Aalborg Universitet

Tongue Control of Upper-Limb Exoskeletons For Individuals With Tetraplegia

Mohammadi, Mostafa

DOI (link to publication from Publisher):
10.54337/aau470866076

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Mohammadi, M. (2022). *Tongue Control of Upper-Limb Exoskeletons For Individuals With Tetraplegia*. Aalborg Universitetsforlag. https://doi.org/10.54337/aau470866076

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from vbn.aau.dk on: May 08, 2024

TONGUE CONTROL OF UPPER-LIMB EXOSKELETONS FOR INDIVIDUALS WITH TETRAPLEGIA

BY
MOSTAFA MOHAMMADI

DISSERTATION SUBMITTED 2022

AALBORG UNIVERSITY
DENMARK

TONGUE CONTROL OF UPPER-LIMB EXOSKELETONS FOR INDIVIDUALS WITH TETRAPLEGIA

by

Mostafa Mohammadi

AALBORG UNIVERSITY
DENMARK

Dissertation submitted 2022

Dissertation submitted: January 2022

PhD supervisor: Associate Prof. Lotte N. S. Andreasen Struijk,
Aalborg University

Assistant PhD supervisor: Associate Prof. Hendrik Knoche,
Aalborg University

PhD committee: Associate Professor Shellie Boudreau (Chair)
Aalborg University, Denmark

Professor Lorenzo Masia
Heidelberg University, Germany

Associate Professor Sadasivan Puthusserypady Kumaran
Technical University of Denmark, Denmark

PhD Series: Faculty of Medicine, Aalborg University

Department: Department of Health Science and Technology

ISSN (online): 2246-1302
ISBN (online): 978-87-7573-947-9

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

© Copyright: Mostafa Mohammadi

Printed in Denmark by Rosendahls, 2022

CV

Mostafa Mohammadi received a BSc degree in Mechanical Engineering from Sharif University of Technology, Iran, in 2014. His BSc thesis was about the design and optimization of a robotic surgical guide for brain tumor biopsy. He obtained an MSc in Biomedical Engineering from Politecnico di Milano, Italy, in 2017. In the last year of his MSc education, he conducted his master thesis research in the Laboratory for Movement Biomechanics, ETH, Zurich, on gait analysis with wearable sensors. He started his PhD at Aalborg University in February 2018 on tongue control of assistive upper-limb exoskeletons for individuals with tetraplegia. After finishing his PhD, he continued working at the center for rehabilitation robotics at Aalborg University as a research assistant. His main research interests include rehabilitation robotics, human-robot interfaces, and assistive exoskeletons.

Publications

1. Mohammadi, Mostafa, Hendrik Knoche, Mikkel Thøgersen, Stefan Hein Bengtson, Frederik Victor Kobbelgaard, Muhammad Ahsan Gull, Bo Bentsen, Kåre Eg Severinsen, Benjamin Yamin Ali Khan, and Lotte NS Andreasen Struijk. "**Tongue control of a five-DOF upper-limb exoskeleton rehabilitates drinking and eating for individuals with severe disabilities,**" *Submitted to International Journal of Human Computer Studies* (2022).
2. Mohammadi, Mostafa, Hendrik Knoche, Mikkel Thøgersen, Stefan Hein Bengtson, Muhammad Ahsan Gull, Bo Bentsen, Michael Gaihede, Kåre Eg Severinsen, and Lotte NS Andreasen Struijk. "**Eyes-free tongue gesture and tongue joystick control of a five DOF upper-limb exoskeleton for severely disabled individuals**." *Frontiers in Neuroscience* (2021).
3. Kirtas, Oguzhan, Mostafa Mohammadi, Bo Bentsen, Peter Veltink, and Lotte NS Andreasen Struijk. "**Design and evaluation of a noninvasive tongue-computer interface for individuals with severe disabilities**." *In 2021 IEEE 21st International Conference on Bioinformatics and Bioengineering (BIBE)*, pp. 1-6. IEEE, 2021.

4. Gull, Muhammad Ahsan, Mikkel Thoegersen, Stefan Hein Bengtson, Mostafa Mohammadi, Lotte NS Andreasen Struijk, Thomas B. Moeslund, Thomas Bak, and Shaoping Bai. "**A 4-DOF Upper Limb Exoskeleton for Physical Assistance: Design, Modeling, Control and Performance Evaluation**." *Applied Sciences 11*, no. 13 (2021): 5865.
5. Vestersoe, Kirstina B. Persson, Mostafa Mohammadi, Emil B. Kromann, and Lotte NS Andreasen Struijk. "**Tendon-based design of wrist joint for tongue-controlled exoskeleton-a case study**." *In 2021 IEEE 21st International Conference on Bioinformatics and Bioengineering (BIBE)*, pp. 1-6. IEEE, 2021.
6. Mohammadi, Mostafa, Hendrik Knoche, and Lotte NS Andreasen Struijk. "**Continuous tongue robot mapping for paralyzed individuals improves the functional performance of tongue-based robotic assistance**." *IEEE Transactions on Biomedical Engineering* (2021).
7. Mohammadi, Mostafa, Hendrik Knoche, Bo Bentsen, Michael Gaihede, and Lotte NS Andreasen Struijk. "**A pilot study on a novel gesture-based tongue interface for robot and computer control**." *In 2020 IEEE 20th International Conference on Bioinformatics and Bioengineering (BIBE)*, pp. 906-913. IEEE, 2020.
8. Thøgersen, Mikkel, Muhammad Ahsan Gull, Frederik Victor Kobbelgaard, Mostafa Mohammadi, Stefan Hein Bengtson, and Lotte NS Andreasen Struijk. "**EXOTIC-A Discreet User-Based 5 DoF Upper-Limb Exoskeleton for Individuals with Tetraplegia**." *In 2020 3rd International Conference on Mechatronics, Robotics and Automation (ICMRA)*, pp. 79-83. IEEE, 2020.
9. Pálsdóttir, Ásgerður Arna, Strahinja Dosen, Mostafa Mohammadi, and Lotte Andreasen NS Struijk. "**Remote tongue based control of a wheelchair mounted assistive robotic arm–a proof of concept study**." *In 2019 IEEE International Conference on Mechatronics and Automation (ICMA)*, pp. 1300-1304. IEEE, 2019.
10. Mohammadi, Mostafa, Hendrik Knoche, Michael Gaihede, Bo Bentsen, and Lotte NS Andreasen Struijk. "**A high-resolution tongue-based joystick to enable robot control for individuals with severe disabilities**." *In 2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, pp. 1043-1048. IEEE, 2019.
11. Struijk, Lotte NS Andreasen, Mostafa Mohammadi, Mikkel Thøgersen, Stefan Hein Bengtson, Frederik Victor Kobbelgaard, Muhammad Ahsan Gull, Anne Marie Kanstrup, Michael Gaihede, Helge Kasch, and Thomas B. Moeslund. "**Tongue control of exoskeletons and assistive robotic arms for individuals with tetraplegia**." *In Abstract book from the 16th Congress of the Nordic Spinal Cord Society: NoSCoS2019*, p. 51. 2019.
12. Mohammadi, Mostafa, Romulus Lontis, Bo Bentsen, Hendrik Knoche, Thomas B. Moeslund, Thomas Bak, Michael Gaihede, and Lotte NS Andreasen Struijk. "**Controlling a drone by the tongue–A pilot study on**

drone based facilitation of social activities and sports for people with complete tetraplegia." *In International Conference on NeuroRehabilitation*, pp. 523-527. Springer, Cham, 2018.

13. Mohammadi, Mostafa and Singh, Navrag B. and Hitz, Marco and Orter, Stefan and Taylor, William R. and Frigo, Carlo. "**Achieving ecological validity in mobility assessment: Validating a wearable sensor technology for comprehensive gait assessment**". *IEEE 3rd International Forum on Research and Technologies for Society and Industry (RTSI)*, IEEE, 2017.

ENGLISH SUMMARY

Spinal cord injury (SCI) at the cervical level can lead to paralysis of both arms and legs (tetraplegia) and leave the affected individual severely disabled. The incidence of SCI is estimated between 250,000 to 500,000 per year worldwide and is more prevalent within young individuals with approximately 38 years of survival time. Individuals with tetraplegia usually cannot perform activities of daily living (ADLs) independently and need full-time assistance. The lack of independence and privacy decreases the quality of life, causing an increased rate of depression and suicidal thoughts. Furthermore, 24-hour caregiving imposes an increased financial burden on the healthcare system, costing approximately 200,000 USD in the United States and 1.3 million DKK in Denmark. Individuals with tetraplegia desired regaining arm and hand function the most for improving their quality of life. Thus, upper-limb exoskeletons (ULEs) that mobilize the arm and hand can improve the functionality and help individuals with arm disabilities to perform some ADLs independently and reduce the assistance time. The more severe disability, the higher is the gain from assistive ULEs. However, providing a control interface enabling full and continuous control of a multi-DOF ULE for individuals with complete functional tetraplegia remains a challenge and requires further research and development. In a previous study, an individual with complete tetraplegia controlled an assistive robotic manipulator using the Inductive Tongue-Computer Interface (ITCI), uncovering the system's potential for upper-limb assistance. Thus, this PhD study aimed to develop a tongue robot interface that provides single modal, full voluntary continuous control of a 5 DOF ULE for the empowerment of users with complete functional tetraplegia.

Through this PhD, a novel sensor data interpolation method was developed and tested, allowing high-resolution tracking of the ITCI activation unit. Then, a new method for designing virtual buttons and a continuous joystick emulation based on the ITCI was implemented and tested in a study with twelve able-bodied participants for controlling an assistive robotic manipulator. Furthermore, a novel tongue-gesture recognition algorithm was developed. These methods were used to create and compare a gesture-based and a joystick-based control layout for a five-DOF ULE in a study with ten able-bodied individuals. In addition, eyes-free use of the control layouts (without visual feedback) was investigated. Finally, a clinical study evaluated tongue control of the five-DOF ULE for empowering individuals with tetraplegia to fully and independently perform highly desired ADLs, including drinking and eating snacks, in a clinical study with ten individuals with tetraplegia.

The studies with able-bodied participants showed that a continuous joystick emulation based on the ITCI improved the performance of assistive robot interfaces as compared to virtual buttons by reducing the task time by up to 16% and the number of commands by 20%. The tongue gesture recognition algorithm identified a set of six gestures with 94.3% accuracy and 23 gestures with 72.3% accuracy, allowing for a high number of control commands with the ITCI. No significant difference was obtained between the gesture-based and the joystick-based control layouts for controlling the five-DOF ULE. Removing the joystick-based layout visual feedback significantly increased the drinking time by 45.3%; however, the gesture-based layout performed similarly with and without visual feedback. The developed tongue-exoskeleton interface was successful in empowering users, even with complete functional tetraplegia, to perform ADLs with the ULE. All ten individuals with tetraplegia who participated in our clinical study successfully controlled the ULE with the ITCI and independently completed the drinking and snacking tasks. The participants rated the intuitiveness of the tongue interface 5.2 on a scale between 1 (low) and 7 (high).

DANSK RESUME

En rygmarvsskade (SCI) på cervikalt niveau kan føre til lammelse af både arme og ben (tetraplegi) og efterlade den berørte person alvorligt invalideret. Forekomsten af SCI er estimeret til mellem 250.000 til 500.000 om året på verdensplan og er mere udbredt blandt unge mennesker med cirka 38 års overlevelsestid. Personer med tetraplegi kan ofte ikke udføre daglige aktiviteter (ADL'er) selvstændigt og har ofte brug for fuldtidshjælp. Manglen på selvstændighed og privatliv nedsætter livskvaliteten, hvilket forårsager en øget hyppighed af depression og selvmordstanker. Ydermere påfører behovet for 24-timers pleje sundhedsvæsenet en øget økonomisk byrde og koster cirka 200.000 USD i USA og 2 millioner DKK i Danmark for hver borger der skal have fuldtidshjælp. Mennesker med tetraplegi prioriterer at genvinde arm og hånd funktion højt for at forbedre kunne deres livskvalitet. Således kan exoskeletter til armene (ULE'er), der mobiliserer armen og hånden, forbedre funktionaliteten og hjælpe brugere med funktionsnedsættelser i armene til at udføre nogle ADL'er selvstændigt og dermed reducere behovet for assistance. Jo mere alvorlig funktionsnedsættelse, desto højere er gevinsten ved hjælpende ULE'er, men jo sværere er det at styre dem. At skabe en styringsmetode, der muliggør fuld og kontinuerlig styring af et ULE med mange frihedsgrader/bevægelsesdimensioner (DOF) for brugere med komplet funktionel tetraplegi, er derfor stadig en udfordring og kræver yderligere forskning og udvikling. I et tidligere studie styrede en bruger med komplet tetraplegi en assisterende robotmanipulator ved hjælp af et tungestyrringsystem, ITCI (Inductive Tongue-Computer Interface), hvilket viste systemets betydelige potentiale for at assistere brugere med lammelser i arme og hænder. Derfor er formålet med dette ph.d.-studie at udvikle en tungebaseret styringsmetode til exoskeletter, der er baseret på en enkelt modalitet, tungen, og som muliggør fuld og kontinuerlig styring af en 5 DOF ULE for at muliggøre at brugere med komplet funktionel tetraplegi selvstændigt kan udføre daglige aktiviteter.

Gennem denne ph.d. udviklede og testede vi en ny metode til interpolation af sensordata, der muliggør sporing af ITCI-aktiveringsenheden i høj opløsning. Derefter implementerede vi en ny metode til at designe virtuelle knapper og en kontinuerlig joystick-emulering baseret på ITCI'et og testede dette i en undersøgelse med tolv raske deltagere der styrede en robot. Desuden udviklede vi en ny algoritme til genkendelse af tungebevægelser. Vi anvendte disse resultater til at skabe og sammenligne et gestus-baseret og et joystick-baseret kontrollayout for en fem-DOF ULE i en undersøgelse med ti raske personer. Derudover evaluerede vi øjenfri brug af ITCI robotstyrings-layouterne (uden visuel feedback). Endelig evaluerede vi tungestyring af et fem-DOF ULE til empowerment af mennesker med tetraplegi til fuldt ud og selvstændigt at kunne udføre højt prioriterede ADL'er, herunder at kunne drikke og spise snacks. Dette blev gjort gennem i et klinisk forsøg med ti brugere med tetraplegi.

Undersøgelserne med raske deltagere viste, at et styringslayout med en kontinuerlig joystick-emulering baseret på ITCI'et forbedrede ydeevnen af assisterende robotgrænseflader, sammenlignet med virtuelle knapper, ved at reducere ADL gennemføringstiden med op til 16 % og antallet af kommandoer med 20 %. Algoritmen til genkendelse af tungebevægelser identificerede et sæt på seks bevægelser med 94,3 % nøjagtighed og 23 bevægelser med 72,3 % nøjagtighed, hvilket giver mulighed for et stort antal styringskommandoer med ITCI. Der blev ikke opnået nogen signifikant forskel mellem de gestus-baserede og de joystick-baserede kontrollayouts til styring af et fem-DOF ULE. Fjernelse af det visuelle feedback for det joystick-baserede layout, øgede drikketiden signifikant med 45,3 % mens det gestus-baserede layout fungerede på samme måde med og uden visuel feedback. Studiet viste at den udviklede tunge-exoskelet- styringsmetode var i stand til at give brugere, selv med komplet funktionel tetraplegi, mulighed for selvstændigt at udføre ADL'er med et ULE. Alle de ti deltagere med tetraplegi, som deltog i vores kliniske undersøgelse, var i stand til at tungestyre ULE'et med det udviklede ITCI layout og fuldførte uafhængigt drikke- og snackopgaverne. Deltagerne vurderede intuitiviteten af tungestyringsmetoden til 5.2 på en skala mellem 1 (lav) og 7 (høj).

ACKNOWLEDGEMENTS

This PhD thesis is a summary of almost four years of intense effort with tough, exciting, challenging, thrilling, frustrating, and happy moments, not only for me, but for many people who contributed to this work, and I would like to represent my gratitude to them.

First, I would like to express my deep appreciation to my supervisor, Associate Professor Lotte N.S. Andreasen Struijk for her support and for always being positive. She was not only a great supervisor for my PhD, but a professional role model and a prominent character. I want to extend a special thank you to my co-supervisor, Hendrik Knoche, for his insightful comments and reflections. His critical and sharp mind always steered me on the right track.

I want to give my warmest gratitude to my wife, who never left supporting me and filling my heart with love and endured the difficult days through my career. She never gave up motivating me and relieving my stress and was my only companion in the lonely days of being far from family and the pandemic. I definitely could not reach this point without you. I also would like to express my outermost thanks to my parents and siblings for their immense support and love. I cannot thank you enough for your never-ending support. My deepest thanks to my father, who guided me through my life. I never fear any risk as far as you are on my side.

I also would like to thank my colleagues, specially Mikkel Thøgersen and Stefan Hein Bengtson, for their companionship and for being available for discussions and reflections. I will never forget the joy of playing CS on Friday evenings and playing gameboards in the weekends.

TABLE OF CONTENTS

TABLE OF FIGURES

CHAPTER 1. INTRODUCTION

"I've often thought how much easier things would be, even if I were a para. Even if I had use of my hands.... How useful they are, they're great, everyone should have working hands."

A man with tetraplegia [1]

1.1. SPINAL CORD INJURY

Spinal cord injury (SCI) affects a population between 250,000 to 500,000 each year worldwide [2]. The prevalence of SCI has been reported to be in the range of 223-755 per million inhabitants, and the incidence has been estimated to be between 10.4 and 83 per million inhabitants per year [3]. In Denmark, the incidence between 1990 to 2012 was 10.2 per million people per year [4]. The incidence rate of SCI is higher among young adults [2], with a mean age of 33 years worldwide [3] and 35 years in Denmark [4] at the time of incidence. Young individuals who sustained an SCI between the ages of 25-34 years usually survive for 38 years after the injury [5], meaning a long life with extreme disability, lack of independence, and low quality of life.

The severity of the injury depends on both the level of the trauma in the spinal cord and the amount of residual nervus connection through the affected site (complete or incomplete) [6]. The American Spinal Injury Association (ASIA) has introduced an SCI impairment scale that ranks the severity of impairment from A to E, where A is the most severe injury, and E is normal functionality. In the cases of damage to the cervical vertebras C1 to C7, the patient may suffer a condition called tetraplegia (also known as quadriplegia), in which all extremities including both legs and arms are affected. The higher the injury level in the spine, the more limbs will be paralyzed [7]. Injuries to C1-C3 vertebras may even lead to paralysis of the diaphragm, which leaves the patient reliant on an active respirator for breathing [7]. Furthermore, based on the intensity of the injury, the patient may preserve some residual muscle control or sensory feedback in the limbs below the injury level. In the case of complete tetraplegia, all the nervous systems below the injury site will be disconnected from the central nervous system, preventing any sensory or motor function in the affected limbs [6].

Approximately one-third of SCI cases are reported to be tetraplegia worldwide [3], and this rate has been reported to be up to 57% in the Netherland [8], from which half of the cases had a complete lesion [3]. Individuals with complete functional tetraplegia who do not possess any or have significantly reduced motor function in their legs and arms rely on a 24-hour assistant for activities of daily living (ADLs). This condition has many severe consequences for the affected individual, the family, and society. In addition to the physical consequences of SCI, individuals with SCI are more susceptible to anxiety and depression [9][10][11], where a study has shown that 27% reported mild to severe depressive symptoms, and 7% had suicidal thoughts within the last two weeks [11].

A significant factor that can mitigate depression in individuals with SCI and improve the quality of life is to regain some levels of independence and autonomy [1]. Individuals with tetraplegia have rated regaining arm and hand function as the highest (48.7%) within seven functions, as the most crucial function that would improve their quality of life, followed by sexual function (13%) [12]. Furthermore, individuals with tetraplegia desired the most to be able to independently perform tasks such as eating snacks, drinking, and scratching their heads [13]. Therefore, an assistive technology that can mobilize the arm and hand of severely disabled individuals and assist with ADLs such as snacking and drinking is highly desired and can significantly improve the quality of life.

The incidence of tetraplegia not only imposes severe physical and psychological challenges to the lives of the affected individuals and their families but also puts a high financial burden on the health care systems. In the United States, high tetraplegia (C1-C4) costs approximately 1.15 million USD on average during the first year after the injury, and 0.2 million USD each subsequent year, leading to 5.1 million USD estimated lifetime cost for an individual who sustained the injury at the age of 25 years [14]. These estimates excluded indirect costs such as losses in wages and productivity. Similarly, caregiving for an individual with tetraplegia approximately costs 2 million DKK per year in Denmark [15].

Another challenge is the lack of caregivers for disabled people due to the demographic changes toward older societies, with an estimated increase in the population aged over 65 in the EU from 17% in 2008 to 23.5% in 2030 [16]. Thus, providing caregivers and the financial burden of that will be a significant challenge for future societies.

1.2. ASSISTIVE ROBOTICS

Robotic devices such as assistive robotic manipulators (ARMs) and upper-limb exoskeletons (ULEs) have been proposed as solutions to empower individuals with tetraplegia to perform ADLs [17][18][19][20]. These solutions can alleviate the psychological pressure of total dependence on helpers and reduce the needed caregiver time by 41% [18] by facilitating independence in performing ADLs. The significant improvement in the quality of life of assistive robotic users has led to the emergence of commercially available 1) ARMs such as JACO (Kinova, Canada) and iARM (Assistive Innovations, Netherlands) [21], and 2) ULEs such as MyoPro (Myomo, United States), iFLOAT (Assistive Innovations, Netherlands), and Armon Ayura (ARMON Products, Netherlands).

Different studies evaluated the efficiency of ARMs in performing ADLs and improving the users' quality of life [22]. For example, Gelderblom et al. showed that a group of iARM users required about 30% less assistance for ADLs. The investigated group carried out 40% more ADLs themselves than another group with a comparable level of disability [23]. Another study observed eight disabled users for four weeks before and after using iARM and reported a 32% decrease in required assistant time. Similar results were reported for JACO, reducing the caregiving time by up to 41% [18].

ULEs also have shown the potential for assisting individuals with tetraplegia in performing ADLs and improving their quality of life [24][25][26][27]. Longatelli et al. assessed how two commercially available ULEs could improve the upper-limb functionality of 36 individuals with muscular dystrophy and showed that most of the users improved upper-limb function using ULEs [24]. Furthermore, the users rated the usability of the ULEs as 'Good' or 'Excellent'. Another study evaluated the user satisfaction, motor performance, and perceived usability of a ULE with six individuals with arm disability and reported high usability (90/100) and user satisfaction (104/120) of the system [25].

ULEs can offer several advantages over ARMs. Firstly, mobilizing the user's own limbs by exoskeletons can elicit neuroplasticity and induce neurological recovery [28][29][30]. Secondly, a discreet ULE such as those in [31][32] may comply higher with the regular appearance of the user and look more aesthetically appealing than a relatively big manipulator attached to the user's wheelchair. Lastly, using an exoskeleton can give a sense of using one own's hand, which may lead to a higher embodiment of the assistive device and acceptance by the users [33]. However, ULEs are more advanced and require complex joints and actuators, especially at the shoulder and fingers [34].

1.2.1. EXOSKELETONS FOR INDIVIDUALS WITH COMPLETE FUNCTIONAL TETRAPLEGIA

Exoskeletons for individuals with tetraplegia due to SCI should support severely paralyzed upper limbs, even to the degree that no functional movements are possible, which we will define as complete functional tetraplegia. These exoskeletons must be able to fully support both arm and hand motions needed to perform the targeted ADLs. Examples of such exoskeletons includes the EXOTIC [32][35], NESM-β [36], BRAVO [37], and BOTAS [38] ULEs. These exoskeletons consisted of at least four actuated DOFs at the arm and at least one DOF at the hand for grasping objects. Design challenges for ULEs include kinematic compatibility with the human anatomy, compact design and aesthetics, functionality, and high-level control [34]. Furthermore, positive ULE attributes identified by individuals with tetraplegia included small and compact size, lightweight, fast mounting, usable while being in a wheelchair, and harmonic movements [13]. However, many of the available ULEs for individuals with tetraplegia are still bulky and unsuitable for the targeted application of assistance.

The EXOTIC ULE is a five-DOF mobile exoskeleton designed to assist individuals with tetraplegia to perform some ADLs independently. The design requirements were obtained through meetings and interviews with the potential users [13]. While the exoskeleton is relatively small and compact with a weight of 4 kg, it can carry a load of 1 kg at the hand in addition to the user's arm (Figure 1). Two ergonomically designed braces at the upper arm and at the forearm carry the arm's weight. The user is only strapped to the exoskeleton at the wrist, allowing easy donning and doffing. Furthermore, this approach results in minimal physical stress to the user's skin, which is crucial for minimizing the risk of provoking autonomic dysreflexia [39]. The exoskeleton can be attached to and powered by an electric wheelchair for mobile applications. However, it was mounted on a custom trolley that allowed donning the exoskeleton while users were sitting in their wheelchairs.

The exoskeleton consists of five DOFs, including shoulder flexion/extension, shoulder external/internal rotation, elbow flexion/extension, wrist supination/pronation, and hand opening/closing (Figure 1). The joint ranges of motion are 172° at the shoulder flexion/extension, 110° at the shoulder external/internal rotation, 148° at the elbow, and 130° at the wrist. The first four DOFs are actuated by motors mounted on the exoskeleton and through gearboxes and rigid power transmission. It uses a commercially available hand exoskeleton (CarbonHand, Bioservo) for closing the hand that transmits the mechanical power through soft strings. This allows for mounting the motors more proximal to the body or on the wheelchair. As the CarbonHand only implements hand closure, an in-house mechanism based on elastic bands is used for opening the hand.

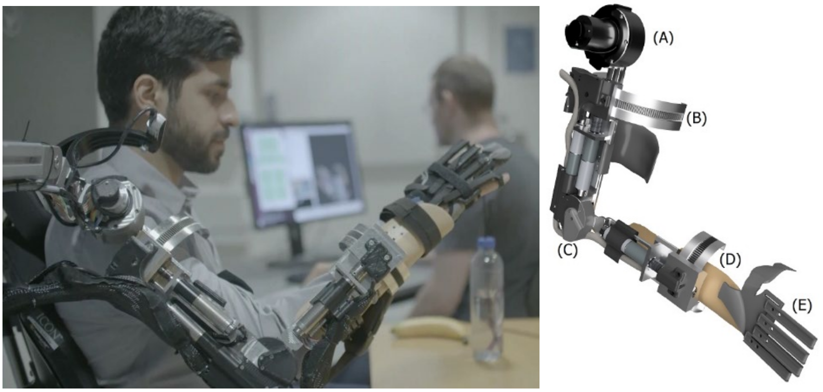


*Figure 1- The five-DOF EXOTIC upper-limb exoskeleton consisted of four DOFs at the arm including **A**: shoulder flexion/extension, **B**: shoulder external/internal rotation, **C**: elbow flexion/extension, **D**: wrist supination/pronation, and **E**: hand opening/closing.*

1.3. CONTROL INTERFACES FOR UPPER-LIMB EXOSKELETONS

A major challenge for the use of ULEs for the assistance of disabled individuals is providing a versatile, robust, and reliable interface that enables full control of a multi-DOF exoskeleton for performing ADLs outside laboratories. This challenge will be more significant for individuals with severe disabilities such as complete functional tetraplegia who possess no functional motions in their arms and legs. At the same time, users with more severe disabilities benefited the most from ULEs [24][40].

Some of the proposed ULE interfaces employed the residual arm functionalities. They assisted the user by augmenting the arm movements or by supporting the arm weight and compensating the gravity force [41][42][43][44][45][46][47]. For example, in control approaches based on impedance and admittance control [45][46][47][48], or force and torque control [49][50][51], a separate physical control interface was not required, and the user's arm movement controlled the ULEs. Nevertheless, these interfaces are not suitable for very weak or paralyzed arms.

Another approach that relies on the residual motor function identified the user's intention for moving the arm through electromyography (EMG) [52][53][54][55] and force myography (FMG)[56][57] sensors. Up to 16 EMG channels were utilized to control the ULEs' DOFs (seven in [58] and eight in [59]), as at least two EMG channels were required to control each DOF. For example, the two actuated DOFs of MyoPro were controlled using four EMG channels reading muscle activities from biceps, triceps, wrist flexors, and wrist extensors [60]. ULE interfaces based on EMG can offer intuitive control and assist individuals with weak muscles. However, determining the optimal placement of electrodes usually requires an expert, and low repeatability is expected [61]. Furthermore, dry EMG electrodes that are usually the primary option for applications outside laboratories are more prone to noise and have a higher impedance than wet electrodes, resulting in lower EMG signal quality [61]. Further, they cannot be used by users with complete tetraplegia.

Taking advantage of the residual hand and arm functionality for ULE control has also been provided through physical buttons and joysticks. A sensitive finger-controlled joystick and a push-button were used for controlling a four-DOF ULE and showed significant improvement in the arm function using the system [31]. Another example is the iFLOAT Power Assist [62] that lifts the user's arm using a pushbutton pressed by the other hand. Even though all the above interfaces are designed for individuals with arm disabilities, they are not applicable for individuals with complete functional tetraplegia who have no functionality in their arms.

Gasperina et al. proposed a vocal and a visual control interface for a five-DOF ULE that could be used by individuals with complete functional tetraplegia [63]. The visual control interface used a table-mounted eye-track to detect the point of gaze on a screen and identify the button that the user was looking at. However, this approach required the user to look at the screen instead of the arm while controlling the ULE, compromising usability. Furthermore, eye-trackers are sensitive to ambient light intensity and require recalibration over time if the user's body moves. The vocal control interface recognized 11 voice commands [63] for activating the control, emergency stop, or a fixed displacement of the user’s hand, compromising fine manipulation. Thus, the user was not continuously in control but through discrete impulses. Furthermore, vocal interfaces may be error-prone in crowded and noisy environments.

Another method for identifying user intention for ULE control relies on users’ brain activities from surface electroencephalography (EEG). Different features for generating a control command are detected from EEG, such as movement-related cortical potentials (MRCPs) [64], motor imaginary potentials (MI) [37][65], and steady-state visually evoked potentials (SSVEP) [38]. These methods only initiated a predefined motion and were limited to being used for performing confined tasks in the test setup. This is mainly due to the insufficient number of inputs and the discrete nature of MI and MRCP commands. Furthermore, the sensitivity of the data recording methods to electromagnetic noise, the requirement of substantial calibration, and the very visible placement of the electrodes limits the application of surface EEG interfaces outside laboratories. However, these methods can be the last resort for severely disabled individuals with locked-in syndrome who cannot use any other interface [66]. Furthermore, they are beneficial for treating stroke and SCI survivors in a clinical setup and training the arm [67].

A solution for the limited number of commands in EEG-based interfaces for controlling a multi-DOF ULE in a 3D space is automatic control through computer vision [36][68][69]. However, computer vision algorithms only assisted in grasping and collision avoidance [70]. Furthermore, the automated assistance methods are usually limited to confined setups, i.e., they only detect specific objects limiting the usability and are sensitive to ambient light intensity. Thus, a study has shown that users prefer full control of assistive robots over automated versions, even when automation improves performance [71]. Another solution to control a ULE with more DOFs than the interface can provide is mode switching. For example, a 2D joystick controlled a four-DOF ULE by mode switching with a push-button [31]. However, JACO users identified mode switching as a key problem both in terms of cognitive load and time, taking about 17.4% of the task time [72].

Some studies incorporated more than one input modality to provide more control commands in BCI-based robot control [36][68][73][74]. For example, a combination of EEG/eye-tracking was used to control a five-DOF ULE [68], in which the eye-tracking and computer vision specified the user’s target object, and the MI (EEG) initiated the grasping action [68]. A limitation of multi-modal interfaces is the accumulated complexity of the two inputs, for example in terms of setup and calibration.

Another method for reading the brain signals and identifying the user's intention is to surgically implant electrodes. To our knowledge, the only reported case of controlling a ULE with an implanted brain interface was an individual with tetraplegia who controlled a two-arm ULE with four-DOFs at each arm and no hand support [75]. Two epidural recorders with 128 electrodes in total were implanted over his sensorimotor cortex to record MI. After 16 months and 122 sessions of training, the participant controlled the eight ULE DOFs for a 3D reach-and-touch task with a 70.9% success rate [75]. Besides the prominent results of this study, sufficient clinical evidence for efficiency over time, repeatability, and risks of this approach is not available yet, nor is data on performing actual ADLs. Furthermore, the solution required invasive implantation, which entails surgical complication risks. Another limitation of implanted brain interfaces is the need for lengthy training and calibration, and recalibration over time (at least every seven weeks in [75]). Still, BCI-based systems can be important last solutions if no other possibilities are available.

An SCI rarely affects tongue functionality, as the tongue is innervated by cranial nerves. Furthermore, the size of the area of the motor cortex region corresponding to tongue control is comparable with that of the hand, allowing for fine manipulation of the tongue [76]. Thus, several tongue interfaces have been developed for individuals with SCI-related tetraplegia [77][78]. For example, the Inductive Tongue-Computer Interface (ITCI) [77] enabled an individual with complete functional tetraplegia to fully control a seven-DOF ARM and perform an ADL [79]. The ITCI provided up to 18 commands [77], which is sufficient for many control applications. However, it had not been used for exoskeleton control before this PhD. A recent study used the Tongue Drive System to control two DOFs of a rehabilitation ULE and move the user’s arm in a horizontal plane [80]. This solution was only proposed for rehabilitation in a laboratory, and due to the lack of a grasping function, it cannot be used for empowering individuals with complete functional tetraplegia to perform ADLs. Furthermore, the TDS system required a headset and time for calibration [81] and provided only four commands, which is insufficient for performing ADLs, except through mode switching or automation.

The state-of-the-art in ULE interfaces for individuals with arm disabilities is summarized in Table 1. The table shows the ULE interface attributes that are important for empowering individuals with complete functional tetraplegia to independently perform ADLs outside a laboratory setup, which are:

1. Provides full control: A full control of a ULE is achieved if the number of available commands by the interface matches the actuated spatial and functional DOFs of the ULE. In the case of discrete switch-like commands, two commands are necessary for controlling each DOF (for example,

moving toward the two sides of an axis). Another type of command provides proportional velocity control of DOFs. For example, a lever controls one DOF and a joystick controls two DOFs. Table 1 shows the types and number of commands that interfaces with different input modalities have provided until now and whether full control was achieved. To compensate for the insufficient number of commands, methods such as mode-switching [31], automation through computer vision [36][68][69], and selecting predefined motions [36][37] have been used (Table 1).

2. Is single modal: Control interfaces receiving inputs through multiple input modalities improved the limited number of commands of single modal interfaces, combining mainly EEG with other modalities such as EOG [36] and eye-tracking [68]. However, a single modal input with the same number of inputs is preferred over a hybrid interface, as less complexity herby will be engaged with the overall interface-ULE system.
3. Provides continuous control: Continuously possessing the control at all instances that the ULE is moving ensures a higher satisfaction and safety and allows fine control of the position and thus fine manipulation. On the contrary, initiating predefined movements or automation involves instances where the user is not actively controlling the ULE [36][37], which compromises safety. For example, in [94] the user initiated small displacements in different directions using a vocal interface. Even though these systems are usually equipped with an emergency stop command, issuing the command may take several seconds [82].
4. Provides direct control: A direct control is achieved if the user does not depend on a screen for issuing a command. Interfaces based on eye-tracking [82] and SSVEP (EEG) [38] mainly provide an indirect control, as the user must look at a certain field on a screen or flashing light in order to issue a command, hereby reducing the user's ability to monitor the actions of the exoskeleton. A video stream from the table in front of the user have typically presented on the screen, as the user could not directly look at it [63]. However, the user may miss some information such as the depth and details of the environment through a video, which compromises fine manipulation.
5. The interface is usable for individuals with complete functional tetraplegia: Individuals with complete functional tetraplegia cannot use interfaces based on the residual arm and hand functions such as force/torque control, EMG, and finger/hand-controlled joysticks. However, this user group might be the one most in need of a ULE.
6. Requires only limited calibration and algorithm training: Calibration of the interfaces and training of algorithms based on machine learning or classification methods is essential for their optimal performance. However, calibration time and sustainability of the calibration may compromise the usability of the interfaces. A long calibration time reaching up to several hours may be required for the calibration of brain-machine interfaces, and up to months may be needed to learn using them, especially if a high number

of commands is recognized [75][83]. Recalibration over time and/or each time the interface is mounted/donned is another major challenge with most interfaces based on EEG, EMG, eye-tracking, and the tongue drive system (Table 1).

7. Is validated through clinical evidence: Important features of interfaces such as their usability, performance, reliability, and risks cannot be assessed except through clinical tests with a sufficient number of the target users. Studies that have only recruited able-bodied participants or a few disabled individuals can demonstrate the concept and the technology but cannot assure the same outcomes for disabled individuals as for able-bodied users. Furthermore, in addition to quantitative outcome measures, qualitative measures obtained through questionnaires or interviews from the primary users can uncover meaningful insights about the system.
8. Is aesthetically acceptable: A critical feature of assistive devices in order to be adopted by the target users is the aesthetics of the device [13], as it may also increase the risk of stigmatization and thus the quality of life [1]. In particular, the attachment of devices to the head and face, such as an EEG cap or a headset, can strongly affect the appearance of the user. Therefore, a desired attribute of an interface is that it is as compact and invisible as possible.
9. Supports ADLs for users with complete functional tetraplegia: The main aim of assistive ULEs is to enable disabled individuals to perform ADLs independently. For individuals with complete functional tetraplegia, this feature of the proposed systems is highlighted in Table 1. For example, a vocal interface provided control of a four-DOF ULE; however, a grasp function was missing, and the system relied on the user's hand for grasping [31].

As shown in Table 1, none of the previously proposed ULE-interface systems supported ADLs for individuals with complete functional tetraplegia and such a system is still lacking. Thus, the ITCI system having up to 18 separate commands [84] that can be issued in a robust manner, also outside the laboratory [85], by an individual with complete functional tetraplegia, seem promising for the use as a single-modal control interface for a ULE, such as the EXOTIC, with sufficient DOFs for performing ADLs.

Table 1- Features of ULE interfaces for disabled individuals.

Studies	**Input modality**	**System supported ADLs for complete functional tetraplegia**	**Actuated DOFs**	**Number of commands**^{a}	**Single modal**	**Continuous**	**Direct**	**Full control**	**Interface usable for complete functional tetraplegia**	**Calibration and algorithm training**	**Clinical study sample size**	**Aesthetic cost**	**Subjective user feedback**
[80], [86]	Tongue drive system	-	≤2	4D or 2J	✓	✓	✓	✓	✓	≥ 4 Minutes	2 [80], 3 [86]	Headset	-
[75]	Invasive BCI	-	4^b + 4	$8D^b$ + 8D	✓	✓	✓	✓	✓	Months	1	Headset	-
[31], [82]	Finger-controlled joystick	-	4	2J + 1D	✓	✓	✓	✓	-	Minutes or less than 1 minute	13 [31], 3 [82]	Visible, but discreet	✓
[52], [53], [87], [54], [55], [58], [41]	EMG/FMG	-	≤8	≤16D	✓	✓	✓	✓	-	Minutes to hours	1 [54], 15 [55], 1 [87]	EMG electrodes on the arm	[53], [54]
[42], [43], [44], [45], [46], [47]	Force/torque control using residual arm ability	-	≤8	≤6J	✓	✓	✓	✓	-	Not reported	38 [24]	Not visible	[44]
[86]	Eye-tracking	-	4	11D	✓	✓	-	✓	✓	Minutes	3 [86]	Visible, but discreet	✓
[80], [86]	Voice command	-	4	11D	✓	-	✓	✓	✓	Not reported	2 [80], 3 [86]	Visible, but discreet	✓
[68]	EEG and eye-tracking	-	4	$1D^c$	-	✓	✓	-	✓	One training session	4	EEG cap	✓

[37], [65], [38], [88], [89], [90]	EEG	[37][d], [38][d]	≤8	≤6D	✓	-	✓	-	✓	From minutes to hours	2 [65], 3 [37]	EG cap	-
[36]	EEG and EOG	[36][d]	7	2D	-	✓	✓	-	✓	From minutes to hours	4	EG cap	✓

a: D: Discrete switch-like commands, J: A control of a DOF that allows multiple velocity values within the velocity range. For example, a joystick is usually 2J.
b: The exoskeleton consisted of two arms, each with four DOFs.
c: The user could also select a target object through eye-gaze.
d: These systems performed ADLs using automation through computer vision or predefined trajectories and are limited to the specific experimental setup.

1.4. INDUCTIVE TONGUE COMPUTER INTERFACE AND ITS POTENTIAL FOR EXOSKELETON CONTROL

The ITCI was developed at Aalborg University to enable individuals with tetraplegia to control electronic and assistive devices such as computers [77], wheelchairs [91], prosthetics [92], drones [93], and robotic manipulators [94]. The system consists of a mouthpiece (MP) similar to a dental retainer which is mounted inside the mouth at the hard palate (Figure 2 - A). The MPU contains 18 inductive sensors arranged in two printed circuit boards (PCBs). The anterior PCB contains ten inductive sensors and was initially considered for typing and was named the tongue keypad (TKP), while the posterior PCB contains eight inductive sensors and was designed as a tongue mousepad (TMP). The proximity of a metallic activation unit (AU, Figure 2 - B) to the inductive sensors can be recognized by measuring each sensor's impedance variations when a current is applied to the sensor coil. The AU is either pierced or glued to the tongue. The signals from the sensors are preprocessed by the MPU and then transmitted to a central unit (CU, Figure 2 - C). The preprocessing includes amplification, rectification, and low-pass filtering.

The ITCI sensors were initially used as on/off switches by thresholding the sensor activation level [77]. Later, a fuzzy inference algorithm was used to interpolate the TMP sensors for emulating a 2D joystick, reaching a throughput of 0.8 bits/s for a pointing task on a screen [95]. The same joystick was used for controlling a wheelchair [96][97].

In the previous studies with the ITCI, visual feedback from AU position in contact with the sensors was provided for the users, either on the central unit screen [91] (Figure 2 - C) or on a separate screen [79]. Visual feedback can facilitate selecting the intended command with the ITCI and avoid fault commands. However, the system could potentially be used without visual feedback, especially for experienced users with the ITCI. In addition, a dwelling time before issuing a command prevented fault

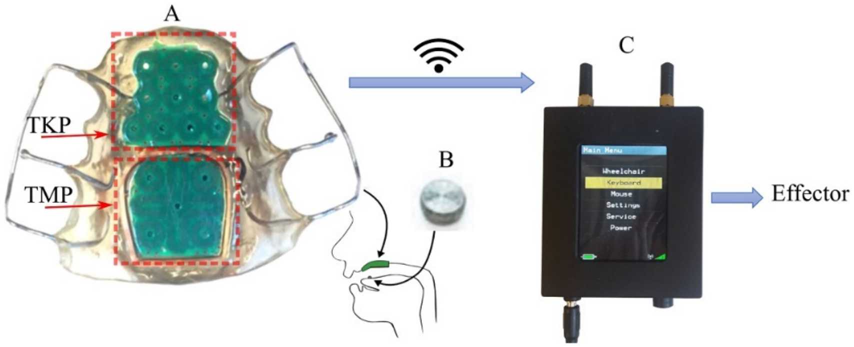


Figure 2- The Inductive Tongue-Computer Interface consists of ***A****: a mouthpiece unit,* ***B****: the activation unit, and* ***C****: the central unit (C).*

commands, for example while speaking, i.e., the effector received a command after a specific time delay from selecting the command.

The pilot study that an individual with tetraplegia used the ITCI for controlling an ARM for performing ADLs uncovered the potential of the system to provide full and continuous control of assistive robotics, without a long calibration or an aesthetic cost [79]. However, further research on improving and testing the control interface for robot control is needed to show how it can be used for ULE control.

CHAPTER 2. AIMS AND OBJECTIVES

The aim of this PhD study was to address the lack of a ULE interface allowing for independent performance of multiple ADLs in an aesthetic, continuous, and direct manner and to develop and test a tongue-based ULE interface for individuals with severe to complete tetraplegia. To reach this goal, the project was formulated into three main studies with the following objectives:

1) **Development and optimization of control layout design methods for assistive robotics based on the ITCI**

   An ITCI based control layout for assistive robotics performs based on several processes such as interpolating the sensor data, identifying the user commands (virtual buttons), and joystick emulation. These processing methods have not been optimized for the new application of interfacing assistive robotics before, and thus this optimization was an objective of this PhD study.

2) **Experimental evaluation of the control layout design factors**

   Meeting the first objective provides a platform for designing control layouts for assistive robotics with different features. Thus, this objective included testing and comparing several control layouts with different features to find how the factors including button size, mode switching, and different joystick emulation affect the performance.

3) **Development and evaluation of tongue interfaces for controlling a five-DOF upper-limb exoskeleton**

   This objective included the implementation and test of a tongue interface for a five-DOF ULE based on ITCI with able-bodied participants as the first step before a clinical study to ensure the safety and reliability of the system.

4) **Clinical evaluation of the tongue-exoskeleton interface in an ADL context**

   Validation of the tongue-exoskeleton interface for individuals with tetraplegia requires clinical experiments with real potential users. Therefore, an objective of this PhD was to clinically test the interface.

2.1. DISSERTATION OVERVIEW

This doctoral thesis presents the methods for implementing tongue-based interfaces for assistive robotics and the results of three experimental studies on evaluating the interfaces. Chapter 3 includes the methods and algorithms that I developed and used to design tongue-robot interfaces. Furthermore, the results of some pilot studies are reported. Chapter 4 summarizes the three main studies that build this PhD thesis. The studies include:

1) **Study I**: Continuous tongue robot mapping for paralyzed individuals improves the functional performance of tongue-based robotic assistance

   This study includes investigating the effect of several factors in the design of control layouts with the ITCI, including button size, mode switching, and continuous joystick emulation to achieve an efficient and intuitive control interface.

2) **Study II**: Eyes-free tongue gesture and tongue joystick control of a five DOF upper-limb exoskeleton for severely disabled individuals

   This study includes developing and comparing two tongue control schemes for a five-DOF ULE: one based on tongue gestures and the other based on a continuous joystick. Furthermore, the study aims at evaluating the feasibility of using the ITCI without visual feedback and the performance of the exoskeleton control in this setup.

3) **Study III**: Tongue control of a five-DOF upper-limb exoskeleton rehabilitates drinking and eating for individuals with severe disabilities

   This study aims at testing the tongue interface of a five-DOF ULE with ten individuals with tetraplegia for performing ADLs.

CHAPTER 3. DESIGN AND IMPLEMENTATION OF TONGUE-ROBOT CONTROL SYSTEMS

3.1. SENSOR INTERPOLATION METHODS

Previous studies with the ITCI used the TKP sensors as on/off buttons (discrete commands) either with assigning one command to each sensor [98][79] or with merging several sensors to a single command [92][91]. In addition, the TMP sensors were used as buttons similar to the TKP [79] or as continuous joystick for controlling a computer cursor [99] or a wheelchair [91]. However, these approaches were limited to the current sensor layout and shapes, which were not designed for robot control, where xxx is desirable.

Therefore, the first step in this PhD was to develop and evaluate different interpolation methods to accurately estimate the AU position when it is in contact with the two PCBs in order to facilitate novel virtual button and joystick layouts specifically targeting robot control. The algorithms merged the data of the 18 sensors and estimated an XY position of the AU. In this way, we could consider the ITCI as two touchpads instead of two sets of buttons. Furthermore, this approach allowed designing arbitrary arrangements of virtual buttons and more flexibility in control layout design.

Requirements for the interpolation algorithms included accuracy (measurement resolution), fast response for real-time processing, fast calibration, and robustness to different conditions (for example, the device battery level).

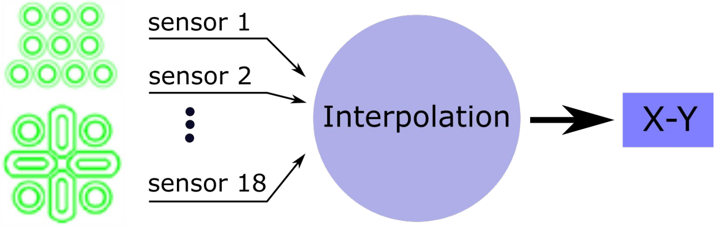


Figure 3- Different interpolation methods were developed to estimate the AU position in a plane (XY) using the 18 sensor signals.

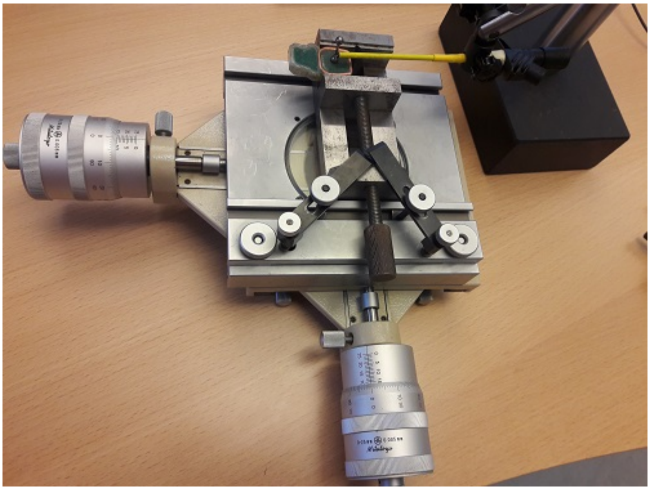


Figure 4- Test setup for recording data sets of AU positions and sensors' values. The precision linear stage provided an accuracy of 0.01 mm [100] (978-1-7281-2755-2/19/$31.00 ©2019 IEEE).

As described in [100], two datasets of AU positions in contact with the PCBs in a mech of 1 mm interval and the sensor values from three different MPUs were recorded. A 2D precision linear stage positioned the AU with an accuracy of 0.01 mm (Figure 4).

The datasets were used to obtain the relation between the magnitude of the sensor activation and the distance between the sensor center and the AU center (Figure 5). These results were in line with the mathematical model of the sensors and a previous measurement [101]. However, the new setup used a more accurate positioning method, and more data points than the previous study were recorded.

Five interpolation methods were developed and tested, including:

- Fuzzy Inference System (FIS)
- Weighted Average of Neighbor Sensors (WAN)
- Non-linear Weighted Average of Neighbor Sensors (NWAN)
- Nearest Neighbor Classification (NNC)
- Fitting a Gaussian Surface to the data (GSF)

Three of these (FIS, WAN, NNC) were reported in [100]. The FIS method was adopted from a previous study [101]. The NWAN was similar to WAN [100], except that the weights were calculated based on a Gaussian relation obtained from Figure 5. The GSF method estimated the AU position by fitting a Gaussian surface and finding the surface’s peak. The surface was fitted to 3D points that represented the sensors,

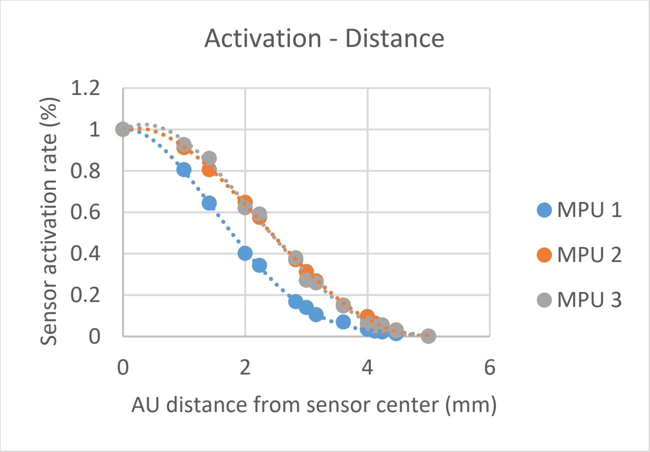


Figure 5- The relationship between sensor activation and the AU distance from sensor center.

with a Z value equal to the activation level and an XY position of the sensor in the PCB plane.

One dataset trained the interpolation methods (FIS and NNC), and the other was used for the accuracy test. The highest accuracy was achieved using the NNC method with 0.97 mm overall root mean square error (RMSE), followed by the WAN with 1.16 mm overall RMSE (Table 2).

Although the NNC measured the AU position with slightly higher accuracy than the WAN, the WAN offered a more suitable performance for the target application, as detailed in the following: firstly, the NNC functioned discretely, meaning that it estimated the AU position within a discrete mesh of points, and jumping between these points was observed when the AU was in motion. Secondly, the WAN method required less calculation and processing, which is more suitable for real-time processing on an embedded system. Lastly, the NNC required a dataset for each MPU to reach its highest accuracy and was not extendable to other devices.

Table 2- Root mean square error (RMSE) of AU position from different interpolation methods. The highest accuracy is highlighted in green (Adopted from [100], 978-1-7281-2755-2/19/$31.00 ©2019 IEEE).

Device	**Mousepad**					**Keypad**					**Overall**				
	FIS	***WAN***	***NWAN***	***NNC***	***GSF***	***FIS***	***WAN***	***NWAN***	***NNC***	***GSF***	***FIS***	***WAN***	***NWAN***	***NNC***	***GSF***
#1	1,41	1,45	1,47	1,48	1,59	2,45	0,94	0,98	0,54	3,74	1,89	1,21	1.24	1,04	2,44
#2	1,40	1,19	1,32	1,07	1,91	2,21	0,78	0,87	0,79	4,86	1,91	1,08	1.27	0,98	3,24
#3	1,32	1,47	1,41	1,13	1,48	1,52	0,88	0,85	0,64	3,31	1,42	1,19	1.15	0,90	2,33
Mean	1,38	1,37	1,40	1,22	1,66	2,06	0,87	0,90	0,66	3,97	1,74	1,16	1.19	0,97	2,67

3.2. A NOVEL METHOD FOR EMULATING A JOYSTICK CONTROL

The concept of a continuous joystick with the ITCI was previously presented [101]. A joystick-like control can provide continuous and proportional control of the velocity and direction in 2D, unlike discrete buttons that only provide control in fixed directions and velocities. However, the method was only applicable to the TMP area, while a study showed that higher throughput was achieved on the TKP, mainly due to the higher accessibility of the anterior sensors with the tongue [102]. Furthermore, our study showed that a higher AU tracking resolution is achieved on the TKP due to the different shapes and layouts of sensors in the two PCBs [100] (Table 2). Thus, for applications such as wheelchair or robot control where the joystick is the central controller and is prioritized over buttons, a continuous joystick on the TKP will provide a higher throughput joystick.

Therefore, the WAN interpolation method described in the previous section was used to emulate a continuous joystick in two ways: 1) mapping the AU position relative to the center of the PCB to a velocity command (position to velocity mapping, P2V) similar to [101], and 2) mapping the AU displacement to a velocity command (displacement to velocity mapping, D2V). A detailed description of the two methods is presented in [100]. The latter method aimed to provide a joystick with a double AU tracking resolution compared to P2V and reduce the need for memorizing the interface

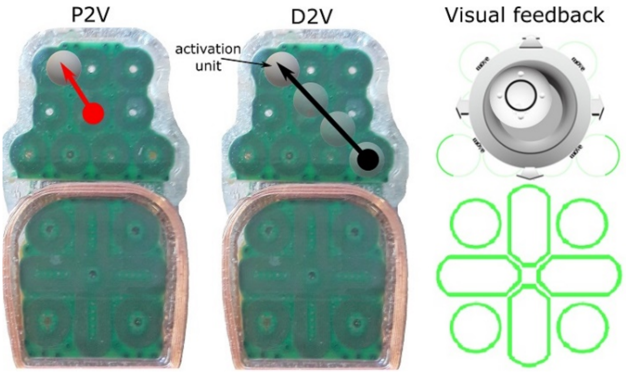


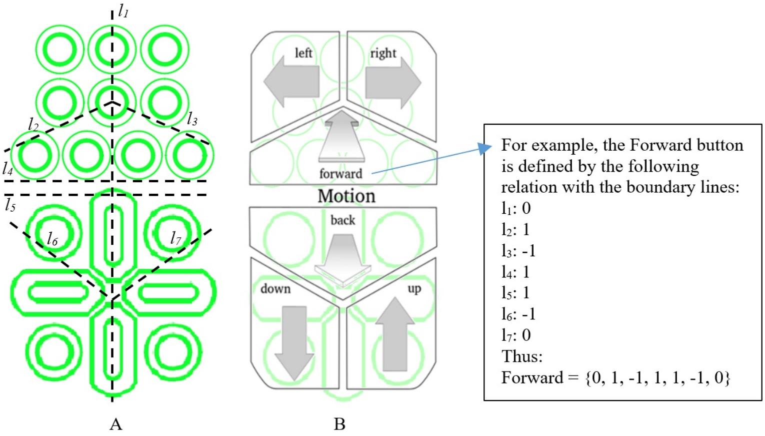
*Figure 6- **Left**: In the P2V method, the vector that connected the center of the TKP area to the AU position determined the direction and magnitude of the velocity command. **Center**: The initial contact of the AU specified the origin of the vector, and the vector was formed by dragging the AU. **Right**: The visual feedback of the joystick control.*

layout or looking at the visual feedback, as there was no fixed mapping of the points on the touch-sensitive areas to velocity commands.

The novel joystick emulation method (D2V) was evaluated using the ISO9241-411 standard, which provides a guideline for evaluating pointing devices and for measuring the throughput by a 2D pointing task. The study showed that the D2V method could provide a throughput of 0.93 bits/s [100], 15% higher than the P2V method [95]. Furthermore, the D2V and P2V methods were compared for continuous joystick control of an ARM in an experiment in which twelve able-bodied individuals controlled JACO ARM and performed two ADLs (*Study I*) [19]. The two joystick methods performed similarly for picking up a tape roll from a mount. However, the participants completed a pouring water task faster with the P2V [19]. Even if the robot moving time was similar between the two methods, the pause time between the commands was longer with D2V, which means it takes more time to activate the D2V joystick.

3.3. ROBOT INTERFACE DESIGN FACTORS

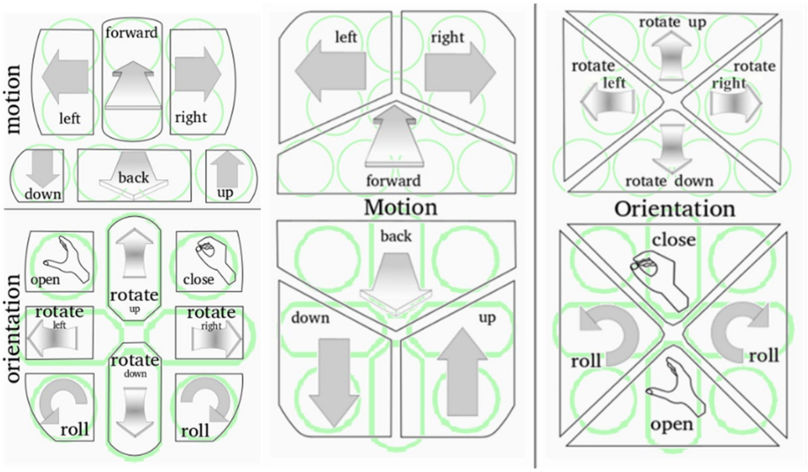
Considering the ITCI as two touchpads using the WAN interpolation method provided a basis for designing control layouts with different button sizes and shapes. As commands were no longer identified by thresholding the individual sensor activations, a new mathematical model was developed for defining virtual buttons with arbitrary sizes and shapes (*Study I,* [19]). In this method, a control layout was defined by a set of boundary lines, and a button was identified by a unique relation to the boundary lines (Figure 7). A control layout design factor was the size of buttons in the layout. Bigger buttons may be easier to select than smaller buttons. However, designing control layouts with bigger buttons required dividing the buttons into multiple control



For example, the Forward button is defined by the following relation with the boundary lines:
l_1: 0
l_2: 1
l_3: -1
l_4: 1
l_5: 1
l_6: -1
l_7: 0
Thus:
Forward = {0, 1, -1, 1, 1, -1, 0}

Figure 7- Each control layout was designed with a set of boundary lines and buttons. For example, A shows the seven lines for layout B. The buttons were recognized based on a mathematical relationship with the boundary lines described in Study I [19].

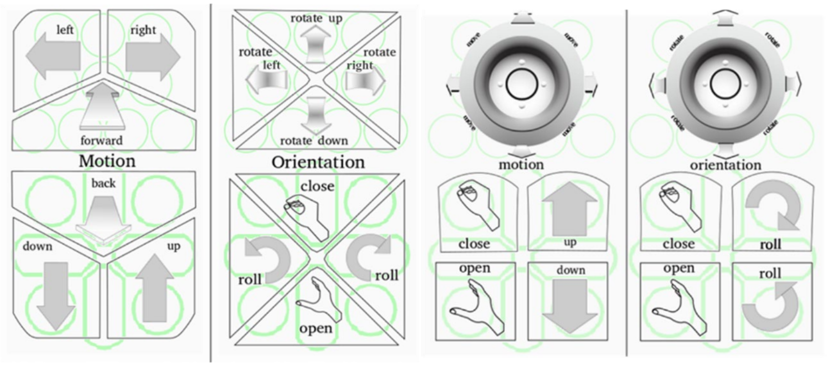
modes for controlling a high number of DOFs (Figure 8). The button size and mode switching factors were investigated in *Study I* [19] by comparing two control layouts for the JACO ARM with seven DOFs requiring 14 buttons: one layout had all buttons



One-mode layout

Two-mode layout

*Figure 8- Two control layouts for a seven-DOF ARM (JACO) was designed and tested. **Left**: In the first layout, all 14 buttons were arranged in one mode. **Right**: The second layout consisted of two control modes, one with six buttons and the other with eight buttons. A double-tap on the TKP area switched between the two modes. The sensor layout is also shown in green under the control layouts (Adopted from [19], 0018-9294 © 2021 IEEE).*



Control layout with discrete commands

Control layout with a continuous joystick

Figure 9- Two-mode control layouts, one with continuous joystick and the other with discrete commands (Adopted from [19], 0018-9294 © 2021 IEEE*).*

in one control mode and the other layout had the buttons divided into two modes (Figure 8). A double-tap with the AU on the TKP area switched the mode.

Another design factor investigated through *Study I* was the choice of continuous joystick emulation compared to discrete commands. The performance of the two-mode layout with discrete commands was compared with another two-mode layout, but with a continuous joystick control in each mode (Figure 9).

3.4. DYNAMIC VIRTUAL BUTTONS WITH A RESPONSIVE COLOR-CODING

The findings of *Study I,* including the optimal number of control modes and the continuous joystick emulation, were used to design an intuitive and high-performance control layout for the five-DOF EXOTIC ULE. Firstly, the 2D continuous joystick controlled the exoskeleton to position the user's hand in a horizontal plane (Figure 10 - B). Furthermore, 1D continuous joystick controls moved the exoskeleton end-effector (the user's hand) in the vertical axis (up/down) and rotated the wrist (Figure 10 – C & D). Secondly, all the controls were implemented in one control mode as mode switching did not improve the performance of the interface [19], while it may confuse the user and compromise the usability [72]. To accommodate all controls in one control mode and at the same time avoid reducing the size of virtual buttons and joystick emulations, a novel approach was developed in which the activation areas related to the buttons/joysticks changed in size after an initial activation (Figure 10 – B-D bottom figures). This novel dynamic sizing of button/joystick areas allowed more

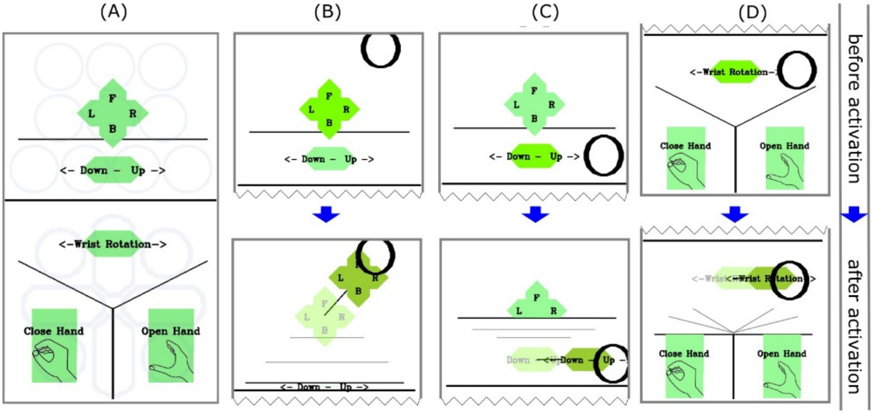


*Figure 10- **A**: The joystick-based control layout in idle state (no AU contact). **B-D**: The controls changed in size after activation (after the dwelling time of 0.5 s). Three green shadings indicated the state of the control within idle (neutral green), selected before activation (light green), and selected after activation (dark green). **B**: A 2D continuous joystick moved the hand in a horizontal plane (XY plane). **C-D**: Two 1D continuous joysticks moved the hand up and down (Z axis) and rotated the wrist [20][103].*

accessible buttons and easier manipulation of the joysticks for fine control of the velocity of the generated exoskeleton motion.

Another attribute of the new control layout was the color-coding that indicated the state of each control. The green color of a control area in the idle state changed to a light green shading while waiting to complete the dwelling time of 0.5 s (no exoskeleton movement) and changed to a dark green shading after the dwelling time was passed (Figure 10 – B-D). A study evaluated the performance of the control layout in with ten able-bodied participants (*Study II*, [20]) and another study with ten individuals with tetraplegia (*Study III*, [103]), described in Chapter 4.

3.5. GESTURE-BASED INTERACTION

Gesture-based interactions are commonly used in addition to virtual buttons for devices with a small touchpad or touchscreen such as smartwatches, mobile phones, and cameras [104][105][106]. Gestures, as an extra interaction mean, can replace physical or virtual buttons and free-up space for bigger buttons or other content on a touchscreen. Furthermore, some studies showed that gestures require less visual attention and can facilitate eyes-free interaction [107][106]. Therefore, a tongue-gesture recognition algorithm through the ITCI was developed to overcome the limitations of the small touchpads and provide more control commands necessary for controlling assistive robots with a high number of DOFs [108].

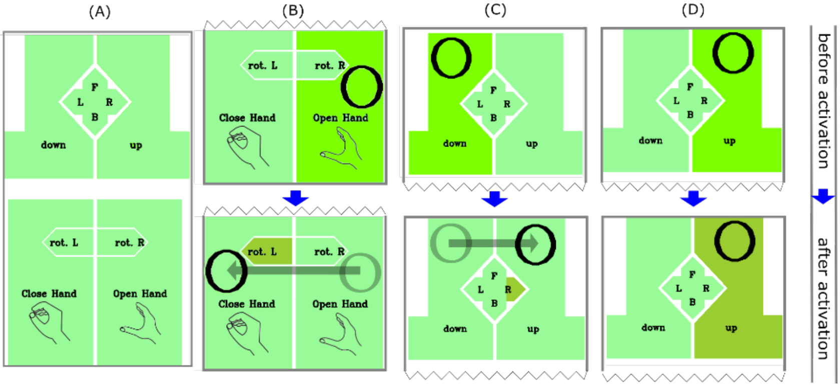


*Figure 11- **A**: The gesture-based control layout in the idle state (no AU contact). **B**: A swipe-press gesture to the left and right on the TMP rotated the wrist counterclockwise and clockwise. **C**: A swipe-press gesture to the left, right, forward, and backward on the TKP moved the hand to toward the gesture direction. **D**: A press gesture on the depicted areas moved the hand up and down [20].*

A pilot study was conducted to evaluate the accuracy of tongue gesture recognition [108]. The recognition algorithm identified a set of six gestures including four swipes (left, right, forward, backward), double-tap, and press with 94.3% accuracy and a set of 23 gestures including swipe, swipe-press, drag, drag-press, rub-press (all in four directions), double-tap, and press with 72.3% accuracy [108]. As the algorithm distinguished between gestures on the TMP and the TKP, up to 46 gestures were recognized. Details of the recognition algorithm and experiment are presented in [108]. Furthermore, a study was conducted to evaluate a gesture-based control layout (Figure 11) for controlling a five-DOF ULE and compare it with a joystick-based control layout (*Study II*, [20]). The two control schemes were compared in two setups for performing a drinking task with the ULE. In the first setup, visual feedback from the ITCI was presented on a screen in front of the participants, and the visual feedback was removed in the second setup.

3.6. EXOSKELETON CONTROL DESIGN IN ROS

The EXOTIC exoskeleton motors were controlled using EPOS4 controller boards (Maxon Motor AG, Switzerland). The controllers received feedback from a differential encoder on the motor shaft and an absolute encoder on the exoskeleton joints for a closed-loop PID control. The control commands from a computer to the

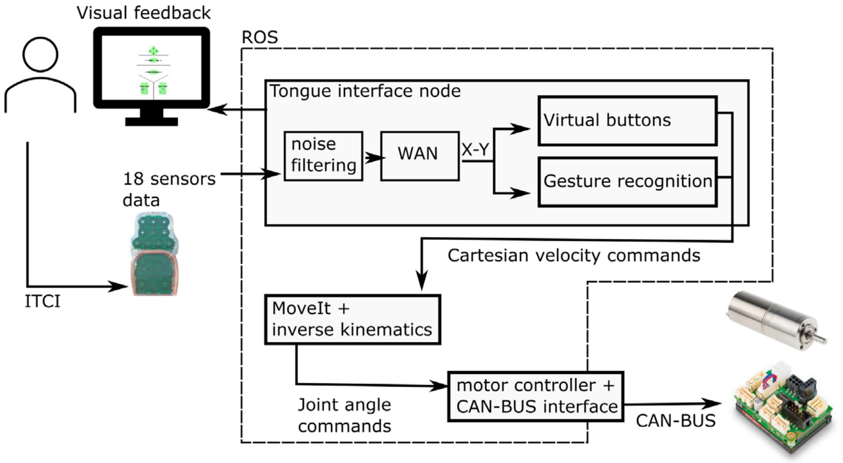


Figure 12- Overview of the exoskeleton controller in ROS. The control system received the ITCI sensors data and sent joint angle commands to the EPOS motor controller.

motor controllers were sent through CAN-BUS communication. A control software was developed in the Robot Operating System (ROS) to handle different modules of the system and the communication between them. The software consisted of a GUI for the experimenters to set up the system and manage data recording. A dedicated ROS node received the raw data from the 18 ITCI sensors with a 30 Hz frequency and estimated the AU position using the WAN method. The user inputs were recognized using the boundary lines method for the joystick-based layout and the gesture recognition method for the gesture-based layout. Furthermore, a GUI based on OpenCV package presented the visual feedback from the control layouts and the AU position (Figure 11).

The control layouts received the user input as velocity commands in a Cartesian frame fixed with respect to the user body. We used MoveIt [109] and the Orocos Kinematics and Dynamics Library [110] for inverse kinematics and trajectory planning and transforming the control commands from the Cartesian space to the motor joint angles. The software sent joint angle commands to the motor controllers in 100 Hz to ensure a smooth motion (Figure 11).

3.7. METHODS FOR PRODUCING TEMPORARY MOUTHPIECES FOR EXPERIMENT PARTICIPANTS

In the case of the commercial version of the ITCI (ITongue, from the TKS company in Denmark [85]), an MPU is custom made for each user using a dental impression of the user’s palate. The mouthpiece consists of the electronic core encapsulated in

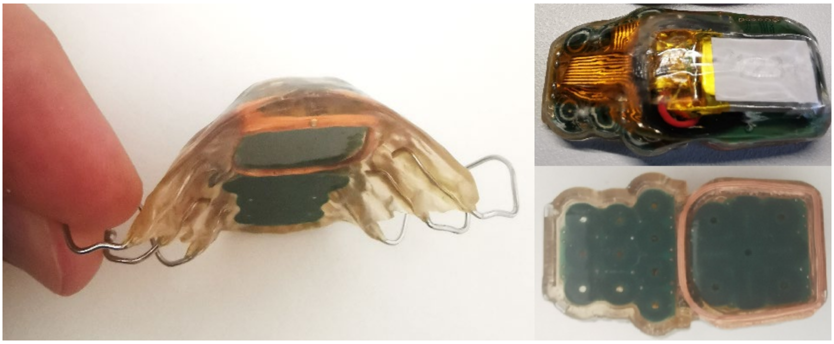


*Figure 13- **Left**: The ITongue MPU custom made for a user. **Right**: The electronic core of the ITCI MPU*

acrylic, and dental wires are used for attaching the mouthpiece to the teeth (Figure 12 - left). Furthermore, the wires act as antennas for wireless communication.

Two other methods were used to produce temporary MPUs for the experimental participants based on the electronic core of the ITCI MPU (Figure 12 - right). These methods allowed reusing the electronic core for several participants.

In the first method, dental sheets were used to mount the electronic core at the palate. The procedure consisted of making an impression of the palate by a dentist, casting a negative mold from the impression in plaster, vacuum-forming two dental sheets below and above the electronic core of the ITCI MPU, and finally trimming the sheets to form a mouthpiece (Figure 13 - A-E).

In the other method, a two-component dental putty (ImpressA Putty, TopDent) was used for making a mouthpiece. We mixed the two putty components and gently pressed the putty and the electronic core of the ITCI MPU toward the participant's palate for two minutes until it solidified as a rubber-like shape. Finally, the residuals were trimmed (Figure 13 - F).

The first method required a dental technician to take the impression. Furthermore, pressing the AU towards the edges of the sheet that held the MPU while using the ITCI resulted in an increased rate of detaching the glued AU. However, this method provided lighter and smaller mouthpieces with a firmer attachment to the palate. On the other hand, a trained experimenter could produce the putty-based mouthpiece without a dental technician. However, the mouthpiece was heavier, bigger, and had a looser attachment to the palate.

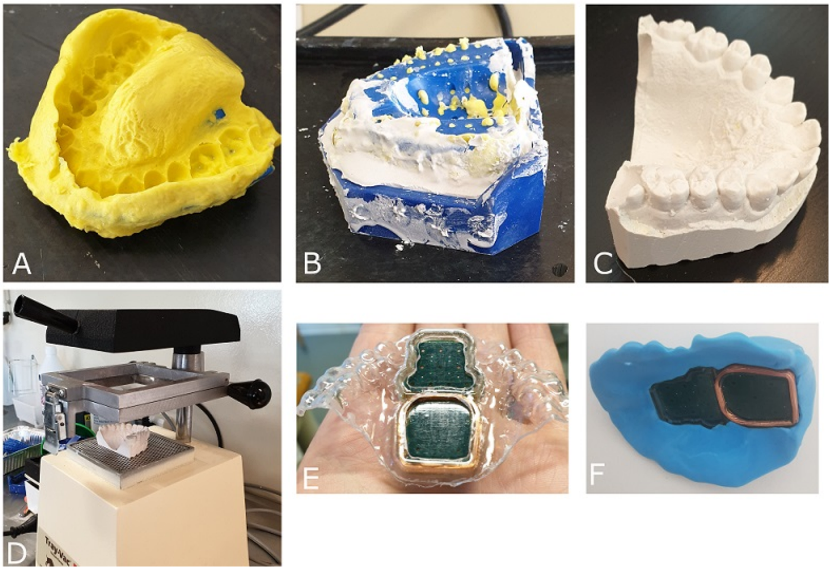


*Figure 14- **A-E**: The process of producing temporary mouthpieces using dental sheets. **A**: Pallet impression. **B**: Casting a negative mold from the impression. **C**: The plaster mold. **D**: Vacuum forming. **E**: The final mouthpiece.*
***F**: The putty mouthpiece.*

CHAPTER 4. THESIS EXPERIMENTAL STUDIES AND FINDINGS

This chapter presents a summary of the three main experimental studies of this PhD thesis. Based on the aims and objectives, the control layout design factors were experimentally evaluated in *Study I* [19]. In *Study II*, the tongue interface for EXOTIC ULE was presented for the first time and was evaluated [20]. Finally, *Study III* presented the results of a clinical study in which ten individuals with tetraplegia tongue controlled the EXOTIC ULE and performed two ADLs with the system [103].

4.1. STUDY I

Title: Continuous tongue robot mapping for paralyzed individuals improves the functional performance of tongue-based robotic assistance [19]

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

Journal: Transactions on Biomedical Engineering, vol. 68, no. 8, pp. 2552-2562, Aug. 2021, doi: 10.1109/TBME.2021.3055250.

In this study, a novel method for designing virtual buttons and robot control layouts with the ITCI (described in section 3.3) was tested for controlling JACO ARM. The new method allowed for the implementation of virtual buttons of different sizes and shapes as well as the implementation of a 2D continuous joystick emulation (section 3.2 and 3.3). Furthermore, a novel mode switching method that identified a double-tap with the AU was proposed and tested. In addition, two different methods for emulating a joystick were compared.

Four control layouts based on the ITCI for the JACO ARM with seven DOFs were developed and tested (Figure 8 and Figure 9). Two control layouts contained discrete commands similar to virtual pushbuttons, one layout with all commands (14 for the seven DOFs) in one control mode (discrete, one mode: D1M) and another with control commands divided into two modes (discrete, two modes: D2M) (Figure 8). A double-tap switched between the modes. Another two control layouts contained a 2D continuous joystick, one based on position to velocity mapping (continuous, two modes, P2V method: C2M-PV) and the other based on displacement to velocity mapping (continuous, two modes, D2V method: C2M-DV) (Figure 6). In total, four control layouts were tested.

In the test, twelve able-bodied participants tongue controlled the JACO ARM with the four control layouts based on the ITCI and performed a "pouring water" task (PW) and a "picking up a roll tape" task (PUT) in three experimental sessions over consecutive days. The PW task consisted of moving the JACO ARM from a home position to a bottle, grabbing the bottle from a table in front of the participant, pouring water in a cup, and placing the bottle back on the table (Figure 14 - A). The PUT test consisted of moving the ARM from the home position to the vicinity of a role of tape located on a mount (gross motion). The task continued with accurately aligning the fingers of the ARM's gripper with the tape (fine motion), grasping it, and lifting it (Figure 14 - B). This required fine control of the ARM as the tape would fall from the mount if it was displaced more than 5 mm before grasping.

In the first and second sessions, the participants performed the PW and PUT tasks with all four control layouts. The order of testing the layouts was counterbalanced over the participants. One successful trial in the first session and three successful trials in the second session were recorded. The third session aimed to compare the tongue interface with the standard joystick of the JACO ARM and provide a baseline for between-study comparisons. The participants completed the tasks three times in three setups: with the standard JACO joystick, with the ITCI used in the hand, and with the ITCI used with the tongue. The ITCI use in hand was tested to exclude the effect of learning to use the control with the tongue (which is unusual for control as compared to the hand) and highlight the system capability. In the third session, the participants only used the control layout that they achieved the lowest task time with that layout

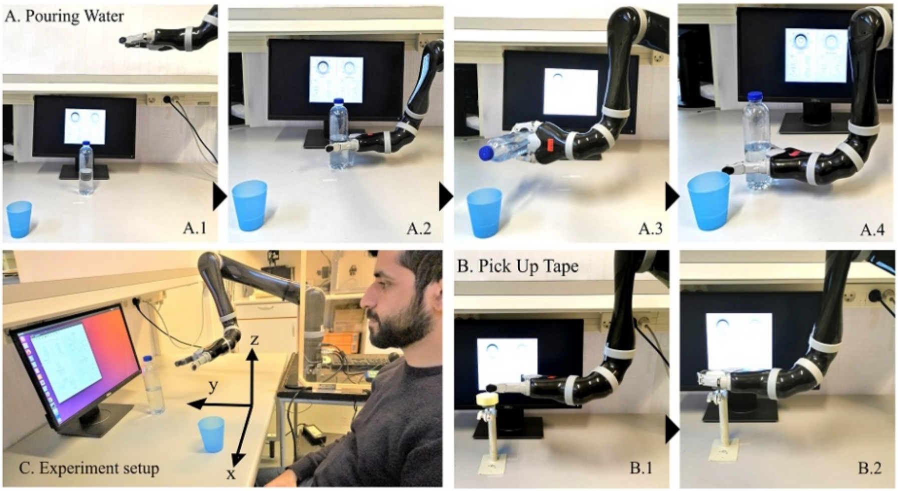


*Figure 15- **A**: The pouring water task started while the ARM was located in the home position (A.1). The task required grasping a bottle of water (A.2), pouring water in a cup (A.3), and placing the bottle on the table (A.4). **B**: Pick up tape roll task started with the ARM in home position similar to A.1. The participants moved the ARM close to the tape (B.1) and fine controlled the ARM for grasping the tape (B.2) (Adopted from [19], 0018-9294 © 2021 IEEE).*

in the second session. After each condition, the participants filled the NASA task load questionnaire (TLX).

We measured the task completion time as the main outcome measure for comparing the control layouts during all trials. Furthermore, the number of issued commands, the trajectory length, and the moving time of the robot were recorded. For the PUT task, the task completion time was divided into the gross motion time (from start time to the time that the gripper of the JACO h reached a 10 cm distance to the tape center) and the fine motion time.

All participants successfully completed the tasks by tongue controlling the JACO ARM with all layouts. The PUT task lasted 32.7 s on average in the third session using the tongue interface, compared to 17.3 s for the hand-controlled JACO joystick. PW task required 71.4 s with the tongue interface, which is 95.6% longer than the JACO joystick (36.5 s).

An ANOVA test with pairwise comparison showed no statistically significant difference between the task completion time of the layouts with discrete commands (Figure 15 - left). This can be due to the time cost of mode switching (2.1 s for each mode switching), which counteracted the contribution of increasing the button sizes. As the mode switching may add to the interface complexity and confuse the user [72], it was concluded that a control layout with a single mode is preferred. However, other mode switching methods may offer a faster and more efficient performance [111]. A significantly faster task completion (18%, p=0.002) was

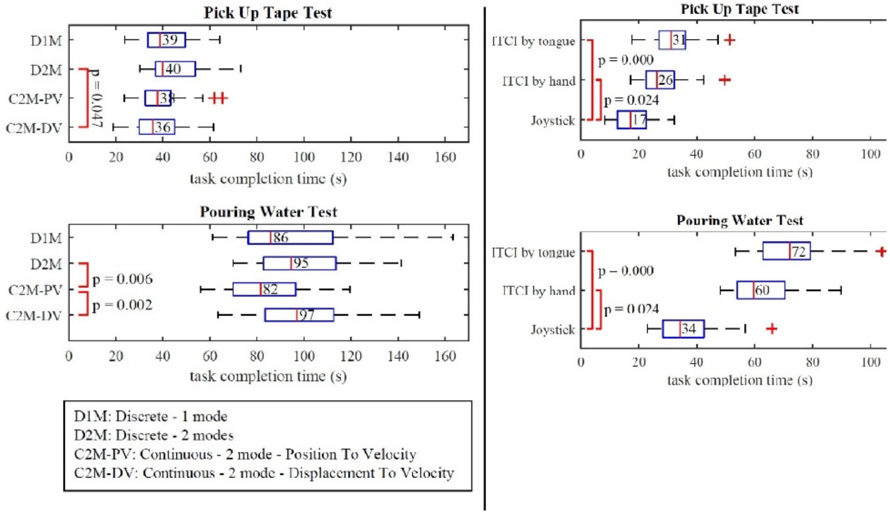


*Figure 16- **Left**: The task completion time of the PUT and PW tasks for the four tongue-based control layouts in the second session. **Right**: the three control schemes in the third session (Adopted from [19], 0018-9294 © 2021 IEEE).*

achieved by the P2V joystick emulation method (C2M-PV layout) compared to the D2V method (C2M-DV layout) for the PW task. However, the two methods performed similarly for the PUT task (Figure 15 - left). The D2V may provide a faster fine positioning as compared to P2V; however, the participants performed gross motion faster with the P2V (Table I and Fig. 7 in *Study I*).

To investigate the difference between the performance of the discrete and the continuous joystick commands, the D2M layout was compared with the two C2M layouts, which all incorporated two control modes. For both tasks, a significantly shorter task completion was found time between the D2M and one of the C2M layouts (16%, p=0.006 for the PW task, 11%, p=0.047 for the PUT task). Furthermore, a significantly shorter moving time and a smaller number of issued commands for the PUT task were achieved by both C2M layouts as compared to the D2M layout.

The participants completed both tasks with the standard JACO joystick significantly faster than with the ITCI based control layouts (Figure 15 - right). These results could be expected, as the participants were more familiar with a hand-controlled joystick. Furthermore, the default maximum linear velocity of the JACO ARM was set to 20 cm/s for the standard joystick but only to 7 cm/s for tongue control. In addition, the JACO joystick afforded simultaneous 3D control that led to a shorter trajectory and faster completion of the tasks.

The participants rated the task load (NASA TLX) of performing the tasks with the ITCI in hand similar to the JACO joystick with no significant difference. However, using the ITCI by tongue required more effort and was physically more demanding (Fig. 11 in *Study I* [19]).

The study showed that the 2D continuous joystick based on the novel interpolation method improved the performance of assistive robotic interfaces based on the ITCI as compared to virtual buttons. The tongue interface can enable individuals with tetraplegia to control a seven-DOF ARM fully and efficiently and perform ALDs such as pouring water in a cup or picking up objects. The overall performance of the tongue control layouts was relatively comparable with the JACO joystick, with 60.1% longer completion time of the PUT task and 68.8% longer completion of the PW task

4.2. STUDY II

Title: Eyes-free tongue gesture and tongue joystick control of a five DOF upper-limb exoskeleton for severely disabled individuals [20]

Authors: Mostafa Mohammadi, Hendrik Knoche, Mikkel Thøgersen, Stefan Hein Bengtson, Muhammad Ahsan Gull, Bo Bentsen, Michael Gaihede, Kåre Eg Severinsen, Lotte NS Andreasen Struijk

Journal: Frontiers in Neuroscience, vol. 15, pp. 1728, Nov. 2021, doi: 10.3389/fnins.2021.739279

This study aimed to demonstrate and evaluate tongue control of the EXOTIC ULE using the ITCI. Furthermore, eyes-free use of the ITCI was investigated for the first time, as in an eyes-free setup, the user can focus the visual attention on the exoskeleton and the target object instead of a screen. Two control layouts for the EXOTIC ULE were compared, one based on continuous joystick controls (section 3.4, Figure 10) and the other based on tongue gestures (section 3.5, Figure 11). In addition, the time to issue the control commands and the number of fault commands before selecting a target command in both layouts were compared.

Ten able-bodied volunteers with no prior experience with the ITCI participated in the main study. Furthermore, one individual with complete functional tetraplegia participated in a case study for testing the tongue control of the exoskeleton.

The able-bodied participants used the tongue interface to control the EXOTIC ULE and perform a drinking task and a button task with two conditions: one with the visual feedback of the ITCI presented on a screen in front of the participants (Figure 16) and the other without any visual feedback. Thus, in total, the tasks were performed with four conditions: with the joystick-based layout with and without visual feedback, and with the gesture-based layout with and without visual feedback. The drinking task consisted of moving the hand from a home position (similar to mounting the hand on the wheelchair armrest) toward a bottle located on a table in front of the participant, picking up the bottle, moving it towards the mouth, and finally putting the bottle back on the table. The button task consisted of selecting a command (on the ITCI layout) presented to the participant with an auditory cue. The command was to be selected as fast as possible and sustained for one second. In each condition, 50 commands, including five repetitions of the ten exoskeleton control commands (up, down, left, right, forward, backward, rotate left, rotate right, open hand, close hand) were presented randomly.

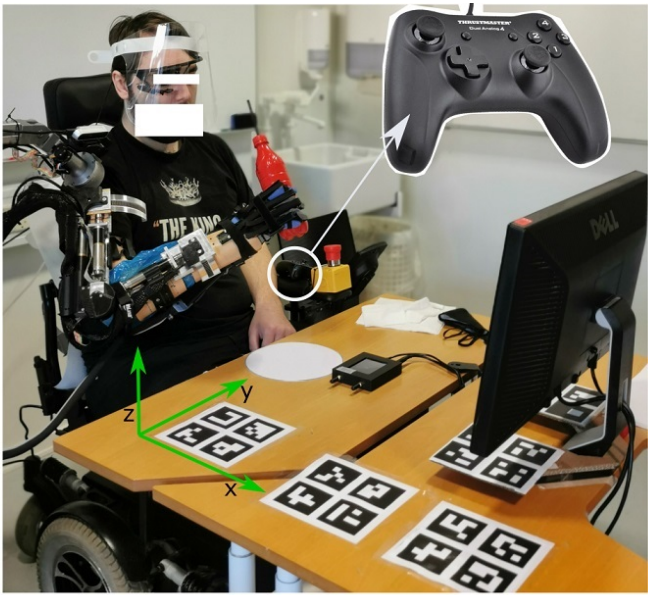


Figure 17- The participants sat on a wheelchair in front of a table and donned the exoskeleton on the right arm. An emergency stop button and the gamepad were mounted on the left wheelchair armrest.

Outcome measures including the task completion time, the number of issued commands, and the trajectory length for the drinking task were measured. In addition, subjective measures including NASA TLX evaluated the perceived task load of performing the drinking task, and INTUI questionnaire to measure the interface intuitiveness. Furthermore, an eye-tracker (Pupil Labs, Germany) measured the time that the participants spent looking at the screen while controlling the exoskeleton. For the button task, the time to select the commands and the number of fault commands issued before selecting the target command were measured.

The study with the able-bodied participants consisted of three experimental sessions. In the first session, the participants performed three repetitions of the drinking task using the joystick-based layout and the gesture-based layout with visual feedback, in order to train the use of the interfaces and the exoskeleton control. In the second session, three repetitions of the drinking task and the button tasks were performed with the two control layouts, both with and without visual feedback. In the third session, in addition to performing the same trials as in the second session, the participants performed three repetitions of the drinking task using a hand-controlled gamepad (Figure 16) to create a baseline for comparing the performance of the tongue interface. Furthermore, the participants filled the two questionnaires at the end of each condition and after using the gamepad (Figure 5 in *Study II*).

The case study was performed after the main study, where none of the able-bodied participants reported any discomfort, pain, or soreness after the experiment. The experiment was conducted at the Spinal Cord Injury Centre of Western Denmark and consisted of two sessions over two consecutive days. On the first day, the participant trained the tongue interface by controlling a computer simulation of the exoskeleton and performing grasping tasks for about two hours. In the second session, eight repetitions of the drinking task were performed. The to simplify the experiment for the user, the participant used the joystick-based ITCI layout only, and the ITCI visual feedback was presented on a screen in front of him at all times.

All participants successfully controlled the exoskeleton with the tongue interface and completed the drinking and button tasks. In the main study, the control layout type (joystick-based and gesture-based) did not produce any significant effect on the performance measures as assessed through a two-way ANOVA. However, removing the screen (visual feedback unavailable when the joystick-based layout was used resulted in a significantly longer task completion time (45.3%simple main effect analysis). On the contrary, the gesture-based layout performed similarly with and without the visual feedback.

The able-bodied participants completed the drinking task significantly faster (35%) with the gamepad as compared to the joystick-based layout with visual feedback

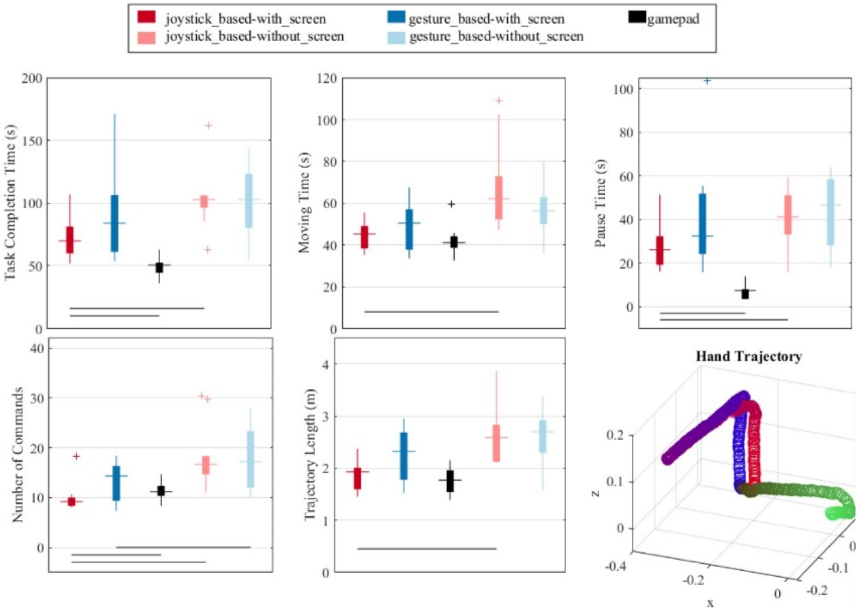


Figure 18- Outcome measures of the drinking task with the ITCI in the four conditions and with the gamepad. A significant difference between two conditions is depicted with a black line on the button of the charts [20].

(assessed by paired t-test, Figure 17). The pause time between commands was the main factor contributing to this difference as no significant difference was found between the moving times (Figure 17). The gamepad's performance was only compared with the joystick-based layout as both interfaces provided a continuous joystick for controlling the hand in a horizontal plane, and only with visual feedback as the participant could see the buttons in both setups.

The participant with complete functional tetraplegia successfully finished all the trials with the same number of issued commands (11.5 commands) and only 5.6% longer task completion time (90.4 s vs. 85.6 s) than the able-bodied participants.

The study presented the first single modal multi-DOF ULE interface that can enable individuals with complete functional tetraplegia to control the ULE fully and continuously and thereby perform ADLs such as drinking independently. Even though the system was only tested for a drinking task, it allows for the performance of any ADLs as long as the physical constraint of the ULE allows for it. Furthermore, the study for the first time showed that tongue control of assistive robotics such as ULEs can be achieved without visual feedback for both the studied layouts and even without worsening the performance when the gesture-based layout was used.

4.1. STUDY III

Title: Tongue control of a five-DOF upper-limb exoskeleton rehabilitates drinking and eating for individuals with severe disabilities [103]

Authors: Mostafa Mohammadi, Hendrik Knoche, Mikkel Thøgersen, Stefan Hein Bengtson, Frederik Victor Kobbelgaard, Muhammad Ahsan Gull, Bo Bentsen, Kåre Eg Severinsen, Benjamin Yamin Ali Khan, Lotte NS Andreasen Struijk

Journal: Submitted to the International Journal of Human-Computer Studies, Dec. 2021

The aim of this study was to evaluate tongue control of the five-DOF EXOTIC ULE in a clinical setup with users with tetraplegia. The study demonstrated the ultimate goal of this PhD, which was to develop a tongue interface for ULEs for individuals with severe to complete tetraplegia that can facilitate independent performance of highly prioritized ADLs such as eating snacks and drinking independently.

Ten individuals with tetraplegia controlled the EXOTIC ULE with the joystick-based control layout (Figure 10) and performed a drinking task similar to the one performed by able-bodied participants in *Study II*, and in addition, a snacking task was performed. The snacking task resembled the drinking task, except that a plastic strawberry was grasped instead of the bottle. This task required a finer control of the hand position and orientation than the drinking task. Furthermore, the hand was

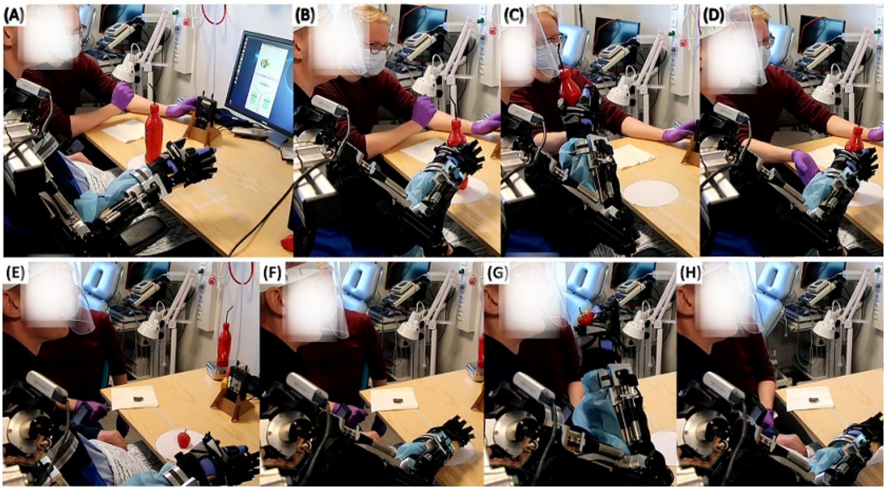


Figure 19- ***A-D****: The drinking task.* ***E-H****: The snacking task [103].*

moved closer to the face to touch the face shield with the strawberry (Figure 20). The same qualitative and quantitative outcome measures as in *Study II* were recorded.

The experiment consisted of three sessions and was conducted at the Spinal Cord Injury Centre of Western Denmark. In the first session, the participants trained the tongue control by controlling a computer simulation of the EXOTIC ULE and performing four different grasping tasks for approximately two hours. In the second session, the participants performed eight repetitions of the drinking task and eight repetitions of the snacking task. Finally, the third session aimed to evaluate the learning effect, and only three repetitions of the drinking task were performed.

All participants successfully controlled the exoskeleton with the tongue interface and performed the two tasks. The drinking task lasted 149.6 s in the second session and 122.9 s in the third session (median), which shows an 18% shorter task completion

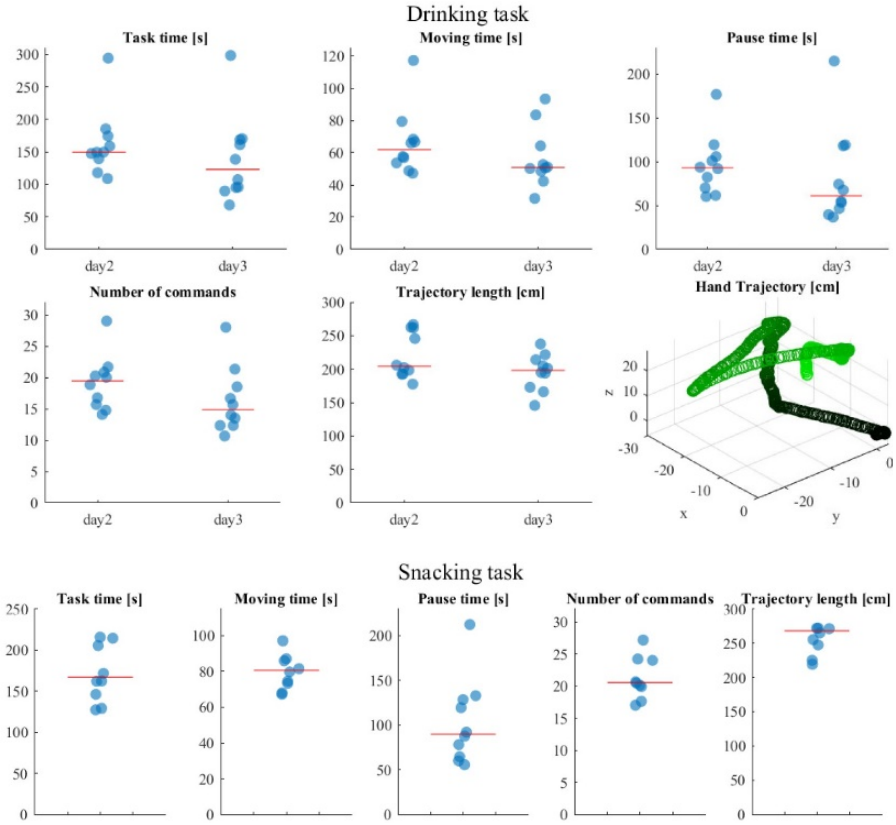


*Figure 21- The drinking task (**top**) and snacking task (**bottom**) outcome measures. All ten data points are depicted, and a red line shows the median [103].*

time after one additional day of using the system. A median task completion time of 167.0 s was achieved for the snacking task in the second session. The INTUI questionnaire revealed average intuitiveness of 5.2 on a scale between 1 (low) and 7 (high). Furthermore, the participants rated the task load by 40/100 (NASA TLX), where a higher score shows a higher task load.

The study showed that ten individuals with tetraplegia, even with complete functional tetraplegia, could fully control the EXOTIC ULE with the ITCI and perform ADLs such as drinking and snaking. Furthermore, the study proved the safety and effectiveness of the system as the participants did not report any side effects, pain, or discomfort after the experiment.

CHAPTER 5. DISCUSSION

5.1. MAIN FINDINGS

This PhD thesis presented the design and development of tongue interfaces for assistive robotics based on the ITCI. Several processing methods were developed and tested to obtain user control inputs from the 18 ITCI sensors. Four methods for sensors data interpolation were compared, showing that an accuracy of 1 mm in tracking the AU position can be achieved using the WAN method. With this approach, the PCBs performed as two touchpads instead of keypads, enabling the design of control layouts with virtual buttons of different sizes and shapes [100]. Like smartphones, a touchpad may provide more interaction possibilities such as gesture-based interaction and improve the user experience [112]. Furthermore, at the TKP area of the ITCI the AU position was measured with 34% higher accuracy than at the TMP area (Table 2). Thus, the TKP allowed for joystick emulation with a higher resolution and the possibility of designing smaller virtual buttons than the TMP.

Furthermore, a new method for identifying user input commands from the ITCI was developed. The method used boundary lines to divide areas on the TKP and TMP into virtual buttons (Figure 7). This method provided a novel platform for designing control layouts with buttons/joysticks of different sizes and shapes. On the contrary, the previous methods used thresholding the sensor activation levels or thresholding the XY position of the AU contact position, which allowed implementing button formed by a set of sensors or in rectangle shape. Further, this PhD thesis used a double-tap detection for mode switching for the first time to avoid dedicating a virtual button for this function. However, a study later showed that a faster mode switching was achieved with a virtual button compared to the double-tap [111].

The novel joystick emulation method that mapped AU displacement to a velocity command (D2V) provided a throughput of 0.93 bits/s, 15% higher than position to velocity mapping (P2V), for a multi-directional tapping test [100]. Furthermore, a faster fine positioning of JACO ARM was achieved by D2V [19]. This can be due to the floating origin of the D2V method (initial AU contact point), allowing for a longer line on the touchpads to determine the velocity between zero and the maximum value (Figure 6). On the contrary, dragging a line (issuing a velocity command by D2V) requires more time and is more complicated than just pointing (issuing a velocity command by P2V), which can describe the faster gross motion in JACO control by P2V than D2V [19].

Study I experimentally evaluated four ITCI-based control layouts designed based on the novel methods mentioned above with different features for interfacing JACO ARM with seven DOFs. The study showed that increasing the virtual button size on a control layout with the cost of adding a control mode did not improve the tongue control performance [19]. Thus, a single-mode control layout is preferred considering mode switching time and mental load [72]. Further, the study showed that a 2D continuous joystick emulation improved the performance of tongue robot control including faster task completion, shorter moving time, and fewer commands than discrete switch-like commands [19]. Therefore, this study was an essential step toward designing an optimized and high-performance interface for ULEs. We used JACO due to the unavailability of the EXOTIC ULE. However, similar outcomes can be expected as both effectors (EXOTIC and JACO) are controlled in a Cartesian coordinate frame through velocity commands and afford grasping.

Study I highlighted two challenges with tongue-controlling assistive robotics for performing ADLs. The first challenge was providing a high number of commands, not only for controlling a robot with a high number of DOFs but for other interactions such as mode switching. The second challenge was the distraction and the mental and physical load due to frequently switching visual attention between the robot and the screen. Therefore, the tongue gesture recognition method was developed to address these two challenges, as several studies on electronic devices with a small touchpad or touchscreen (smartphones, smartwatches, cameras, etc.) have shown gesture-based interaction can provide extra inputs in addition to virtual buttons and facilitate eyes-free control (Section 3.5). *Study II* confirmed that gesture-based interaction was less dependent on visual feedback [20]. Furthermore, the possibility to identify 46 tongue gestures makes gesture-based interaction a strong tool for the design of tongue-based interfaces.

The dynamic virtual buttons with a responsive color-coding (Section 3.4) were developed to achieve a one-mode control layout for the EXOTIC ULE. This method allowed implementing the buttons and joysticks for full control of all five DOFs of the EXOTIC ULE in a single mode with an easy manipulation of joysticks and buttons.

Study II was an essential step before a clinical evaluation of the tongue-exoskeleton interface. The study showed that the ITCI can provide efficient and safe control of a five-DOF ULE and allows for direct, full, and continuous control of all DOFs in a single control mode [20]. A drinking task was performed with the tongue interface at 65% of the speed of a hand-controlled gamepad [20]. Furthermore, *Study II* showed that the ITCI could be used for controlling ULEs and performing ADLs both with and without visual feedback [20].

The ultimate goal of this PhD, which was developing an efficient tongue-based ULE interface to enable individuals with complete functional tetraplegia to perform ADLs, was presented in *Study III.* Ten individuals with tetraplegia controlled a five-DOF ULE with the ITCI and performed a drinking and snacking task in a clinical study. The study showed that the system is safe and reliable and can rehabilitate performing ADLs [103].

Recruiting able-bodied participants is a common approach for evaluating assistive devices for disabled individuals, as experiments with able-bodied participants entail fewer risks, are easier to conduct, and in some cases, similar results can be achieved compared with studies recruiting participants with SCI. In particular, some studies that included both able-bodied and disabled participants for evaluating tongue interfaces reported comparable results [113][98], as tongue functionality usually remains intact after SCI due to cranial innervation of the tongue. The ten able-bodied participants in *Study II* [20] and the ten participants with tetraplegia in *Study III* [103] completed the drinking task in the second session of tongue controlling the EXOTIC ULE at a comparable speed (median task time of 85.6 s and 122.9 s respectively, 30% shorter for the able-bodied group). Furthermore, these two groups rated the task load of the drinking task (able-bodied:38.4/100, disabled: 40/100) and the intuitiveness of the tongue-ULE interface (able-bodied: 5.2/7, disabled: 5.4/7) similarly with no significant difference (paired t-test). The difference in the drinking time between the two groups can be due to the difference in the average participants' age (able-bodied: 24,7 years, disabled: 53.3 years) and the more experience of younger participants with using control interfaces, for example for video games.

The need for piercing the AU to the user's tongue may limit the user's adaptation of the ITCI system, as a study showed six participants from the 25 individuals with tetraplegia did not desire to pierce the AU for using the tongue interface [114]. Therefore, a modified version of the ITCI with no need for a piercing is under development [115]. Furthermore, the ITCI users can drink and speak with the ITCI mouthpiece inside the mouth with a discomfort between 1 to 3 on a 1-10 scale (1 = no discomfort, 10 = highest discomfort) [116], and even speak while controlling a wheelchair with the ITCI [117]. In addition, a dwell time of 0.6 s prevented unintended commands while speaking and drinking [118]. The ITCI mouthpiece may alter the user's speaking at the beginning of using the system. However, we observed a user who used a dental prosthesis before adopting the ITCI and embedding the ITCI in her dentures did not change her speaking. Overall, requiring a piercing seems to be the main limitation of the ITCI, which may be solved by developing the modified version that does not require a piercing [115].

The three main studies of this PhD thesis showed that the ITCI could provide full and continuous control of assistive robotics such as ARMs and ULEs. To our knowledge, no other studies have shown a control interface for a ULE that possess all the essential attributes (explained in Section 1.3) for empowering individuals with complete functional tetraplegia to independently perform ADLs outside a laboratory setup (Table 1 and Table 3). Even though the interface was only tested for performing drinking and snacking, it allows for any possible motion and performing other ADLs as far as the exoskeleton workspace allows.

Table 3- Main features of the tongue-exoskeleton interface developed through this PhD.

Input modality	**System supported ADLs for complete functional tetraplegia**	**Actuated DOFs**	**Number of commands**	**Single modal**	**Continuous**	**Direct**	**Full control**	**Interface usable for complete functional tetraplegia**	**Calibration and algorithm training**	**Clinical study sample size**	**Aesthetic cost**	**Subjective user feedback**
ITCI	✓	5	10D or 2D+4J	✓	✓	✓	✓	✓	Not required	10	Not visible	✓

Another tongue interface, the Tongue Drive System, was recently used for controlling two DOFs of a ULE, enabling the hand to move in a horizontal plane [80]. However, the system did not support ADLs for complete functional tetraplegia due to the lack of grasping function and the insufficient number of actuated DOFs, and only a 2D reaching task was performed.

The ITCI provided enough commands for fully controlling the five DOFs of the EXOTIC ULE in a single control mode. Providing full control of a ULE is crucial for utilizing the ULE capabilities and performing arbitrary ADLs outside a laboratory setup, contrary to automation through predefined trajectories or camera-based object detection that limit the user to a restricted performance and setups.

Using the ITCI did not require constantly looking at a screen while controlling the exoskeleton (direct control), and the users could use the system even without any visual feedback on a screen [20]. Depending on a screen for issuing control commands may reduce the safety and usability of the system, for examples interfaces based on eye-tracking [82] or SSVEP [38], as the user needs to frequently switch the gaze between the screen and the environment or may miss some information by seeing the environment through the screen.

Three studies proposed ULEs that could enable an individual with complete functional tetraplegia to perform an ADL, of which two use EEG [37] [38] and one used EEG and EOG for controlling the ULEs [36]. However, these interfaces only allowed initiating predefined and automated movements and were limited to a single ADL in a fixed setup. Thus, the systems were not suitable for assisting the users outside a laboratory setup. Furthermore, all three interfaces required training and calibration of the EEG processing algorithms. In addition, the three studies used an EEG cap, which can affect the normal appearance of the user. An alternative to EEG caps for recording brain potentials is implanting electrodes inside the skull. Nevertheless, implanted electrodes mostly required wearing a headset [75][119]. An individual with tetraplegia fully controlled a ULE with four DOFs at each arm 16 months after implanting a set of 128 electrodes over the sensorimotor area of the brain [75]. However, the system did not support ADL, and only a reach-and-touch task was performed with a maximum success rate of 71.4% for controlling the exoskeleton in a 3D space [75]. In addition to a long training for using the interface (16 months for full control), the interface required recalibration at least after seven weeks.

Even though ULE interfaces based on the user's residual arm functionality (EMG/FMG, force/torque control, finger-controlled joysticks and buttons) can provide full, direct, and continuous control of a ULE (Table 1), individuals with complete functional tetraplegia who may be the most in need cannot use these interfaces.

5.2. CONCLUSION

This PhD study developed a high-performance tongue interface for ULEs for individuals with severe tetraplegia. Through three main studies recruiting 22 able-bodied and ten individuals with tetraplegia and recording data of tongue controlling assistive robotics in 96 experimental sessions, different tongue interface features and performance were investigated. The PhD resulted in a deeper understanding of control interface design factors and based on them, a high-performance tongue interface for the five-DOF EXOTIC ULE was implemented. The interface was further tested in a clinical study by individuals with tetraplegia. The conclusions of this dissertation according to the aims and objectives are:

- Objective 1: The novel methods for tracking the AU contact position and identification of user control commands through the boundary lines method and tongue-gesture recognition established a platform for designing tongue control interfaces based on ITCI for assistive robotics.
- Objective 2: Experimental evaluation of four control layouts for a seven-DOF ARM through *Study I* revealed that continuous joystick emulation improved the ARM control performance compared to virtual buttons.
- Objective 3: A tongue interface for the EXOTIC ULE was developed and tested. The interface provided full, direct, and continuous control of the ULE and utilized dynamic buttons to avoid mode switching.
- Objective 4: Clinical evaluation of the tongue interface of the EXOTIC ULE proved the efficiency and safety of the system for empowering individuals with tetraplegia to perform highly prioritized ADLs, with positive feedback from the end-users.

Furthermore, *Study I* and II showed that the ITCI-based interface for the EXOTIC ULE was the first and the only ULE interface that possessed all the required functional attributes (described in Section 1.3 and Table 1) for empowering individuals with complete functional tetraplegia to perform ADLs independently in an efficient and robust manner.

5.3. FUTURE PERSPECTIVES

A tongue gesture recognition algorithm based on a state-machine approach was proposed, which identified a set of six gestures with 94.3% and 23 gestures with 72.3% accuracy. However, this accuracy can be improved using more advanced recognition methods. Therefore, future work will implement and compare different recognition methods to improve tongue gesture recognition accuracy.

A limitation of the ITCI system is the need for piercing the AU on the tongue, which is not desirable by one-fourth of the potential users [114]. In a pilot study, a non-invasive approach for using the ITCI system was presented, and promising results were obtained. The study showed that a naïve subject performed a multi-dimensional tapping and a text typing task with the non-invasive approach similar to the current invasive approach [115]. The non-invasive approach will be further developed and tested as an alternative for the current system.

Study I showed that the JACO ARM moved a shorter trajectory for performing the tasks when it was controlled with the standard JACO joystick compared to tongue control. Trajectory data showed that the participants used the 3D simultaneous control feature of the JACO joystick to move in the 3D Cartesian space and reach a shorter trajectory (*Study I*, Fig. 10). However, a 2D touchpad like the ITCI only affords 2D simultaneous control. A possible approach to providing 3D simultaneous control of assistive robots for individuals with tetraplegia is to add another input modality such as EMG to the tongue interface.

LITERATURE LIST

[1] P. J. Manns and K. E. Chad, "Components of Quality of Life for Persons With a Quadriplegic and Paraplegic Spinal Cord Injury," 2001.

[2] P. and W. H. O. and others Bickenbach, Jerome and Officer, Alana and Shakespeare, Tom and von Groote, "International Perspectives on Spinal Cord Injury," 2013.

[3] M. Wyndaele and J. J. Wyndaele, "Incidence, prevalence and epidemiology of spinal cord injury: What learns a worldwide literature survey?," *Spinal Cord*, vol. 44, no. 9, pp. 523–529, Sep. 2006.

[4] B. Bjørnshave Noe, E. M. Mikkelsen, R. M. Hansen, M. Thygesen, and E. M. Hagen, "Incidence of traumatic spinal cord injury in Denmark, 1990-2012: A hospital-based study," *Spinal Cord*, vol. 53, no. 6. Nature Publishing Group, pp. 436–440, 08-Jun-2015.

[5] M. A. McColl, J. Walker, P. Stirling, R. Wilkins, and P. Corey, "Expectations of life and health among spinal cord injured adults," *Spinal Cord*, vol. 35, no. 12, pp. 818–828, 1997.

[6] T. T. Roberts, G. R. Leonard, and D. J. Cepela, "Classifications In Brief: American Spinal Injury Association (ASIA) Impairment Scale," *Clin. Orthop. Relat. Res.*, vol. 475, no. 5, p. 1499, May 2017.

[7] A. Rodríguez-Fernández, J. Lobo-Prat, and J. M. Font-Llagunes, "Systematic Review on Wearable Lower-Limb Exoskeletons for Gait Training in Neuromuscular Impairments."

[8] F. W. A. Van Asbeck, M. W. M. Post, and R. F. Pangalila, "An epidemiological description of spinal cord injuries in The Netherlands in 1994," *Spinal Cord 2000 387*, vol. 38, no. 7, pp. 420–424, Aug. 2000.

[9] A. R. Craig, K. M. Hancock, and H. G. Dickson, "A longitudinal investigation into anxiety and depression in the first 2 years following a spinal cord injury," *Paraplegia*, vol. 32, no. 10, pp. 675–679, 1994.

[10] A. Ubeda, J. M. Azorin, E. Ianez, and J. M. Sabater, "Eye-tracking interface based on artificial vision for robot controlling," in *Proceedings of the IASTED International Conference on Artificial Intelligence and Soft Computing, ASC 2009*, 2009, pp. 45–50.

[11] C. J. Anderson, L. C. Vogel, K. M. Chlan, R. Betz, and C. M. McDonald,

"Depression in Adults Who Sustained Spinal Cord Injuries as Children or Adolescents," *J. Spinal Cord Med.*, vol. 30, no. sup1, pp. S76–S82, 2016.

[12] K. D. Anderson, "Targeting Recovery: Priorities of the Spinal Cord-Injured Population," *J. Neurotrauma*, vol. 21, no. 10, 2004.

[13] F. V. Kobbelgaard, A. M. Kanstrup, and L. N. S. A. Struijk, "Exploring User Requirements for an Exoskeleton Arm Insights from a User-Centered Study with People Living with Severe Paralysis," in *IFIP Conference on Human-Computer Interaction*, 2021, vol. 12932 LNCS, pp. 312–320.

[14] NSCISC, "Spinal Cord Injury Facts and Figures at a Glance," Birmingham, 2021.

[15] T. Fendinge, "Håndbog for BPA-ordningen i Aarhus Borgerstyret Personlig Assistance Servicelovens § 96," 2021.

[16] K. Giannakouris, "Regional population projections EUROPOP2008: Most EU regions face older population profile in 2030," *Stat. Focus*, vol. 1, 2010.

[17] C.-S. Chung, H. Wang, and R. A. Cooper, "Functional assessment and performance evaluation for assistive robotic manipulators: Literature review," *J. Spinal Cord Med.*, vol. 36, no. 4, pp. 273–289, 2013.

[18] V. Maheu, P. S. Archambault, J. Frappier, and F. Routhier, "Evaluation of the JACO robotic arm: Clinico-economic study for powered wheelchair users with upper-extremity disabilities," in *IEEE International Conference on Rehabilitation Robotics*, 2011, pp. 1–5.

[19] M. Mohammadi, H. Knoche, and L. N. S. Andreasen Struijk, "Continuous tongue robot mapping for paralyzed individuals improves the functional performance of tongue-based robotic assistance," *IEEE Trans. Biomed. Eng.*, 2021.

[20] M. Mohammadi *et al.*, "Eyes-Free Tongue Gesture and Tongue Joystick Control of a Five DOF Upper-Limb Exoskeleton for Severely Disabled Individuals," *Front. Neurosci.*, vol. 15, p. 1728, Dec. 2021.

[21] C.-S. Chung and R. A. Cooper, "Literature Review of Wheelchair-Mounted Robotic Manipulation: User Interface and End-user Evaluation," *RESNA Annu. Conf.*, 2012.

[22] M. Beaudoin, J. Lettre, F. Routhier, P. S. Archambault, M. Lemay, and I. Gélinas, "Impacts of robotic arm use on individuals with upper extremity

disabilities: A scoping review," *Can. J. Occup. Ther.*, vol. 85, no. 5, pp. 397–407, Dec. 2018.

[23] G. J. Gelderblom *et al.*, "Cost-effectiveness of the MANUS robot manipulator," *Integr. Assist. Technol. Inf. age*, vol. 9, pp. 340–345, 2001.

[24] V. Longatelli *et al.*, "User-centred assistive SystEm for arm Functions in neUromuscuLar subjects (USEFUL): a randomized controlled study," *J. Neuroeng. Rehabil.*, vol. 18, no. 1, pp. 1–16, Dec. 2021.

[25] E. Ambrosini *et al.*, "Functional and usability assessment of a robotic exoskeleton arm to support activities of daily life," *Robotica*, vol. 32, pp. 1213–1224, 2014.

[26] A. Kumar and M. F. Phillips, "Use of powered mobile arm supports by people with neuromuscular conditions," vol. 50, no. 1, pp. 61–70, 2013.

[27] B. Koo *et al.*, "Design and evaluation of a hybrid passive and active Gravity Neutral Orthosis (GNO)," *Proc. 31st Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. Eng. Futur. Biomed. EMBC 2009*, pp. 1573–1576, 2009.

[28] J. Narayan, B. Kalita, and S. K. Dwivedy, "Development of Robot-Based Upper Limb Devices for Rehabilitation Purposes: a Systematic Review," *Augment. Hum. Res. 2021 61*, vol. 6, no. 1, pp. 1–33, Jan. 2021.

[29] A. R. C. Donati *et al.*, "Long-Term Training with a Brain-Machine Interface-Based Gait Protocol Induces Partial Neurological Recovery in Paraplegic Patients," *Sci. Reports 2016 61*, vol. 6, no. 1, pp. 1–16, Aug. 2016.

[30] A. M. Stewart, C. G. Pretty, M. Adams, and X. Q. Chen, "Review of Upper Limb Hybrid Exoskeletons," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 15169–15178, Jul. 2017.

[31] M. Gandolla *et al.*, "An assistive upper-limb exoskeleton controlled by multi-modal interfaces for severely impaired patients: development and experimental assessment," *Rob. Auton. Syst.*, vol. 143, p. 103822, Sep. 2021.

[32] L. N. A. Thøgersen, Mikkel and Gull, Muhammad Ahsan and Kobbelgaard, Frederik Victor and Mohammadi, Mostafa and Bengtson, Stefan Hein and Struijk, "EXOTIC-a discreet user-based 5 DoF upper-limb exoskeleton for individuals with tetraplegia," in *2020 IEEE 3rd International Conference on Mechatronics, Robotics and Automation*, 2020, pp. 1–5.

[33] M. Pazzaglia and M. Molinari, "The embodiment of assistive devices—from

wheelchair to exoskeleton," *Phys. Life Rev.*, vol. 16, pp. 163–175, Mar. 2016.

[34] M. A. Gull, S. Bai, and T. Bak, "A review on design of upper limb exoskeletons," *Robotics*, vol. 9, no. 1, p. 16, Mar. 2020.

[35] M. A. Gull *et al.*, "A 4-DOF Upper Limb Exoskeleton for Physical Assistance: Design, Modeling, Control and Performance Evaluation," *Appl. Sci. 2021, Vol. 11, Page 5865*, vol. 11, no. 13, p. 5865, Jun. 2021.

[36] M. Nann *et al.*, "Restoring Activities of Daily Living Using an EEG/EOG-Controlled Semiautonomous and Mobile Whole-Arm Exoskeleton in Chronic Stroke," *IEEE Syst. J.*, vol. 15, no. 2, pp. 2314–2321, Jun. 2021.

[37] M. Barsotti *et al.*, "A full upper limb robotic exoskeleton for reaching and grasping rehabilitation triggered by MI-BCI," in *IEEE International Conference on Rehabilitation Robotics*, 2015, vol. 2015-September, pp. 49–54.

[38] T. Sakurada, T. Kawase, K. Takano, T. Komatsu, and K. Kansaku, "A BMI-based occupational therapy assist suit: asynchronous control by SSVEP," *Front. Neurosci.*, vol. 7, no. 7 SEP, p. 172, Sep. 2013.

[39] K. C. Eldahan and A. G. Rabchevsky, "Autonomic dysreflexia after spinal cord injury: Systemic pathophysiology and methods of management," *Auton. Neurosci.*, vol. 209, pp. 59–70, Jan. 2018.

[40] L. van der Heide and L. de Witte, "The perceived functional benefit of dynamic arm supports in daily life," vol. 53, no. 6, pp. 1139–1150, 2016.

[41] K. Little *et al.*, "IMU-based assistance modulation in upper limb soft wearable exosuits," *IEEE Int. Conf. Rehabil. Robot.*, vol. 2019-June, pp. 1197–1202, Jun. 2019.

[42] E. Y. Chia *et al.*, "Velocity Field based Active-Assistive Control for Upper Limb Rehabilitation Exoskeleton Robot," *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 1742–1748, May 2020.

[43] L. He, C. Xiong, K. Liu, J. Huang, C. He, and W. Chen, "Mechatronic Design of a Synergetic Upper Limb Exoskeletal Robot and Wrench-based Assistive Control," *Artic. J. Bionic Eng.*, vol. 15, pp. 247–259, 2018.

[44] S. Charoenseang and S. Panjan, "4 DOF Exoskeleton Robotic Arm System for Rehabilitation and Training," *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 10917 LNCS, pp.

147–157, Jul. 2018.

[45] Q. Wu and X. Wang, “Development of an upper limb exoskeleton for rehabilitation training in virtual environment,” *IEEE Int. Conf. Multisens. Fusion Integr. Intell. Syst.*, vol. 2017-November, pp. 174–179, Dec. 2017.

[46] D. Sui, J. Fan, H. Jin, X. Cai, J. Zhao, and Y. Zhu, “Design of a wearable upper-limb exoskeleton for activities assistance of daily living,” in *IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM*, 2017, pp. 845–850.

[47] S. Bai, S. Christensen, and M. R. U. Islam, “An upper-body exoskeleton with a novel shoulder mechanism for assistive applications,” *IEEE/ASME Int. Conf. Adv. Intell. Mechatronics, AIM*, pp. 1041–1046, Aug. 2017.

[48] E. Trigili *et al.*, “Design and experimental characterization of a shoulder-elbow exoskeleton with compliant joints for post-stroke rehabilitation,” *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 4, pp. 1485–1496, Aug. 2020.

[49] C. Liu and J. Song, “Servo-assisted Control of a 7-DOF Exoskeleton for Upper Limb Rehabilitation,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 252, no. 2, p. 022079, Apr. 2019.

[50] T. Petrič, L. Peternel, J. Morimoto, and J. Babič, “Assistive arm-exoskeleton control based on human muscular manipulability,” *Front. Neurorobot.*, vol. 13, p. 30, 2019.

[51] T. Chen, R. Casas, and P. S. Lum, “An Elbow Exoskeleton for Upper Limb Rehabilitation with Series Elastic Actuator and Cable-driven Differential,” *IEEE Trans. Robot.*, vol. 35, no. 6, p. 1464, Dec. 2019.

[52] N. Lotti *et al.*, “Adaptive model-based myoelectric control for a soft wearable arm exosuit: A new generation of wearable robot control,” *IEEE Robot. Autom. Mag.*, vol. 27, no. 1, pp. 43–53, Mar. 2020.

[53] B. Schabron, J. Desai, and Y. Yihun, “Wheelchair-Mounted Upper Limb Robotic Exoskeleton with Adaptive Controller for Activities of Daily Living,” *Sensors 2021, Vol. 21, Page 5738*, vol. 21, no. 17, p. 5738, Aug. 2021.

[54] P. T. C. Straathof *et al.*, “Design and control of the A-Arm: An active planar arm support for adults with Duchenne muscular dystrophy,” *Proc. IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics*, vol. 2016-July, pp. 1242–1247, Jul. 2016.

[55] C. Nam *et al.*, "An Exoneuromusculoskeleton for Self-Help Upper Limb Rehabilitation After Stroke," *https://home.liebertpub.com/soro*, Dec. 2020.

[56] A. Malik Mohd Ali *et al.*, "Preliminary Design of a Robotic Exoskeleton for Arm Rehabilitation," *J. Phys. Conf. Ser.*, vol. 1049, no. 1, p. 012067, Jul. 2018.

[57] M. Raza, U. Islam, and S. Bai, "Intention Detection for Dexterous Human Arm Motion with FSR Sensor Bands."

[58] R. A. R. C. Gopura, K. Kiguchi, and Y. Yi, "SUEFUL-7: A 7DOF upper-limb exoskeleton robot with muscle-model-oriented EMG-based control," *2009 IEEE/RSJ Int. Conf. Intell. Robot. Syst. IROS 2009*, pp. 1126–1131, Dec. 2009.

[59] J. L. Ren, Y. H. Chien, E. Y. Chia, L. C. Fu, and J. S. Lai, "Deep learning based motion prediction for exoskeleton robot control in upper limb rehabilitation," *Proc. - IEEE Int. Conf. Robot. Autom.*, vol. 2019-May, pp. 5076–5082, May 2019.

[60] H. T. Peters, S. J. Page, and A. Persch, "Giving Them a Hand: Wearing a Myoelectric Elbow-Wrist-Hand Orthosis Reduces Upper Extremity Impairment in Chronic Stroke," *Arch. Phys. Med. Rehabil.*, 2016.

[61] P. Cattarello and R. Merletti, "Characterization of dry and wet Electrode-Skin interfaces on different skin treatments for HDsEMG," *2016 IEEE Int. Symp. Med. Meas. Appl. MeMeA 2016 - Proc.*, Aug. 2016.

[62] "iFloat Powered Assist," *Assistive Innovations*. [Online]. Available: https://www.assistive-innovations.com/en/arm-supports/ifloat-e. [Accessed: 29-Dec-2021].

[63] S. D. Gasperina *et al.*, "Multi-Modal Human-Machine Control Interfaces of Upper Limb Motorized Exoskeletons for Severely Impaired Patients," in *Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2018, vol. 2018-Augus, pp. 491–496.

[64] N. A. Bhagat *et al.*, "Design and optimization of an EEG-based brain machine interface (BMI) to an upper-limb exoskeleton for stroke survivors," *Front. Neurosci.*, vol. 10, no. MAR, Mar. 2016.

[65] D. Brauchle, M. Vukelic, R. Bauer, and A. Gharabaghi, "Brain state-dependent robotic reaching movement with a multi-joint arm exoskeleton:

combining brain-machine interfacing and robotic rehabilitation," *Front. Hum. Neurosci.*, vol. 9, Oct. 2015.

[66] A. O. Andrade, G. Bourhis, E. Losson, C. G. Pinheiro, E. L. Naves, and P. Pino, "Alternative communication systems for people with severe motor disabilities: a survey," *Biomed. Eng. Online*, vol. 10, no. 1, p. 31, 2011.

[67] M. S. Al-Quraishi, I. Elamvazuthi, S. A. Daud, S. Parasuraman, and A. Borboni, "EEG-Based Control for Upper and Lower Limb Exoskeletons and Prostheses: A Systematic Review," *Sensors 2018, Vol. 18, Page 3342*, vol. 18, no. 10, p. 3342, Oct. 2018.

[68] A. Frisoli *et al.*, "A new gaze-BCI-driven control of an upper limb exoskeleton for rehabilitation in real-world tasks," *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.*, vol. 42, no. 6, pp. 1169–1179, 2012.

[69] A. Al Bakri, M. Y. Lezzar, M. Alzinati, K. Mortazavi, W. Shehieb, and T. Sharif, "Intelligent Exoskeleton for Patients with Paralysis," *2018 IEEE 9th Annu. Inf. Technol. Electron. Mob. Commun. Conf. IEMCON 2018*, pp. 189–193, Jan. 2019.

[70] S. H. Bengtson, T. Bak, L. N. S. Andreasen Struijk, and T. B. Moeslund, "A review of computer vision for semi-autonomous control of assistive robotic manipulators (ARMs)," *Disabil. Rehabil. Assist. Technol.*, pp. 1–15, Jul. 2019.

[71] D. J. Kim *et al.*, "How Autonomy Impacts Performance and Satisfaction: Results from a Study with Spinal Cord Injured Subjects Using an Assistive Robot," *IEEE Trans. Syst. Man, Cybern. Part A Syst. Humans*, 2012.

[72] L. V. Herlant, R. M. Holladay, and S. S. Srinivasa, "Assistive teleoperation of robot arms via automatic time-optimal mode switching," *ACM/IEEE Int. Conf. Human-Robot Interact.*, vol. 2016-April, pp. 35–42, Apr. 2016.

[73] N. A. Bhagat *et al.*, "Design and optimization of an EEG-based brain machine interface (BMI) to an upper-limb exoskeleton for stroke survivors," *Front. Neurosci.*, vol. 10, no. MAR, 2016.

[74] T. Kawase, T. Sakurada, Y. Koike, and K. Kansaku, "A hybrid BMI-based exoskeleton for paresis: EMG control for assisting arm movements," *J. Neural Eng.*, vol. 14, no. 1, p. 016015, Jan. 2017.

[75] A. L. Benabid *et al.*, "An exoskeleton controlled by an epidural wireless brain–machine intdemoerface in a tetraplegic patient: a proof-of-concept

nstration," *Lancet Neurol.*, vol. 18, no. 12, pp. 1112–1122, Dec. 2019.

[76] E. Kandel, J. Schwartz, T. Jessell, and S. Siegelbaum, *Principles of neural science*. New York: McGraw-hill, 2000.

[77] L. N. S. A. Struijk, "An Inductive Tongue Computer Interface for Control of Computers and Assistive Devices," *IEEE Trans. Biomed. Eng.*, vol. 53, no. 12, pp. 2594–2597, 2006.

[78] M. Ghovanloo, "Tongue operated assistive technologies," in *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings*, 2007, pp. 4376–4379.

[79] L. N. S. A. Struijk *et al.*, "Wireless intraoral tongue control of an assistive robotic arm for individuals with tetraplegia," *J. Neuroeng. Rehabil.*, vol. 14, no. 1, p. 110, Nov. 2017.

[80] Z. Zhang, B. I. Prilutsky, A. J. Butler, M. Shinohara, and M. Ghovanloo, "Design and Preliminary Evaluation of a Tongue-Operated Exoskeleton System for Upper Limb Rehabilitation," *Int. J. Environ. Res. Public Heal. 2021, Vol. 18, Page 8708*, vol. 18, no. 16, p. 8708, Aug. 2021.

[81] X. Huo, J. Wang, and M. Ghovanloo, "A magneto-inductive sensor based wireless tongue-computer interface," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 16, no. 5, pp. 497–504, Oct. 2008.

[82] S. Dalla Gasperina *et al.*, "Multi-Modal Human-Machine Control Interfaces of Upper Limb Motorized Exoskeletons for Severely Impaired Patients," *Proc. IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics*, vol. 2018-Augus, pp. 491–496, Oct. 2018.

[83] B. Wodlinger, J. E. Downey, E. C. Tyler-Kabara, A. B. Schwartz, M. L. Boninger, and J. L. Collinger, "Ten-dimensional anthropomorphic arm control in a human brain-machine interface: Difficulties, solutions, and limitations," *J. Neural Eng.*, vol. 12, no. 1, p. 016011, Dec. 2015.

[84] E. R. Lontis *et al.*, "Development and functional demonstration of a wireless intraoral inductive tongue computer interface for severely disabled persons," *Disabil. Rehabil. Assist. Technol.*, vol. 12, no. 6, pp. 631–640, 2016.

[85] "TKS-Technology." [Online]. Available: http://tks-technology.dk/.

[86] C. Yarbrough *et al.*, "Tongue-controlled robotic rehabilitation: A feasibility study in people with stroke," *J. Rehabil. Res. Dev.*, vol. 53, no. 6, pp. 989–

1006, 2017.

[87] N. Johan *et al.*, “Preliminary design of an Intention-based sEMG-controlled 3 DOF upper limb exoskeleton for assisted therapy in activities of daily life in patients with hemiparesis,” *Proc. IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics*, vol. 2020-November, pp. 292–297, Nov. 2020.

[88] Z. Li, J. Li, S. Zhao, Y. Yuan, Y. Kang, and C. L. P. Chen, “Adaptive Neural Control of a Kinematically Redundant Exoskeleton Robot Using Brain-Machine Interfaces,” *IEEE Trans. Neural Networks Learn. Syst.*, pp. 1–14, 2018.

[89] D. C. Irimia, M. S. Poboroniuc, F. Serea, A. Baciu, and R. Olaru, “Controlling a FES-EXOSKELETON rehabilitation system by means of brain-computer interface,” in *2016 International Conference and Exposition on Electrical and Power Engineering (EPE)*, 2016, pp. 352–355.

[90] J. Webb, Z. G. Xiao, K. P. Aschenbrenner, G. Herrnstadt, and C. Menon, “Towards a portable assistive arm exoskeleton for stroke patient rehabilitation controlled through a brain computer interface,” in *Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2012, pp. 1299–1304.

[91] E. R. Lontis, B. Bentsen, M. Gaihede, and L. N. S. Andreasen Struijk, “Sensor Activation for Wheelchair Driving in Confined Spaces with a Tongue Controlled Oral Interface,” in *Proceedings of the International Convention on Rehabilitation Engineering & Assistive Technology*, 2016, pp. 15:1--15:4.

[92] D. Johansen, C. Cipriani, D. B. Popovic, and L. N. S. A. Struijk, “Control of a Robotic Hand Using a Tongue Control System-A Prosthesis Application,” *IEEE Trans. Biomed. Eng.*, vol. 63, no. 7, pp. 1368–1376, 2016.

[93] M. Mohammadi *et al.*, “Controlling a drone by the tongue – A pilot study on drone based facilitation of social activities and sports for people with complete tetraplegia,” in *Converging Clinical and Engineering Research on Neurorehabilitation III*, 2019, vol. 21, pp. 523–527.

[94] S. R. Maloney, “Wireless intraoral controller disposed in oral cavity with electrodes to sense E.M.G. signals produced by contraction of the tongue,” 28-Sep-1990.

[95] E. R. Lontis, H. A. Caltenco, B. Bentsen, H. V. Christensen, M. E. Lund, and L. N. S. Andreasen Struijk, “Inductive pointing device for tongue control system for computers and assistive devices,” in *Proceedings of the 31st*

Annual International Conference of the IEEE Engineering in Medicine and Biology Society: Engineering the Future of Biomedicine, EMBC 2009, 2009, pp. 2380–2383.

[96] M. E. Lund, H. Vie Christiensen, H. A. Caltenco, E. R. Lontis, B. Bentsen, and L. N. S. Andreasen Struijk, “Inductive tongue control of powered wheelchairs,” *2010 Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBC’10*, pp. 3361–3364, 2010.

[97] E. R. Lontis, B. Bentsen, M. Gaihede, F. Biering-Sorensen, and L. N. S. A. Struijk, “Wheelchair Control with Inductive Intra-Oral Tongue Interface for Individuals with Tetraplegia,” *IEEE Sens. J.*, vol. 21, no. 20, pp. 22878–22890, Oct. 2021.

[98] L. N. S. Andreasen Struijk, B. Bentsen, M. Gaihede, and E. R. Lontis, “Error-Free Text Typing Performance of an Inductive Intra-Oral Tongue Computer Interface for Severely Disabled Individuals,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 11, pp. 2094–2104, Nov. 2017.

[99] L. N. S. A. Struijk, E. R. Lontis, B. Bentsen, H. V. Christensen, H. A. Caltenco, and M. E. Lund, “Fully integrated wireless inductive tongue computer interface for disabled people,” in *Proceedings of the 31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society: Engineering the Future of Biomedicine, EMBC 2009*, 2009, pp. 547–550.

[100] M. Mohammadi, H. Knoche, M. Gaihede, B. Bentsen, and L. N. S. Andreasen Struijk, “A high-resolution tongue-based joystick to enable robot control for individuals with severe disabilities,” in *IEEE International Conference on Rehabilitation Robotics*, 2019, vol. 2019-June.

[101] H. A. Caltenco, E. R. Lontis, and L. N. S. Andreasen Struijk, “Fuzzy inference system for analog joystick emulation with an inductive tongue-computer interface,” in *IFMBE Proceedings*, 2011, vol. 34 IFMBE, pp. 191–194.

[102] H. A. Caltenco, E. R. Lontis, S. A. Boudreau, B. Bentsen, J. Struijk, and L. N. S. Andreasen Struijk, “Tip of the tongue selectivity and motor learning in the palatal area,” *IEEE Trans. Biomed. Eng.*, vol. 59, no. 1, pp. 174–182, Jan. 2012.

[103] M. Mohammadi *et al.*, “Tongue control of a five-DOF upper-limb exoskeleton rehabilitates drinking and eating for individuals with severe disabilities,” *Int. J. Hum. Comput. Stud.*, 2022.

[104] A. K. Karlson, B. B. Bederson, and J. SanGiovanni, “AppLens and LaunchTile: Two Designs for One-Handed Thumb Use on Small Devices,” in *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI ’05*, 2005, p. 201.

[105] I. Oakley, D. Y. Lee, M. D. R. Islam, and A. Esteves, “Beats: Tapping gestures for smart watches,” in *Conference on Human Factors in Computing Systems - Proceedings*, 2015, vol. 2015-April, pp. 1237–1246.

[106] Y. Kubo, B. Shizuki, and J. Tanaka, “B2b-swipe: Swipe gesture for rectangular smartwatches from a bezel to a bezel,” in *Conference on Human Factors in Computing Systems - Proceedings*, 2016, pp. 3852–3856.

[107] A. Bragdon, E. Nelson, Y. Li, and K. Hinckley, *Experimental Analysis of Touch-Screen Gesture Designs in Mobile Environments*. 2011.

[108] M. Mohammadi, H. Knoche, B. Bentsen, M. Gaihede, and L. N. S. Andreasen Struijk, “A pilot study on a novel gesture-based tongue interface for robot and computer control,” in *2020 IEEE 20th International Conference on Bioinformatics and Bioengineering (BIBE)*, 2020.

[109] D. Coleman, I. Sucan, S. Chitta, and N. Correll, “Reducing the Barrier to Entry of Complex Robotic Software: a MoveIt! Case Study,” Apr. 2014.

[110] P. Soetens, T. Issaris, H. Bruyninckx, S. Joyeux, and R. Smits, “Orocos Kinematics and Dynamics Library (KDL),” *The Orocos Project: Smarter control in robotics & automation!*, 2020. [Online]. Available: https://orocos.org/kdl.html.

[111] Á. A. Pálsdóttir and L. N. S. Andreasen Struijk, “Comparing double click versus direct sensor activation for mode switching when controlling a 7 DOF JACO robotic manipulator by the tongue,” in *18. Nordic-Baltic Conference on Biomedical Engineering and Medical Physics, NBC 2020*, 2020.

[112] L. Punchoojit and N. Hongwarittorrn, “Usability Studies on Mobile User Interface Design Patterns: A Systematic Literature Review,” *Adv. Human-Computer Interact.*, vol. 2017, 2017.

[113] J. Kim *et al.*, “The tongue enables computer and wheelchair control for people with spinal cord injury,” *Sci. Transl. Med.*, vol. 5, no. 213, 2013.

[114] H. A. Caltenco, B. Breidegard, B. Jönsson, and L. N. S. Andreasen Struijk, “Understanding Computer Users With Tetraplegia: Survey of Assistive Technology Users,” *Int. J. Hum. Comput. Interact.*, vol. 28, no. 4, pp. 258–

268, 2012.

[115] O. Kirtas, M. Mohammadi, B. Bentsen, P. Veltink, and L. N. S. A. Struijk, “Design and evaluation of a noninvasive tongue-computer interface for individuals with severe disabilities,” *2021 IEEE 21st Int. Conf. Bioinforma. Bioeng.*, pp. 1–6, Oct. 2021.

[116] E. R. Lontis *et al.*, “Clinical evaluation of wireless inductive tongue computer interface for control of computers and assistive devices,” in *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC’10*, 2010, pp. 3365–3368.

[117] L. N. S. A. Struijk, B. Bentsen, M. Gaihede, and R. Lontis, “Speaking Ability while Using an Inductive Tongue-Computer Interface for Individuals with Tetraplegia: Talking and Driving a Powered Wheelchair - A Case Study,” in *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, 2018, vol. 2018-July, pp. 2483–2486.

[118] H. A. Caltenco, E. R. Lontis, B. Bentsen, and L. N. S. Andreasen Struijk, “Effects of sensory feedback in intra-oral target selection tasks with the tongue,” *Disabil. Rehabil. Assist. Technol.*, vol. 8, no. 4, pp. 330–339, Jul. 2013.

[119] B. Wodlinger, J. E. Downey, E. C. Tyler-Kabara, A. B. Schwartz, M. L. Boninger, and J. L. Collinger, “Ten-dimensional anthropomorphic arm control in a human brain−machine interface: difficulties, solutions, and limitations,” *J. Neural Eng.*, vol. 12, no. 1, p. 016011, Feb. 2015.

ISSN (online): 2246-1302
ISBN (online): 978-87-7573-947-9

AALBORG UNIVERSITY PRESS