome measures showed that control in 2D significantly decreased the performance (TCT: p=0.017, F=8.592; trajectory length: p=0.002, F=17.288; UsedCmd: p=0.009, F=10.836; MT: p=0.040, F=5.775). The mean decreases from 3D to 2D were 27.7% for TCT, 13.6% for trajectory length, 23.8% for UsedCmd, and 12.7% for MT. The difference in trajectory length was biggest for the L1_TF (17.6%) and smallest for L2_TF (7.0%). The TCT decreased with 13.6% when controlling in 3D using the Joystick_BF compared with control in 2D.

B. Difference between the Control Methods

There were no significant performance differences in the robot control methods based on the iTongue, both in 2D and 3D. As would be expected, the Joystick_BF performed significantly better than the iTongue-based control methods in terms of TCT, GT, and MT compared with the tongue control methods (p<0.001, F=21.622; p<0.001, F=10.477 and p<0.001, F=30.477, respectively) in both 2D and 3D. On average over both 2D and 3D, the TCT, GT, and MT of the Joystick_BF was

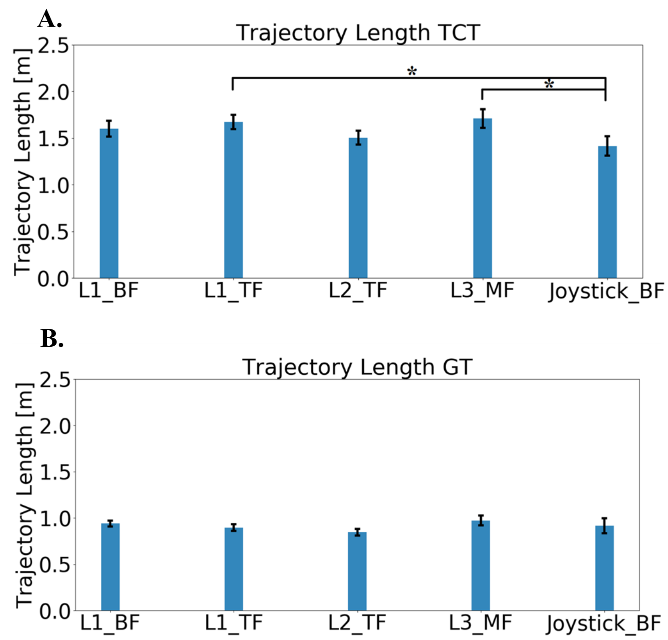

Fig. 9. Trajectory length for **A)** completing the trial (TCT) and **B)** gripping the bottle (GT). The * indicates a significant difference.

90.5%, 83.4%, 59.3% and 83.2% shorter than for L1_BF, L1_TF, L2_TF and L3_MF.

The pairwise comparisons of the trajectory length of TCT show a significant difference between L1_TF and the Joystick_BF (p=0.01) and L3_MF and the Joystick_BF (p=0.023), indicating that the Joystick_BF performs better, as could be expected. Nevertheless, there is no significant difference between any of the other TCI layouts (L1_BF and L2_TF) and the Joystick_BF. This suggests that these iTongue-based layouts have an efficiency similar to the Joystick_BF with regard to trajectory length. The mean trajectory length of the L2_TF differed from the Joystick_BF with only 3% in 2D on Day 3. There was no difference in the trajectory length between the different methods when gripping the bottle. The participants mostly used the same strategy for picking up the bottle and then the path varied when moving the bottle towards the cup to pour water.

The participants used significantly more commands when controlling the JACO2 using the L3_MF method compared with L1_BF (p=0.03, F=5.807). Although there was a significant difference only between L3_MF and L1_BF, the mean number of issued commands was higher for L3_MF than for the rest of the tongue controlling methods (table III).

C. Mode Switching

There was no statistical difference between the times it took to perform correct mode switching in the two different mode switching methods: double click and button activation (Fig. 10 A). Likewise, there was no statistical difference in error mode switches between the two methods (Fig. 10 B).

Participants 1 and 4 had problems with switching modes using the double click method as implemented in L1_BF and L1_TF. By excluding these two participants from the analysis, the difference between the two mode switching methods in

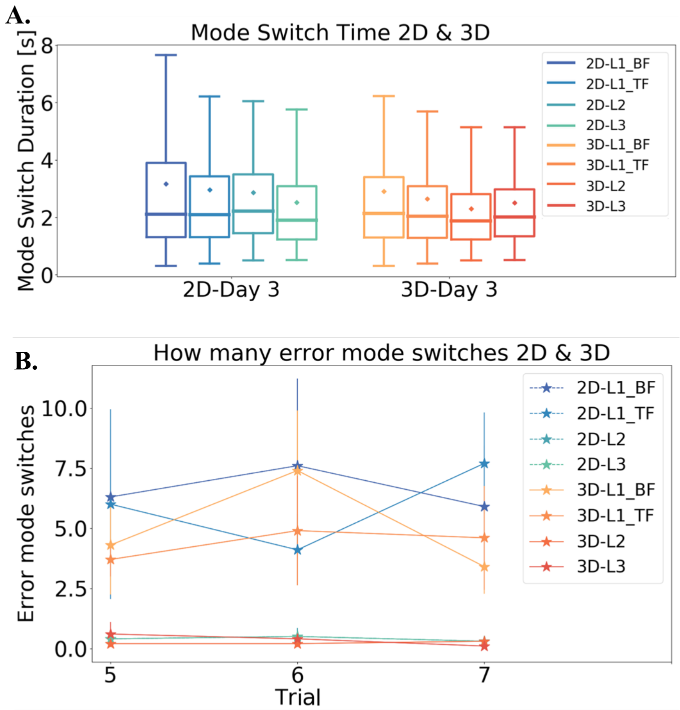

Fig. 10. **A)** Boxplot of the time it took to switch modes. There is no significant difference between the two mode switch methods: double click (L1_BF and L1_TF) and button activation (L2_TF and L3_MF). **B)** More error mode switches were performed when using double click compared with button activation.

terms of error mode switches became statistically significant ($p<0.001$, $F= 13.959$).

D. NASA-TLX Questionnaire

Changing from 3D to 2D increased the perceived effort of controlling the robot with the tongue while the perceived effort decreased when using the Joystick_BF (Fig 11) even though TCT increased in both cases (Fig 7). The Joystick_BF had the best overall score from the NASA-TLX Questionnaire, both for control in 2D and 3D. On both day 1 and day 3, the difference between the Joystick_BF and the iTongue methods was significant ($p<0.001$, $F = 21.937$ and $p<0.001$, $F=14.088$). On the first day, while the participants were learning to use the system, the difference between controlling the robot through the computer screen or with direct vision had no effect. On day three, the participants had learned how to control the robot and rate the 3D vision better ($p= 0.011$, $F = 10.355$).

At the end of the experiment, the participants were asked to rank the methods from what they preferred the most to what they preferred the least (table IV). Eight of the ten participants chose L2_TF as the preferred method out of the iTongue control methods. Joystick_BF was always the preferred method, i.e., chosen as number one.

TABLE IV
RANKING OF CONTROL METHODS BY PARTICIPANTS FROM 1-5 WHERE ONE THE MOST PREFERRED METHOD AND FIVE IS THE LEAST PREFERRED METHOD.

2D	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Mean (SD)
L1_BF	2	4	5	5	4	4	4	5	4	5	**4.2 (0.9)**
L1_TF	3	5	3	3	5	5	5	2	5	4	**4 (1.1)**
L2_TF	5	2	2	2	2	2	2	3	2	2	**2.4 (0.9)**
L3_MF	4	3	4	4	3	3	3	4	3	3	**3.4 (0.5)**
Joystick_BF	1	1	1	1	1	1	1	1	1	1	**1 (0.0)**
3D											
L1_BF	2	5	3	3	4	4	4	3	4	5	**3.7 (0.9)**
L1_TF	3	4	4	5	5	5	5	4	5	4	**4.4 (0.7)**
L2_TF	5	2	2	2	2	2	2	5	2	2	**2.6 (1.2)**
L3_MF	4	3	5	4	3	3	3	2	3	3	**3.3 (0.8)**
Joystick_BF	1	1	1	1	1	1	1	1	1	1	**1 (0.0)**

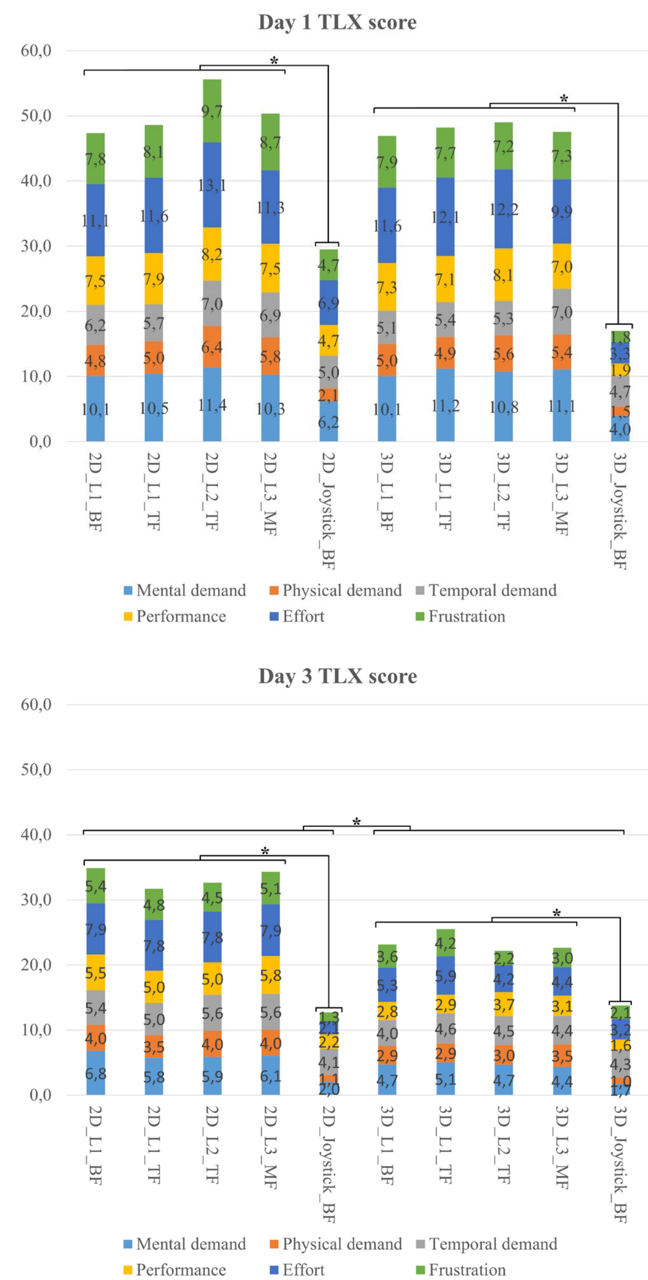

Fig. 11. NASA-TLX questionnaire results from Day 1 and 3. L1_BF was presented in [29] and implemented for control in base-frame and tool-frame (L1_BF and L1_TF). L2_TF is the new improved layout for control in tool-frame where a "GO" button and a dedicated button for mode switching were introduced. L3_MF was adjusted for control in BF. In order to maintain control of all of the available DOF's, two DOF's were introduced as toggle buttons (forward/backward and roll+/roll-). Joystick_BF represents control with the standard joystick that comes with the JACO ARM. The * indicates a significant difference.

IV. Discussion

In order for an individual with tetraplegia to be self-sufficient when lying in bed, an efficient robotic system is needed. As stated earlier, two critical challenges have to be addressed for this to be a reality: an efficient interface for control through a 2D representation of the 3D remote workspace and an efficient robot control scheme for 2D tele operation are needed. In this study, five different robot control methods were compared under two different conditions. The results showed the feasibility of remote controlling JACO for a pouring water task using an interface that is suitable for an individual with tetraplegia. The presented system has the potential to enable individuals with tetraplegia to fully control a robotic manipulator through a computer screen when e.g. lying in bed, and therefore the opportunity to perform some desired tasks, such as picking up objects that are far away, turning switches on/off, and opening/closing doors. The interface method allows for control over all of the robots DOFs, eliminating the need for automation, as has been the focus in many previously developed systems. Automation can in turn be implemented to ease the control for the user instead of a necessity to perform a given task. This expands the use of the system, as the tasks does not need to be previously defined.

A. 2D versus 3D

Controlling a robotic arm in 3D was 27.7% faster than controlling in 2D. The difference is smallest in the beginning of the experiment but as the participants performed more trials, the difference between 2D and 3D became larger. This indicates that it is more difficult to learn how to use the system in 2D, as could be expected. A particular challenge in controlling the ARM in 2D is that the depth information is missing. This is underlined by the results showing a significant difference (27.7%) between completing the task in 2D and in 3D. The difference between 2D and 3D when gripping the bottle (GT) using the tongue control methods was not significant and can be explained by the camera placement. One of the cameras was placed on the end-effector of the robot and therefore the depth information was not a problem during this part of the trial. After picking up the bottle, the view from this camera was blocked and thus the participants had to rely on camera feedback from the headrest of the wheelchair to finish pouring the water into the cup. This part of the trial showed a mean difference of 34.4% between 2D and 3D for the iTongue layouts and a 70.9% difference for the joystick. Furthermore, this part highlights the need for depth information as it was very difficult to predict if the water was poured into the cup or to the side of it. Here, the participants had to rely on information gathered from the environment (shadows, size, etc.) which is not optimal as it changes under different environmental conditions.

B. Layout Difference

As expected, the Joystick_BF performed better in most of the outcome measures compared with the tongue control methods. However, individuals with tetraplegia most often cannot make use of this option.

Although not significant, the GT was better when controlling the robot using the tool frame (L1_TF and especially L2_TF) as compared with the other layout designs (L1_BF and L3_MF) indicating that it could be a better method for control during this part of the task, especially when controlling through a 2D computer screen. The trajectory length for L2_TF being slightly shorter than for the other methods, even the Joystick_BF, may further indicate L2_TF as a superior method for control. The tool frame based control allowed the user to look around using the camera attached on the end-effector and reach directly towards the desired object to pick it up. Hildebrand et al. [28] showed that the tool frame control decreased the TCT and path efficiency compared with the base frame when solving a simple pick and place task. However, as mentioned by Campeau-Lecours et al. [30], tool-frame control can be difficult to understand and this is especially true when controlling through a stationary 2D visual feedback as was provided by the camera at the headrest of the wheelchair in this experiment. The present system could possibly be improved by allowing access to both tool frame and base frame control. This could be implemented in two ways: by allowing the participants to manually choose the frame or by implementing automation. That is, the system would use tool frame when the fingers of the end-effector are open and base frame when the fingers are closed.

The measured trajectory length correlated well with the amount of used commands. As seen in table III, the mean

TABLE V
COMPARISON WITH PREVIOUS STUDIES

Paper	Interface applicable for users with complete tetraplegia	Task	# Subjects (abled-bodied/ disabled)	# Trials	TCT	GT	Robot type	Automation required	Evaluated in 2D/3D	Robustness 2D/3D transition
Palsdottir et al. 2021 – this study	Yes - iTongue	Pouring Water	10/0	10 per method	~140s	-60s	JACO 6 DOF	No	Yes/Yes	~16-20% reduction in TCT
Fattal et al. [33] 2018	Yes – Computer software	Object Pickup	0/17	3 per task	N/A	N/A	JACO 6 DOF	No	Yes/Yes	12% reduction in success rate
Bugmann et al. [34] 2017	No - Touchscreen	Object Pickup	3/0	1 per task	~180s	~180s	CHAP V1 4 DOF	No	No/Yes	N/A
Veras et al. [32] 2012	No – Omni device	Pick and Place	3/0	1	~ 47s	N/A	PUMA 560 6 DOF	Yes	Yes/No	N/A
Stoelen et al. [31] 2012	No - 6 DOF SpaceNavi-gator joystick	Object Placement	5/0	30 per task	~ 6s	N/A	Simulated end-effector 3 DOF	Shared control	Simulated/No	N/A

amount of commands was largest for L3_MF. This is most likely because of the toggle buttons. L3_MF utilized toggle buttons and in order to change the state of the toggle button or change the mode from e.g. Mode 2a to Mode 2b (Fig. 5), the "Forward" command needed to be activated for a short period. If the desired command was "Backward" but the Mode was 2a, the "Forward" command should be activated for a short period to make the state change to Mode 2b. After this, the "Backward" command could be activated, as desired. This caused the amount of commands to increase. The participants had a hard time making the activation of the toggle buttons stable enough to do one activation. This was especially true when doing fine manipulation, for example if the command needed to be activated when in close proximity to the bottle, e.g., when using roll+/roll- to pour water in the cup. Often the participants had to activate the command a few times before activating it in the right way. This also influenced the task completion time and the overall satisfaction of using the system. Although this is not reflected in the results of the NASA-TLX Questionnaire, several of the participants expressed frustration, such as "it is annoying when the mode is switched when I am trying to activate another command ", and other physical signs of frustration such as sighing and jaw clenching, when using this system. The fact that the system either switched modes or the toggle buttons changed to their alternative state was confusing and frustrating for the user. This might have been exposed by incorporating another questionnaire; perhaps QUED2.0 would have been a better choice (as was suggested in [40]).

At the end of the experiment, the participants were asked to rank the methods from what they preferred the most to what they preferred the least (table IV). Most of the participants rated L2_TF as the preferred choice of the iTongue control methods. This might be because there were no unexpected movements of the robot due to erroneous mode switching/toggling while using L2_TF. Usually, the participants found a specific strategy to control the robot and did not change that between the different control methods or trials. Most participants' kept the robot's end-effector leveled with the table while they moved the robot. There was no big difference in the overall TLX score between tool frame and base frame (L1_BF and L1_TF). This may partly explain why L2_TF was often rated as the preferred method as compared with the other iTongue layouts, despite the previous suggestions of tool frame being difficult to understand by [30]. Further, we expected a dedicated mode switch button as implemented in L2_TF to be less frustrating than the implementation of double click for mode switch or the toggle button for activating forward/backward and roll+/roll-. This may also have led to a higher rating of L2_TF.

As mentioned earlier, the robot control is compromised by a lack of suitable interface for individuals with tetraplegia and an efficient robot control scheme for 2D tele-operation. Table V shows a comparison between the current and previous studies. All of the studies performed some form of object manipulation. Two incorporated automation in order to ease the operation for the user but both of these studies did not use a suitable interface for individuals with tetraplegia [31], [32]. Bugmann et al. [34] introduced a system using a touchscreen for control in a local setting but this system can easily be adjusted to work in a tele-setting by individuals with tetraplegia. Fattal et al. [33] used an interface that was suitable for individuals with tetraplegia and evaluated the system in a local and tele-setting. It is difficult to compare with this study as they present success rate for completing a task rather than the time it took to complete. However, the study indicated that there is a reduction in performance when controlling in a tele-setting compared with local, as is the case in this study (reduction in success rate and reduction in TCT/GT). The importance of the results presented in this study is high because it provides baseline numbers that can be used for comparison in future studies.

When developing a HMI for assistive robotics, many factors must be taken into account, including the user satisfaction. It is important that the HMI is stable and predictable. The duration and repetitiveness of the experiment may have an impact reacted to fatigue of the participants. During this experiment, some of the trials lasted for more than 10 minutes, which might have affected other trials. However, this was reduced on day three where the participants had enough experience in using the iTongue and the JACO robot.

V. Conclusion

This study compared five different robot control methods under two different conditions and showed that it is possible to remote control JACO for a pouring water task, showing the feasibility of further improving the QoL of severely disabled individuals. The dedicated tool frame based tongue interface layout, L2_TF, improved the 2D visually guided control of the 7-DOF ARM used in this study. The double click and toggle buttons were frustrating factors contributing to the decreased performance of the other layout designs. With regard to trajectory length, the efficiency of tongue controlling the robot using L2_TF was comparable to the efficiency of the standard handheld robot Joystick_BF in 2D, although it was slower in TCT. The mean trajectory length of completing the task using L2_TF was only 3% longer than using the Joystick_BF when controlling through 2D on Day 3. Considering the reaching and grabbing task (GT), the trajectory length was shortest for L2_TF compared with all other control methods, including the joystick. The iTongue control layouts performed well when reaching and grabbing the bottle (GT) showing no significant difference between 2D and 3D. However, the transition from 2D to 3D resulted in a mean decrease of 27.7% for TCT across all interfaces. L2_TF and the Joystick_BF had the strongest and most similar robustness to the transition between 3D and 2D.

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