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Lontis, Romulus; Bentsen, Bo; Gaihede, Michael; Biering-Sørensen, Fin; Struijk, Lotte N. S. Andreasen

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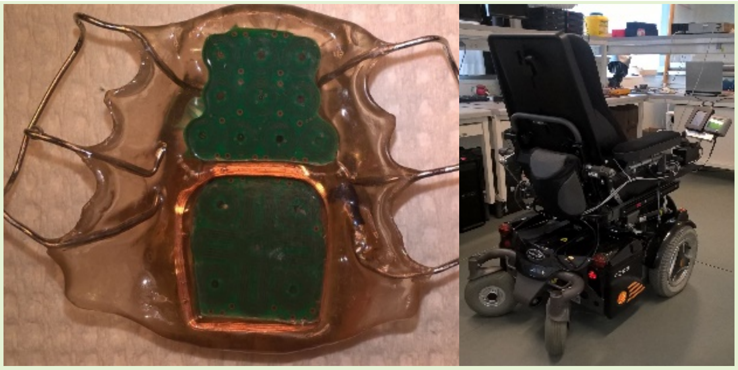
Wheelchair Control with Inductive Intra-Oral Tongue Interface for Individuals with Tetraplegia

Eugen R. Lontis, *Member, IEEE,* Bo Bentsen, Michael Gaihede, Fin Biering-Sørensen, and Lotte N. S. Andreasen Struijk



***Abstract*— High level spinal cord injury drastically reduces the quality of life of the injured person. Various systems attempted to interface the still intact or residual abilities following injury in various monomodal or multimodal designs to compensate for the highly affected mobility. An intra-oral inductive tongue computer interface (ITCI) has been designed to provide real-time discrete and proportional control for computers and assistive devices and to meet specific requirements for individuals with tetraplegia. Operation of the ITCI for wheelchair control was demonstrated with two participants with tetraplegia in a short-term training study. Additionally, two able-bodied individuals participated in the study. For each participant, the ability to drive a Permobil C500 with the ITCI was compared to that when driving the wheelchair with joystick (mouth-stick in one case) along two different lanes of 39 m, by reporting the speed along the lanes and the number of obstacles hit. The lanes consisted of 90^0, 360^0, and complex maneuver segments linked by linear segments. The ITCI featured a mouthpiece encapsulating two pads of inductive sensors, driving electronics, and battery. The mouthpiece was attached to the palate of the participant's oral cavity with dental retainers. A piercing-like activation unit was attached to the tongue. Data were transmitted wirelessly to a central unit that controlled the wheelchair through wired interface. Among all participants, mean speeds along lane A or B reached maximal values between 0.42 and 0.74 m/s when driving with the ITCI, representing 41 to 71% of that obtained when driving with the joystick.**

***Index Terms*— Rehabilitation, tongue computer interface, tetraplegia, wheelchair control.**

I. INTRODUCTION

SPINAL cord injury at the cervical level results in a dramatic loss of mobility highly influencing the quality of life of the injured individual [1-3]. Assistive devices are deployed in an attempt to compensate for the loss of mobility by exploiting the still intact or residual abilities of the disabled individual. Muscles [1-6], head movements [7-8], eyes [9-10], voice [11-14], brain [15-17], and tongue [18-20] or combinations hereof have been used for text inputting and pointing tasks to control computers and wheelchairs. These solutions have been used as alternatives to the classic mouth-operated joystick, called mouth-stick, aiming to improve the functional output (e.g. speed, accuracy, functional design) and usability by addressing specific needs for the disabled (e.g. physical constraints, aesthetics, fatigue).

A wireless intra-oral tongue computer interface, ITCI, has been developed based on inductive sensors [21-23]. Sensors have been manufactured with the printed circuit board technology exploiting the possibility of forming various geometries for assemblies of sensors with reproducible low tolerance electrical parameters [24]. Furthermore, this technology facilitates miniaturizing, integration, and encapsulation of the driving electronics and a battery within a mouthpiece. The sensors have been built on a sandwich structure with geometries allowing real-time discrete and proportional control when placing and gliding a soft ferromagnetic cylindrical activation unit along the surface of the sensor pads. The activation unit was attached to the tongue as the upper ball of a piercing [25]. These design features allow multiple programmable functional layouts, e.g. text input [26], [27], pointing device [28], [29], control of hand prosthesis [30], robotic arm [31], and drone [32]. Thus, the ITCI would possibly provide control of any type of interface or device.

Driving a wheelchair safely in various environments (e.g. in confined spaces or crossing trafficked areas) requires a control system with a high degree of maneuverability that reliably

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E. R. Lontis, B. Bentsen, and L. N. S. Andreasen Struijk are with the Department of Health Science and Technology, Aalborg University, 9200 Aalborg, Denmark (e-mail:lontis@hst.aau.dk; brasse@hst.aau.dk; naja@hst.aau.dk).

M. Gaihede is with the Department of Otolaryngology, Head & Neck Surgery, Aalborg University Hospital, 9000 Aalborg, Denmark, and also with the Department of Clinical Medicine, Aalborg University, 9200 Aalborg, Denmark (e-mail: mlg@rn.dk).

Fin Biering-Sørensen is with the Clinic for Spinal Cord Injury, Rigshospitalet, University of Copenhagen, 2100 Copenhagen, Denmark (fin.biering-soerensen@regionh.dk).

responds to the user's intentions. These features are provided satisfactorily by the hand-operated joystick, which is the standard control system in most powered wheelchairs. However, a joystick cannot be used by individuals with severe tetraplegia. Therefore, a mouth-operated joystick is often interfaced with the wheelchair as a standard control system for users with spinal cord injury at the most rostral cervical levels. Nevertheless, specific limitations such as muscle fatigue, mouth discomfort when driving over bumpy terrain, aesthetics, and physical constraint during driving challenge the user satisfaction of the mouth-operated joystick interface. The ITCI features intuitive, real-time control of direction and speed similar to that of the joystick. Furthermore, the ITCI's design may overcome the challenges with discomfort while driving over bumpy terrain and the issues related to constraints of the head and neck as well as aesthetics.

Performance of a pointing device controlling a computer has often been evaluated based on the Fitt's law [33]. Throughput is a measure that combines the completion time for a pointing task based on targets and the index of difficulty that reflects constraints imposed by geometrical characteristics of the pointing tasks. Throughput is a very convenient measure in that it allows direct comparison of various pointing devices while performing pointing tasks of various degrees of difficulty, however with some limitations [34-36]. Similar to Fitt's law, the steering law establishes a linear relation between the completion time and the index of difficulty of the task. The two parameters of this linear dependency reflect performance of pointing devices when performing trajectory base tasks within given categories, allowing definition of an index of performance [36].

Performance comparison of pointing devices based on pointing and trajectory tasks performed on computers have been reported in the literature on a much more structured background than that of pointing devices controlling powered wheelchairs. As such, the trade between speed and accuracy was illustrated by reporting the completion time, speed, and number of obstacles hit when driving a powered wheelchair controlled by the Tongue Drive System along a complex lane defined by a set of obstacles [19]. Accuracy was evaluated by the movement variability and deviations to the center of path when driving a powered wheelchair at constant speed along a complex path using the Tongue Rudder [17]. Performance metrics of wheelchair control based on EMG-controller were evaluated through time of completion, as well as system and user specific measures [6].

This study reports for the first time data from two participants with tetraplegia controlling a powered wheelchair with ITCI and compares with that from two able-bodied participants. The ITCI used a setup requiring an activation unit attached to the tongue as the upper ball of a piercing. Furthermore, the ability of the four participants to control driving the powered wheelchair with ITCI along complex lanes has been compared with that of controlling driving the wheelchair with a joystick (mouth-stick in one case, i.e. a mouth operated version of a joystick) after short-term training. The lanes have been delimited by a set of obstacles. Segments representing linear and maneuver driving have been identified for each lane. Speed characterizing the short-term learning process for each lane, as well as speed along segments of the two lanes have been reported. Additionally, the number of obstacles hit has been reported. The complex lanes have been segmented in the attempt to provide categories of driving paths that may help form a more structured ground for comparison of driving performance. An index of performance based on the steering law has been evaluated for the linear and maneuver driving segments. Data have been reported as cases, attempting to identify possible factors affecting the outcome of the short-term learning process that may help personalize the ITCI to each user. Comparison of cases of participants with tetraplegia with cases of able-bodied participants may outline specific differences between these cases, even if all participants fulfilled the inclusion criterion of normal physiological control of the tongue.

II. METHODS

The experiment was conducted on two consecutive days, with one session of three hours each day, including preparation time. The first session consisted of 30 min of typing and pointing tasks on a computer and a 30-min warm up wheelchair test drive on straight and triangular test lanes. For the remaining experimental time, wheelchair driving was performed with Joystick (mouth-stick in one case) and ITCI (Fig. 1) as control interfaces on two lanes, A and B, of the same length and width and requiring the same type of maneuvers (Fig. 2).

A. Participants

Two able-bodied and two individuals with tetraplegia gave written consent to participate in the experiment. The two able-bodied participants were 27 and 35 year-old and they had jewelry piercing for nine and five years prior to the experiment, respectively. The two participants with tetraplegia were 49 and 58 year-old and they had a spinal cord injury at C5 level and C1-C2 level, respectively, receiving their medical piercing 14 months prior to this experiment. The experimental protocol was approved by the local ethics committee (N-20120039). All participants in this experiment had previously participated in a computer control experiment using the ITCI [26]. Notations for able-bodied (Par01 and Par04) and individuals with tetraplegia (Par02 and Par03) will be used throughout the manuscript.

B. Inductive Intra-Oral Tongue Computer Interface

1) Mouthpiece and Sensors of the ITCI: The mouthpiece of the tongue computer interface consisted of 18 inductive sensors built on two pads (usually denoted as keypad and mousepad), electronics, and a rechargeable battery encapsulated in a dental retainer (abstract figure and Fig. 1) [25]. The keypad and mousepad were built in the printed circuit board technology PCB (PrintLine A/S, Denmark). They were placed forward and backwards, respectively, in the oral cavity [22]. The mouse pad was placed backwards mainly due to safety reasons when controlling the wheelchair, as false activation may occur in normal resting positions of the tongue. The upper and lower pads consisted of ten round coils and eight round and oval coils, respectively. The round coils had the inner and outer diameter of 4.6 and 6.3 mm, respectively. The PCB boards were 1 mm thick, incorporating a sandwich structure of 10 conductive layers, separated by a 100 μm pre-

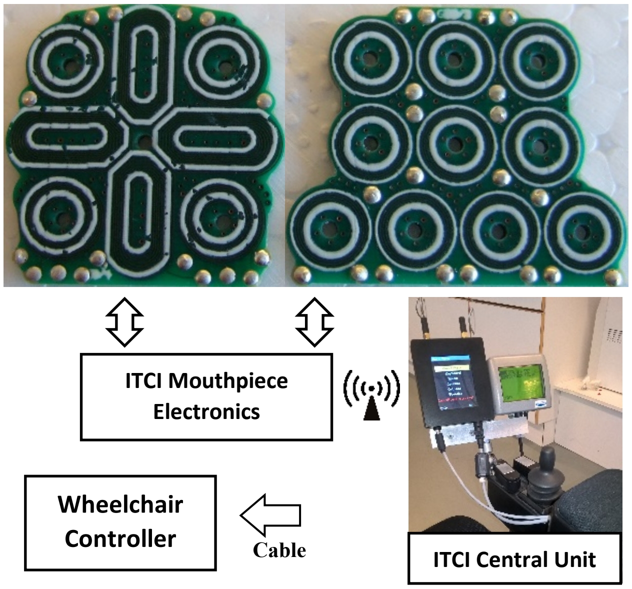

Fig 1. Sensors (mousepad, left, and keypad, right) of the ITCI mouthpiece. Electronics of the ITCI mouthpiece process information from sensors and send it wirelessly to the central unit of the ITCI. The central unit of ITCI replaces the original Joystick control system (stick and screen, as seen on the right of the ITCI central unit) of the wheelchair. The Central Unit controls the wheelchair through wired connection. Bluetooth connection ensures communication from Central Unit to a computer/tablet/smartphone.

impregnated bonding layer. The copper track and spacing had a width of 75 μm. The height of the copper track was 35 μm. Each layer had 10 windings for each coil, connected through plated through-holes, of 200 μm diameter, across the sandwich structure. These through-holes were placed inside and outside of the windings. They are slightly visible, besides the larger solder dots that are the plated through-holes connecting the two endings of a sensor to a flex print (Fig. 1). Two flex prints connected the sensors pads with the driving electronics. This design of the PCB boards ensured a higher sensitivity for activation and a reduced size of the boards compared to that previously reported (1.55 mm thick PCB boards with 10 layers sandwich structure with copper line and spacing of 100 μm width) [24]. An activation unit made of a 4.5 mm diameter and 5.2 mm height ball (DYNA® ferromagnetic steel) with a flat top was attached to the tongue as the upper ball of a piercing.

The mouthpiece ensured wireless transmission of raw sensors data to a central unit.

2) Central Unit of the ITCI: The central unit filtered and processed the raw data depending on the functional mode of operation and transmitted data wirelessly to a computer and hardwired to the control system of the wheelchair [22-23]. To each functional mode of operation corresponded a functional sensors layout that defined how sensors signals from the two PCB pads were processed. The central unit of the ITCI had three functional modes: (a) text input mode with a keyboard-like function, (b) pointing mode with a joystick-like cursor control and (c) a wheelchair mode with a similar joystick-like function. In the text input mode, signals from sensors signals were filtered to provide an on-off switch-like discrete control. In the pointing and wheelchair modes, real-time proportional control similar to that of a joystick was provided on the lower pad. A fuzzy-logic processing filtered and normalized signals from three neighbor sensors and radial interpolation ensured a unique determination of the activation unit. Consequently, placing the activation unit along the surface of the sensors of the mouse pad generated speed and direction of the wheelchair linearly proportional to the length and direction of the vector defined by the position of the activation unit relative to the pad center.

The central unit provided appropriate signals to the control unit of the wheelchair, substituting the analogue signals of the standard joystick (forward-reverse, right-left) and the two associated buttons. The output signals of the fuzzy-logic encoded a 2D mapping of position of the activation unit relative to surface of the mouse pad and provided the pulse width modulated signals representing the x and y coordinates of the 2D map. These signals were conditioned with regard to safety issue by a watch dog. The watchdog was activated by absence of a valid data transmission package from the mouthpiece to the central unit [23].

3) ITCI development: Design of the ITCI used in this study represented a step in the continuous technical development of the system. Design of the sensors and control of the wheelchair previously presented [23] formed the backbone of the current ITCI version. However, the activation unit was attached as the upper ball of piercing in this study, whereas the former study used a glued activation unit. Technical updates of the current ITCI version included improvement of the mouthpiece (new antenna, improved data transmission, and safer encapsulation) and of the central unit (addition of a touch screen, user control of system settings and calibration of sensors, complete navigation between functional layouts, and bluetooth communication with digital devices).

C. Data Acquisition and Wheelchair Setup

A Permobil C500 electric powered wheelchair was used for the experiment. The central unit of the ITCI was mounted on the arm support holding the original control system of the wheelchair joystick and display (Joystick) as illustrated in Fig. 1. For safety reasons, an auxiliary master control system was placed at the back of the wheelchair to allow an assisting person to stop the wheelchair, if needed.

A video camera was mounted at the back of the wheelchair with a 90^0 view of the back wheels in order to record the relative position of the wheelchair in relation to the test lane. Markers delimitated the lanes and the segments within the lanes for easy identification of the wheelchair position along and within the lane. An additional video camera monitoring the overall driving performance was positioned in different locations around the lane. The central unit of the ITCI transmitted all raw and processed data from the inductive sensors to a computer through a Bluetooth connection. The computer was placed on a table outside of the test lane. The detected dynamic position of the activation unit relative to the sensor pads of the ITCI was displayed on the computer screen by the ITCI visual feedback software. All data were saved on files on the computer's hard disk. Computer and camera time were synchronized through a short sound played at the beginning of each trial.

The wheelchair speed could be set at five levels: S1, S2, S3, S4, and S5 with maximal speeds of 0.39, 0.89, 1.42, 1.91, and 2.45 m/sec, respectively. By programming the wheelchair with a given speed level, the ITCI allowed the participant to increase the speed from zero up to the corresponding maximal speed (e.g. from 0 to 1.42 m/s for S3), when gliding the activation unit from the center of the mousepad towards the inner edge of the charging coil of the battery. These maximal speeds were determined by letting an able-bodied test person drive the wheelchair along the last 6 m of a 10 m straight lane in a six trials test using the standard joystick of the wheelchair. This test person did not participate in the experiment.

D. Test Lanes and Trials of Short-term Training

Each with a length of 39 m and a width of 1.2 m, the two lanes, A and B, consisted of 90^0 and 360^0 turns as well as complex maneuvers performed in both directions linked by linear segments (Fig. 2, right panel). Lane B was designed to complement lane A in that the participant drove the wheelchair in a direction opposite to lane A in all segments, linear or maneuver. Lane A and B were defined by the sequence of segments A-B-F-G-F-H-I-J-K-L-D-C-A, outlined by arrowed red track, and A-C-D-E-L-K-J-I-H-F-G-F-B-A, outlined by arrowed blue track, respectively (Fig.2). The position of the wheelchair relative to the lane was estimated by the middle point between the main wheels. The participants were instructed to drive within the marked width of the lane (i.e. projection of the wheelchair on the lane should always be within the edges of the lane). Additionally, 28 obstacles (cone shaped markers of 0.2 m diameter and 0.15 m height, made of soft plastic) were placed at the outer and inner edges of each segment of the lane (dots in Fig. 2, right panel).

The index of difficulty (ID) for each segment was computed according to the steering law [32] as the ratio between the length l and width of the segment w, $ID = l / w$.

Trials of this study were designed considering the planned short-time training. Par01, Par02, and Par04 hand controlled the standard joystick of the wheelchair, whereas Par03 used a mouth controlled type of joystick (mouth-stick), in this study. Par01 and Par04 had extensive experience in using the joystick (hand controlled) in applications other than wheelchair driving. Par02 currently used the standard joystick (hand controlled) of the wheelchair, given the residual ability to control part of the left hand. Par03 used the mouth-stick (mouth controlled) when driving the powered wheelchair occasionally at home. Par02 had regularly daily use of the wheelchair using the standard joystick. Consequently, the number of trials testing driving with Joystick (mouth-stick in case of Par03) was limited to two for each of the two speed settings planned. These trials were performed in the beginning of the experiment. Additional two trials for each speed level setting were recorded in case of Par04, given the time available at the end of the training period. The speed levels for wheelchair settings were chosen by the participants given their previous experience with this type of control.

All participants had no previous experience in controlling the wheelchair with ITCI, however all participants used the ITCI in controlling a pointer on the screen of a computer in a previous experiment [26]. The warm-up session allowed the participants to accommodate with this type of control, deciding on which speed level for wheelchair settings they should start with when first driving along the lane A. For consecutive trials during training driving with ITCI, lane A and lane B were chosen alternating. For each trial, the participant chose the speed level of the wheelchair setting based on their previous trial experience. Each participant performed as many trials possible within the limited time provided by this short-term design. Few technical issues and different resting periods required by each participant influenced as well the total number of trials achieved by each participant.

E. Data Processing

The short-term learning process was given by the sequence of trials over time. Each trial was characterized by a mean speed value along the lane. The maximum of all mean values recorded for each participant was denoted as maximal mean speed ($\text{ITCI}^{\text{mean-max}}$). This value reflected the best performance in terms of speed obtained within the given training time. However, this value did not necessarily represent the ability of the system to perform consistently over a longer period of time. Consequently, a mean value was computed from several of the mean speeds recorded that provided the best results up to 30% of the total number of trials. The resulted estimator was denoted as mean of top mean speeds representing

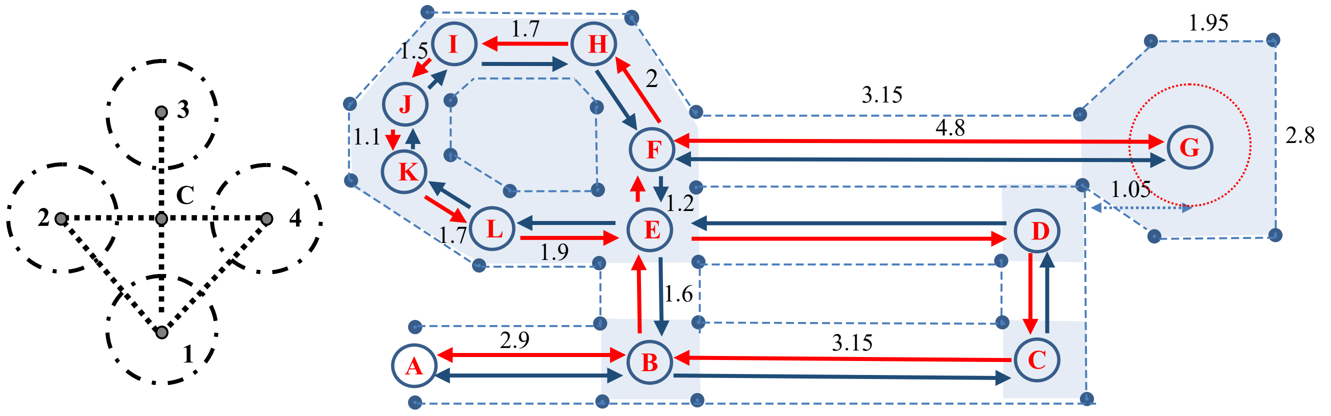

Fig. 2. Triangular test lanes and lanes A (A-B-F-G-F-H-I-J-K-L-D-C-A, red) and B (A-C-D-E-L-K-J-I-H-F-G-F-B-A, blue). Dots represent obstacles delimiting the lanes. Lane edges, entrance and exit points of each segment were marked with strips. The number associated with each segment represents the length in meters of the segment defined between two points. The width of the lane was 1.2 m.

approximately 30% of the number samples (ITCI$^{\text{mean-top-30\%samples}}$). These estimators were compared with maximal mean (Joystick$^{\text{mean-max}}$) and mean of mean speeds (Joystick$^{\text{mean-mean}}$) recorded when driving with Joystick, respectively. Joystick$^{\text{mean-max}}$ was defined in the same way as ITCI$^{\text{mean-max}}$. Joystick$^{\text{mean-mean}}$ was computed as mean values of all mean speed values along lane A and B for Joystick.

Learning curves for wheelchair driving with ITCI were evaluated for mean speeds along lanes A and B. Linear fit according to $S=b*s^{a}$ was evaluated where S was the estimated modelled speed, s was the mean speed of each trial for lanes A or B, and a and b were the linear parameters of the model.

Similar estimators to those characterizing the mean speed along lane A or B were defined for driving by each participant with ITCI along each segment (linear or maneuver) of lane A or B. The maximum of all speed values recorded on the corresponding segment was denoted as maximal speed (ITCI$^{\text{max}}$). The mean computed from best speeds recorded up to 30% of total number of trials on the corresponding segment was denoted as mean of top speeds representing approximately 30% of the number of samples (ITCI$^{\text{top-30\%samples}}$). These estimators were compared with maximal (Joystick$^{\text{max}}$) and mean (Joystick$^{\text{mean}}$) speeds recorded when driving with Joystick, respectively, for the corresponding segment.

The number of obstacle hits was recorded for each trial along lane A and B.

Linear correlation between mean speeds (Joystick$^{\text{mean}}$ vs. ITCI$^{\text{top-30\%samples}}$) for all segments (linear and maneuver) was computed for each lane, according to $s^{\text{Joystick}} = b+a*s^{\text{ITCI}}$, where s^{Joystick} and s^{ITCI} were the corresponding speeds when driving along a segment with Joystick and ITCI, respectively.

Mean value (MT$^{\text{30\%samples}}$) of the movement time corresponding to speed values included in computation of ITCI$^{\text{top-30\%samples}}$ along each segment was computed. Linear correlations were computed between means of movement time (MT$^{\text{30\%samples}}$) and ID for linear segments as well as for maneuvers segments of each lane when driving with ICTI. This computation was used in the analysis of a possible performance estimator based on the steering law [36].

Speed ratios (ITCI vs. Joystick) were evaluated for the two lanes.

III. RESULTS

A. Driving along Lane A and B

Able-bodied participants Par01 and Par04 completed 23 and 27 trials and participants with tetraplegia Par02 and Par03 completed 14 and 11 trials, respectively, when driving with ITCI along the two lanes during the short-term training. Mean value of the speed for each trial, when driving along the lane A or B with ITCI, is presented for able-bodied participants (left panels, Fig. 3) and for participants with tetraplegia (right panels, Fig. 3), describing the short-term learning process given by the sequence of trials performed. The mean speed value for each trial was marked by a blue symbol corresponding to the speed level of the wheelchair setting associated to that trial (Legend, Fig. 3). The number of obstacles hit for each trial is presented on the top of the panel for each participant when driving with ITCI. Driving with Joystick (mouth-stick in one case) resulted in no obstacle hit. Mean value of the speed for each trial when driving along lane A or B with Joystick (mouth-stick for Par03) is presented in the inset of each panel of Fig. 3, for the corresponding participant. The learning curve, modelling the time evolution of the mean speed along the lane, is presented for each participant. Statistics of the learning curve are shown in each panel (lower inset) of Fig. 3. Table 1 presents speed estimators for maximal (ITCI$^{\text{mean-max}}$ and Joystick$^{\text{mean-max}}$) and mean values (ITCI$^{\text{mean-top-30\%samples}}$ and Joystick$^{\text{mean-mean}}$) for each participant, with corresponding ratios. The speed levels corresponding to speed values defining the speed estimators presented in Table I are specified as superscript for each value of these estimators.

Besides the total number of obstacles hit, crossing the edge of the lane was occasionally observed along the linear edge between the obstacles. Most of these crossing resulted when attempting to correct the position of the wheelchair in the nearby vicinity of the edge. Rotating the wheelchair resulted in crossing the edge of the lane by the projection of the wheelchair on the lane (front or back wheels). Wrong angle when following a turn in a maneuver or following a linear track led as well to crossing of the linear edge in few cases. These crossings, both obstacle hit and crossing of the linear edge, did not exceed 0.3 m, so that the center point between the four wheels of the wheelchair remained within the edges of the lane. Exceptions were for Par02 trial 5 (segment C), for Par03 trial 2 (segments FG and G), trial 8 (segments FE, EB, and BA), and for Par04 trial 20 (segments EF$_{\text{round}}$ and FG) where the wheel crossed the edge of the lane up 0.5 m. These segments were removed from further analysis. Trial 12 for Par02 and trial 1 for Par03 were not included in the speed analysis along segments of lane A and B due to missing recording from the rear camera and temporary interruptions in data transmission, respectively.

B. Driving along Maneuver Segments

For each maneuver segment of lane A and B, maximal speeds (ITCI$^{\text{max}}$ and Joystick$^{\text{mean-max}}$, first row) and mean speeds (ITCI$^{\text{top-30\%samples}}$ and Joystick$^{\text{mean}}$, second row) with standard deviations for able-bodied participants and participants with tetraplegia are presented in Table II (left and right columns, respectively). Speed levels of the wheelchair settings set for the trials providing the speed values used by the estimators presented in Table II were indicated as superscript for the corresponding estimator. The table indicates segment identifier along the two lanes (Fig. 2) and the length of the segment.

C. Driving along Linear Segments

Similar to maneuver segments, maximal speeds (ITCI$^{\text{max}}$ and Joystick$^{\text{mean-max}}$, first row) and mean speeds (ITCI$^{\text{top-30\%samples}}$ and Joystick$^{\text{mean}}$, second row) with standard deviations for able-bodied participants and participants with tetraplegia are presented in Table III (left and right columns,

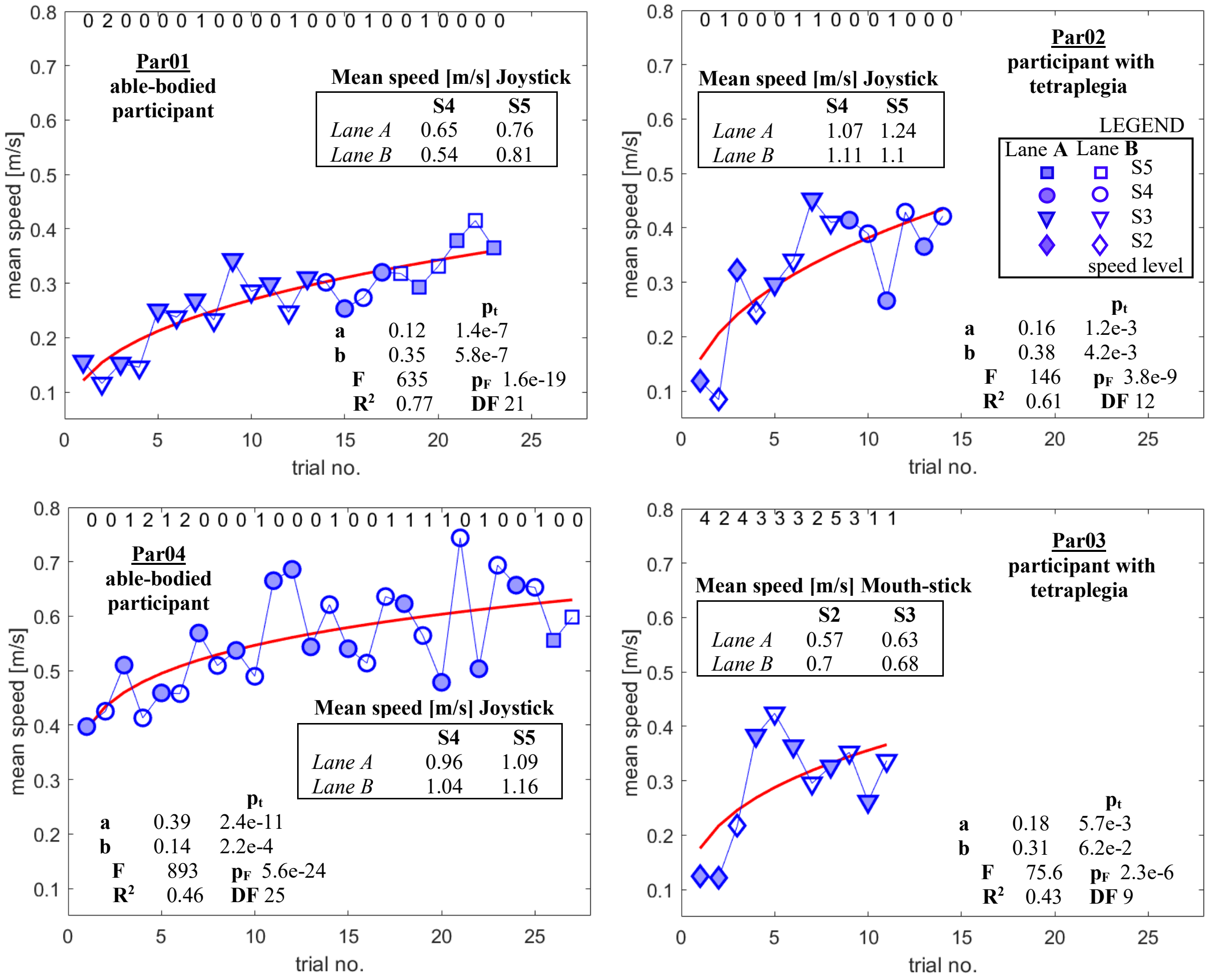

Fig. 3 Mean speed (blue, with symbols for speed level of wheelchair setting according to Legend, inset upper left panel) for each participant for consecutive trials of driving with ITCI along lane A and B, with associated fitted learning curve (red, with statistics of curve fitting, lower inset). The number of obstacle hits corresponding to each trial is displayed at the top of the panel for each participant. Upper inset with mean speed values for driving with Joystick, with corresponding speed level of wheelchair settings and lane.

respectively) for each linear segment of lane A and B. Speed levels of the wheelchair settings set for the trials providing the speed values used by the estimators presented in Table III were indicated as superscript for the corresponding estimator.

Linear correlation ($p < 0.05$) was found for all participants between the mean speeds $\text{Joystick}^{\text{mean}}$ and $\text{ITCI}^{\text{top-30\%samples}}$ along segments (linear and maneuver) of lane A and B (Table IV). The linear model explained most of the variability (R^2 between 0.8 and 0.87) for Par01 and Par04, whereas for Par02 and Par03 the factors affecting the data variability beyond that explained by the linear model must be further identified (R^2 between 0.5 and 0.57).

D. Movement Time and Index of Difficulty

Mean values ($\text{MT}^{30\%\text{samples}}$) of movement time were linearly correlated ($p < 0.05$) with the index of difficulty ID for linear segments as well as with the ID for maneuver segments along

TABLE I: MEAN SPEEDS FOR LANE A AND B AND CORRESPONDING SPEED RATIO ITCI VS. JOYSTICK

Mean speeds and ratio	**Par01**	**Par04**	**Par02**	**Par03**^{a}
	able-bodied participants		**participants with tetraplegia**	
$\text{ITCI}^{\text{mean-max}}$ / $\text{Joystick}^{\text{mean-max}}$	0.42^{S5} / 0.81^{S5} 52%	0.74^{S4} / 1.04^{S4} 71%	0.45^{S4} / 1.11^{S4} 41%	0.42^{S3} / 0.68^{S3} 62%
$\text{ITCI}^{\text{mean-top-30\%samples}}/\text{Joystick}^{\text{mean-mean}}$	**$0.36^{S3\text{-}S4\text{-}S5}$ / $0.69^{S4\text{-}S5}$** **52%**	**0.67^{S4} / $1.05^{S4\text{-}S5}$** **64%**	**$0.43^{S3\text{-}S4}$ / $1.13^{S4\text{-}S5}$** **38%**	**0.39^{S3} / $0.64^{S2\text{-}S3}$** **61%**

Maximal mean speed values of the experimental learning curve $\text{ITCI}^{\text{mean-max}}$ and $\text{Joystick}^{\text{mean-max}}$, expressed in m/s, obtained for the same speed level of the wheelchair settings, with corresponding ratios, expressed in percentage (first row). Mean of the mean speeds of the experimental learning curve $\text{ITCI}^{\text{mean-top-30\%samples}}$ and $\text{Joystick}^{\text{mean-mean}}$, expressed in m/s, with corresponding ratios, expressed in percentage (second row). Speed levels S_2 to S_5 of wheelchair settings for the maximal mean speed values and for mean speed values included in the computation of mean of the mean speed values are indicated as superscript. ^{a}Permobil wheelchair interfaced with mouth-stick.

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TABLE II: SPEED CORRESPONDING TO MANEUVERING SEGMENTS OF LANE A AND B

Segment	Par01		Par04		Par02		Par03^a	
	able-bodied participants				participants with tetraplegia			
	ITCI	*Joystick*	*ITCI*	*Joystick*	*ITCI*	*Joystick*	*ITCI*	*Joystick*
90^0_{left}	0.34^{S3}	0.75^{S5}	0.95^{S4}	1.41^{S5}	0.59^{S3}	1.15^{S5}	0.73^{S2}	0.9^{S3}
B, C, D	**0.23**	**0.32**	**0.73**	**0.92**	**0.46**	**0.91**	**0.6**	**0.56**
l: 1.2 m	**± 0.06**$^{S3-S5}$	**± 0.26**$^{S4-S5}$	**± 0.14**$^{S4-S5}$	**± 0.28**$^{S4-S5}$	**± 0.09**$^{S3-S4}$	**± 0.19**$^{S4-S5}$	**± 0.1**$^{S2-S3}$	**± 0.2**$^{S2-S3}$
90^0_{right}	0.3^{S4}	0.6^{S5}	1.3^{S4}	1.4^{S5}	1.03^{S3}	1.21^{S4}	0.93^{S3}	1.07^{S3}
B, C, D	**0.24**	**0.29**	**0.88**	**0.89**	**0.66**	**1.1**	**0.74**	**0.78**
l: 1.2 m	**±0.04**$^{S3-S4-S5}$	**± 0.15**$^{S4-S5}$	**± 0.25**^{S4}	**± 0.3**$^{S4-S5}$	**± 0.26**$^{S2-S3-S4}$	**± 0.1**$^{S4-S5}$	**± 0.13**^{S3}	**± 0.17**$^{S2-S3}$
360^0_{left}	0.42^{S5}	0.46^{S5}	0.72^{S4}	1.03^{S5}	0.6^{S3}	0.93^{S4}	0.35^{S3}	0.51^{S2}
G	**0.36**	**0.43**$^{S4-S5*}$	**0.58**	**0.84**	**0.59**	**0.89**$^{S4-S5*}$	**0.33**	**0.5**$^{S2-S3*}$
l: 4.88 m	**± 0.07**^{S5}		**± 0.1**^{S4}	**± 0.14**$^{S4-S5}$	**± 0.02**$^{S3-S4}$		**±0.02**^{S3}	
360^0_{right}	0.46^{S5}	0.44^{S5}	0.71^{S4}	0.83^{S4}	0.33^{S4}	0.76^{S4}	0.33^{S3}	0.46^{S2}
G	**0.4**	**0.4**$^{S4-S5*}$	**0.63**	**0.76**	**0.32**	**0.755**$^{S4-S5*}$	**0.29**	**0.41**$^{S2-S3*}$
l: 4.88 m	**± 0.04**$^{S4-S5}$		**± 0.07**^{S4}	**± 0.1**$^{S4-S5}$	**± 0.02**^{S4}		**±0.06**^{S3}	
$\text{Complex}_{long}^{left}$	0.44^{S5}	0.55^{S5}	1.01^{S4}	1.48^{S5}	0.38^{S3}	1.2^{S4}	0.48^{S3}	0.81^{S3}
FE_{round}	**0.35**	**0.54**$^{S4-S5*}$	**0.92**	**1.24**	**0.36**	**1.195**$^{S4-S5*}$	**0.4**	**0.8**$^{S2-S3*}$
l: 11.1 m	**± 0.08**$^{S3-S5}$		**± 0.11**^{S4}	**± 0.19**$^{S4-S5}$	**± 0.03**$^{S3-S4}$		**± 0.12**^{S3}	
$\text{Complex}_{long}^{right}$	0.38^{S4}	0.86^{S5}	0.84^{S4}	1.11^{S4}	0.61^{S4}	1.25^{S4}	0.74^{S3}	0.76^{S2}
EF_{round}	**0.36**	**0.7**$^{S4-S5*}$	**0.8**	**1.05**	**0.59**	**1.24**$^{S4-S5*}$	**0.62**	**0.6**$^{S2-S3*}$
l: 11.1 m	**± 0.01**$^{S3-S4-S5}$		**± 0.04**^{S4}	**± 0.04**$^{S4-S5}$	**± 0.02**$^{S3-S4}$		**± 0.17**^{S3}	
$\text{Complex}_{short}^{left}$	0.36^{S4}	0.26^{S5}	1.3^{S4}	1.39^{S5}	0.48^{S4}	1.21^{S4}	0.69^{S3}	0.67^{S2}
FE_{short}	**0.27**	**0.21**$^{S4-S5*}$	**1.03**	**1**	**0.46**	**1.08**$^{S4-S5*}$	**0.62**	**0.66**$^{S2-S3*}$
l: 2.4 m	**± 0.07**$^{S3-S4-S5}$		**± 0.28**$^{S4-S5}$	**± 0.26**$^{S4-S5}$	**± 0.03**$^{S2-S3}$		**± 0.1**^{S3}	
$\text{Complex}_{short}^{right}$	0.58^{S3}	0.44^{S4}	1.03^{S4}	1.24^{S5}	0.79^{S4}	1.04^{S4}	0.94^{S3}	1.04^{S2}
EF_{short}	**0.42**	**0.39**$^{S4-S5*}$	**0.84**	**0.87**	**0.7**	**0.97**$^{S4-S5*}$	**0.82**	**0.83**$^{S2-S3*}$
l: 2.4 m	**± 0.14**$^{S3-S4-S5}$		**± 0.22**^{S4}	**± 0.31**$^{S4-S5}$	**± 0.12**^{S2}		**± 0.17**$^{S2-S3}$	

Speed expressed in m/s for 90^0 turns, 360^0 turns, and complex maneuvers of lane A and B. For each maneuvering segment and each participant: maximal speed values $ITCI^{max}$ and $Joystick^{max}$ (first row) and mean speed values $ITCI^{top\text{-}30\%samples}$ and $Joystick^{mean}$ (bold, second row) with corresponding standard deviations; Index of difficulty for each segment (of length l and width w = 1.2 m) is defined by ID = l/w. Speed levels S_2 to S_5 of wheelchair settings for maximal speed values and for speed values included in the computation of mean speed values are indicated as superscript. ^{a} Permobil wheelchair interfaced with mouth-stick. * Missing standard deviation due to only two samples measure.

lane A or B having variations explained by the linear model between 62 and 97% (Table IV).

IV. DISCUSSION

The ability to drive a wheelchair with the ITCI and with Joystick (mouth-stick in one case), during a short-term training was presented in this feasibility study including two participants with tetraplegia and two able-bodied participants. Control of the Permobil C500 wheelchair was evaluated for driving along two complex lanes, each having the same number of left and right 90^0 and 360^0 turns and complex maneuvers linked by linear segments. The lane width was double of that of wheelchair, representing a relative narrow geometry constraining movements of the wheelchair. The two lanes were designed so that the wheelchair drove in both directions along each maneuver and linear segment.

Speed has been evaluated as performance measure along the two complex lanes and their linear and maneuver segments. Additionally, the number of obstacles hit when driving the wheelchair along the lanes were reported, representing a more qualitative measure of the accuracy of driving. Speed represented a normalized distance over time allowing easier comparison between different driving tasks and wheelchair settings, easier association with the design of the ITCI output, and possibly a closer and more natural parameter to the user.

As defined by the steering law, analysis of linearity between movement times and the index of difficulty of the segment attempted to provide a performance measure for ITCI alternative to that represented by speed and number of obstacles hit.

Analysis of the linear fit between estimators of mean speed for ITCI and Joystick attempted to provide a characterization of the ability to drive the wheelchair controlled by the two systems relative to geometries of the segments of the two lanes.

A. Performance Measures and the Learning Process

Maximal speed values reflect the best performance obtained, subjected to given experimental conditions such as training time, participant's ability, geometry of the path, and

TABLE III: SPEED CORRESPONDING TO LINEAR SEGMENTS OF LANE A AND B

Segment	Par01		Par04		Par02		Par03[a]	
	able-bodied participants				participants with tetraplegia			
	ITCI	*Joystick*	*ITCI*	*Joystick*	*ITCI*	*Joystick*	*ITCI*	*Joystick*
L_1 BE, DC, CD, EB *l*: 0.4 m	1^{S4} **0.73** **± 0.2**$^{S3-S4-S5}$	1.14^{S4} **0.59** **± 0.31**$^{S4-S5}$	0.89^{S4} **0.61** **± 0.13**$^{S4-S5}$	1^{S5} **0.51** **± 0.2**$^{S4-S5}$	0.63^{S4} **0.43** **±0.11**$^{S2-S3-S4}$	1.11^{S5} **0.56** **± 0.26**$^{S4-S5}$	0.35^{S3} **0.27** **± 0.05**$^{S2-S3}$	0.74^{S3} **0.37** **± 0.19**$^{S2-S3}$
L_2 DE, ED *l*: 1.85 m	1.38^{S5} **1.1** **± 0.2**$^{S3-S5}$	2.17^{S4} **1.35** **± 0.59**$^{S4-S5}$	1.68^{S4} **1.41** **± 0.15**^{S4}	1.97^{S5} **1.36** **± 0.41**$^{S4-S5}$	1.1^{S3} **0.94** **±0.14**$^{S3-S4}$	1.99^{S5} **1.75** **± 0.25**$^{S4-S5}$	1.26^{S3} **1.03** **± 0.27**^{S3}	1.21^{S3} **0.94** **± 0.18**$^{S2-S3}$
L_3 AB, BA *l*: 2.3 m	1.44^{S4} **1.14** **± 0.2**$^{S3-S4-S5}$	1.15^{S5} **0.87** **± 0.25**$^{S4-S5}$	1.55^{S4} **1.25** **± 0.21**^{S4}	2.05^{S5} **1.23** **± 0.45**$^{S4-S5}$	0.91^{S3} **0.8** **±0.1**$^{S3-S4}$	1.2^{S4} **1.06** **± 0.18**$^{S4-S5}$	1.1^{S3} **0.76** **± 0.29**^{S3}	0.84^{S2} **0.7** **± 0.11**$^{S2-S3}$
L_4 FG, GF *l*: 3.15 m	1.43^{S5} **1.14** **± 0.14**$^{S3-S4-S5}$	1.5^{S4} **1.27** **± 0.15**$^{S4-S5}$	2.27^{S5} **1.63** **± 0.26**$^{S4-S5}$	2.33^{S5} **1.57** **± 0.42**$^{S4-S5}$	1.66^{S4} **1.36** **±0.2**$^{S3-S4}$	2.23^{S5} **1.78** **± 0.23**$^{S4-S5}$	1.31^{S3} **0.97** **± 0.18**^{S3}	1.22^{S3} **0.89** **± 0.22**$^{S2-S3}$
L_5 AC, CA *l*: 5.45 m	1.4^{S5} **1.07** **± 0.18**$^{S3-S4-S5}$	1.8^{S5} **1.2** **± 0.43**$^{S4-S5}$	1.8^{S5} **1.38** **± 0.19**$^{S4-S5}$	2.07^{S5} **1.42** **± 0.38**$^{S4-S5}$	1.28^{S4} **0.95** **±0.28**$^{S2-S3-S4}$	1.38^{S5} **1.3** **± 0.06**$^{S4-S5}$	0.75^{S3} **0.7** **± 0.05**$^{S2-S3}$	0.86^{S3} **0.8** **± 0.06**$^{S2-S3}$

Speed expressed in m/s for linear segments of lane A and B. For each linear segment and each participant: maximal speed values ITCI^{max} and Joystick^{max} (first row) and mean speed values $\text{ITCI}^{top\text{-}30\%samples}$ and Joystick^{mean} (bold, second row), with corresponding standard deviations. Index of difficulty for each segment (of length l and width $w = 1.2$ m) is defined by ID = l/w. Speed levels S_2 to S_5 of wheelchair settings for maximal speed values and for speed values included in the computation of mean speed values are indicated as superscript. [a] Permobil wheelchair interfaced with mouth-stick.

the wheelchair settings. However, these values fail to characterize the ability of ITCI's user to consistently perform various maneuvers after acquiring skills in operating the ITCI during a period of training. An estimator used in this study was defined as the mean of the top speed values contributing from 30% of the number of samples, attempting to provide a measure that captures the best mean partly skilled performance out of a series of trials following an incomplete learning process. Even though not reported in the results section, two other estimators defined by the mean of top speed values within 25% of the maximum speed and within 50% of the maximum speed were analyzed. However, a less consistent number of samples, varying from 1% to 100% of total number of samples, contributed to these estimators, making them less reliable than the one reported. Ideally, such estimators should include speed values from the plateau area of the learning curve only for optimal characterization of the performance of the system, minimizing the influence of task-dependent or external factors inherent to the learning process [37]. However, the short-term training did not allow the participants to fully acquire the skills to overcome the influence of all possible factors (e.g. speed level of wheelchair settings, type of maneuver, experience in using the piercing as the activation unit, previous experience in maneuvering a wheelchair) in order to reach a plateau area towards the end of the learning curve, as can be seen in Fig. 3. Inevitably, a short-training design would introduce variability in the balance between trials required for learning and trials with acquired skills leading probably to a less robust comparison between ITCI and Joystick. Furthermore, even though the center of wheelchair was maintained within the edges of the lane for the trials contributing to estimates of speed reported in Table II and Table III, reporting accuracy by the number of obstacles hit may represent a less precise measure of accuracy, given the more qualitative nature of this measure. Reporting accuracy based on a quantitative measure such as deviations for the planned driving path [6] may better contribute to the analysis of performance of wheelchair driving.

Besides the speed and number of obstacles hit reported in this study, analysis of linear fit movement time versus index of difficulty for linear and maneuver segments attempted to approach analysis of performance according to the steering law for pointing devices controlling computers [34-36]. Even though one cannot directly compare performance of a pointing device controlling a computer to that of pointing device controlling a wheelchair, given objective limitations (e.g. size, weight, speed settings of wheelchair, and linear acceleration), identification of categories of paths with associated index of difficulty possibly leading to validation of use of the steering law may be a valuable asset in performance analysis of such devices. The steering law defines the index of difficulty in an integral form on a general path, not including the shape of the path in this form. Only particular shapes of the path have been tested [35]. Chained shapes such as the ones found in lanes requiring complex maneuvers have not yet been tested. Possible effect of the types of start and end segments of a given segment of the lane A and B in the variability in the linear model, MT vs. ID (Table IV), may emphasize the importance of considering measures of difficulty associated with the start-end maneuvers to that of the linear segment,

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TABLE IV: LINEAR CORRELATIONS

Lane	Par01			Par04			Par02				Par03[a]			
	able-bodied participants						participants with tetraplegia							
*Linear correlation for mean speed Joystick^{mean} vs. ITCI$^{top\text{-}30\%samples}$ according to $s^{Joystick} = a*s^{ITCI}$ or $s^{Joystick} = b+a*s^{ITCI}$ (all with $p < 0.05$).														
Speed evaluated along lane A or B (linear segments and maneuvers) when driving with ITCI and Joystick. Degrees of freedom: 12														
A*	**R^2** 0.87	a 1.17	F 347	**R^2** 0.8	a 1.1	F 580	**R^2** 0.5	a 1.64		F 183	**R^2** 0.53	a 1.13		F 261
B*	**R^2** 0.8	a 0.98	F 236	**R^2** 0.82	a 1.05	F 508	**R^2** 0.52	a 0.64	b 0.62	F 12	**R^2** 0.71	a 0.57	b 0.36	F 27
**Linear correlation for MT$^{30\%samples}$ vs. ID: MT = a*ID or MT = b + a*ID (all with $p < 0.05$)														
Movement time MT$^{30\%samples}$ evaluated along maneuvers segments when driving with ICTI versus index of difficulty ID. Degrees of freedom: 5														
A**	**R^2** 0.97	a 3.46	F 360	**R^2** 0.97	a 1.59	F 325	**R^2** 0.94	a 2.79		F 187	**R^2** 0.9	a 3.7		F 109
B**	**R^2** 0.94	a 3.71	F 186	**R^2** 0.97	a 1.53	F 309	**R^2** 0.94	a 3.73		F 195	**R^2** 0.95	a 4.11		F 102
Movement time MT$^{30\%samples}$ evaluated along linear segments when driving with ITCI versus index of difficulty ID. Degrees of freedom: 6														
A**	**R2** 0.85	a 1.26	F 176	**R^2** 0.81	a 0.87	F 147	**R^2** 0.8	a 1.89		F 94	**R^2** 0.68	a 2.32		F 73
B**	**R^2** 0.93	a 1.24	F 261	**R^2** 0.9	a 0.89	F 200	**R^2** 0.79	a 1.6		F 134	**R^2** 0.62	a 2		F 57

Coefficient of determination R^2, model parameters a and b, F value, and p value resulted from data fit with linear model (one or two parameters). The speed along a corresponding segment was denoted as $s^{Joystick}$ and s^{ITCI} for driving with Joystick and ITCI, respectively. [a]Permobil wheelchair interfaced with mouth-stick. For linear correlation movement time MT$^{30\%samples}$ vs. index of difficulty ID the slope a of the linear regression is expressed in s/bit.

linking the two maneuvers. Finally, factors like the length of the linear segment and the speed level setting (i.e. the ability of the wheelchair to drive faster) should be additionally considered. The linear segment was chosen as an example in the MT vs. ID analysis of this study as it belongs to the tunnel category exemplified in the literature [35]. However, the same issue of conditioning of the pre- and post- segments of any segment of a chained path may be considered in the performance analysis for the steering tasks. The inverse of the slope (the a parameter in Table IV) may discriminate between the effect of the user's ability to control the ITCI and the type of the lane when analyzing performance on linear segments. Furthermore, the type of the lane indirectly reflects the effect of the segment preceding and following the segment under analysis. Analysis of maneuver segments may have a higher degree of uncertainty since grouping these maneuvers into the same category may not be straightforward. In this study, unadapted speed and inadequate entry direction were noted in a segment that required additional maneuvers for maintaining the wheelchair within the limits of the corresponding segment.

B. Sources of Variability

Comparing the ITCI speed to that of the Joystick may represent a relative measure when evaluating the ability of these systems to control a powered wheelchair. The already acquired skills and learning rate in controlling the Joystick and ITCI, along lane A or B or segments of the two lanes, may vary between and within the two groups of participants (able-bodied participants, Par01 and Par04, and participants with tetraplegia, Par02 and Par03). Par02 controlled the standard hand-operated Joystick using the remaining abilities of the left hand (incomplete tetraplegia) during the Joystick trials. As a daily user of this control system, this participant chose speed levels S4 and S5 and obtained the best results (Fig. 3 and Table I). Par03 occasionally used the mouth-stick joystick (i.e. a mouth operated version of joystick) at home and chose S2 and S3 speed levels for the Joystick trials. Par03 obtained the lowest mean speed (both maximal and mean of mean) along lane A or B when using Joystick, close to and under that obtained by Par01. Par03 had similar results to Par01 and Par02 when driving along lane A and B with ITCI. However, Par03 had a higher number of obstacles hit, the highest among all participants, where Par01, Par02, and Par04 had a relative low number of obstacles hit. The seat of the wheelchair was leaned more backwards in the case of Par03, reducing the visibility in the nearby vicinity of the front wheels of the wheelchair. In addition, the relatively low cone shapes marking the obstacles of the lane, with a cone height of just 0.15 m that represented a flaw in design of the lane, may possibly explain a higher number of obstacles hit for Par03. Par04 obtained the second best results (tightly close to that of Par02) for Joystick. However, Par04 obtained the best results when driving with ITCI along lane A or B. Furthermore, even though the steering law has not been validated for powered wheelchairs driving on types of lanes used in this study and considering the aspects outlined in the previous subsection, a look at the index of performance (the inverse of the slope parameter a of the linear regression from Table IV) may possibly indicate a similar analysis of speeds estimators along segments (Table II and Table III) as that of speeds estimators along the lane A and B (Table I). As such, Par04 differentiated with the best results from Par01, Par02, and Par03 that had more or less similar results when driving with ITCI along maneuver and linear segments of the lane A and B. Nevertheless, parameters of the linear fit between mean speed values of the two systems (Table IV) shows the ability of the ITCI to follow that of Joystick in providing control of a wheelchair when driving along segments of the two lanes, as shown in the case of the two able-bodied participants Par01 and Par04. Lower performance could be seen in Par02 and Par03 possibly due to lower training experienced with ITCI

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gained during the short-term training.

Par04 obtained the best results when driving with ITCI probably due to the ability to maneuver the activation unit at the surface of the two sensors pads. This was also proven in a previous computer experiment [26] and may be due to the fact that this participant has had a jewelry tongue piercing for nine years. Par04 reported using to play with the piercing every day, randomly touching and rubbing the teeth with the head of the jewelry piercing (i.e. the part corresponding to the activation unit installed on the shaft of the piercing during experiment). Par02 and Par03 have had their piercing implanted for 14 months and Par01 for five years.

The piercing was inserted at least one centimeter away from the tip of the tongue according to medical procedures, given anatomical particularities of the tip of the tongue [25]. The length of the shaft was chosen so that the two balls attached to the shaft did not exert pressure on the tongue. Inappropriate pressure exerted by these balls on the tongue may generate an ischemic process. Given this length, the piercing changed position when placed normal to the surface of the sensors and moved along that surface, creating an angle between the flat top of the activation unit, reducing sensors' sensitivity of detection of the activation unit. This effect was enhanced at the margins of the pads, especially when attempting to activate the lowest row of sensors of the mousepad (Par04 was able to twist the tongue compensating for this effect, given the experience from playing with the jewelry piercing, prior to participating in the study). This issue was not present when a 5 mm diameter and 2 mm height flat cylindrical activation unit is glued to the tongue. Maximal mean speeds obtain in this study higher than those obtained in a previous pilot study by an able-bodied person with glued activation unit [23] suggest that the ITCI is able to overcome this negative aspect of the piercing.

The choice of speed level at the participant's convenience for consecutive trials may introduce variability in the learning process. However, adapting the participant's current ability of controlling the wheelchair to the wheelchair settings may increase the learning rate. Nevertheless, the number of trials reached within the experimental time frame by each participant makes comparison of the learning curves within participants uneven with respect to the data interpretation.

C. Comparative Analysis

Evaluation of the added value of an assistive device for persons with tetraplegia is often based on comparison with standard control devices, with assistive devices currently used at home, or with emerging designs. The basis of comparison is often given by a performance function or metrics and user requirements. Comparison is, however, not always straightforward as design and evaluation of performance as well as consideration of user requirement may vary for each assistive device.

Our study demonstrated wheelchair control with a version of ITCI requiring a tongue piercing in two participants with tetraplegia along a driving lane including maneuvers and linear driving. Reference to the ability of two able-bodied participants to control the wheelchair with ITCI has been added in the study to outline possible specific differences between the two groups, even though all participants fulfilled the inclusion criterion of normal physiological control of the tongue. Furthermore, driving ability when controlling the wheelchair with ITCI has been compared to that when controlling the wheelchair with the standard joystick (mouth-stick in one participant with tetraplegia) on the same lane.

Earlier in this section, we raised concerns on validity of the estimators used in comparison between Joystick and ITCI, given the initial level of expertise in maneuvering the joystick and considering the short-term character of the learning process involved. Analysis of dynamics of the joystick movements and of completion times for various tasks during three trials of right and left maneuvers according to the Wheelchair Skills Test (v 4.1 guidelines) reported differences between expert wheelchair users (10 participants with reduced mobility due to neuropathy or diabetes) and novice (13 able-bodied participants) when controlling the powered wheelchair with a standard joystick [42]. Lower speed settings were chosen for the novice group, whereas participants from the expert group were allowed to decide which speed setting to be used in the study, based on their experience. Mean completion time of 6.26 ± 2.73 s and 4.40 ± 2.14 s were reported for the novice and expert group, respectively, while performing Turns 90^0 While Moving Forward along a path of approximate 6 m length, with no statistically significant difference between the groups. Mean completion time of 11.29 ± 7.07 s and 6.63 ± 4.59 s were reported for the novice and expert group, respectively, while performing Turns 90^0 While Backward along a path of approximate 6 m length, with statistically significant difference between the groups. Mean completion time of 12.93 ± 6.59 s and 8.41 ± 4.46 s were reported for the novice and expert group, respectively, while performing Rolls Backward along a linear path of 5 m length, with statistically significant difference between the groups. The estimated mean speeds would be 0.96 and 1.36 m/s (forward turns), 0.53 and 0.9 m/s (backward turns), and 0.39 and 0.59 m/s (rolls backward) for the novice and expert group, respectively. Participants from novice and expert group performed Turns 180^0 in place within a confined square space of 1.5^2 m in 8.36 ± 5.45 s and 5.80 ± 3.81 s, respectively. Attempting to calculate a mean speed given a mean path for the wheelchair movement, we estimated the mean path at 1.95 m as a radial path allowing to rotate a wheelchair of 0.6 m width within the square with sides of 1.22 m representing the confined space. Estimated mean speed along this circular path within a confined space would be 0.23 and 0.33 m/s for the novice and expert group, respectively. We reported the same U-turn maneuver, however denoted as 360^0 turn, along a 4.9 m circular path (i.e. larger confined space). Based on these estimated mean speed values and mean speed values from Table II, one may suggest that Par02 (participant with tetraplegia) and Par04 (able-bodied participant) driving abilities when controlling the wheelchair by joystick may be comparable to that of the expert group reported in [42]. Remarkably, Par04 never used a joystick controlled wheelchair, yet performance approached an expert level. This may be in line with the observation attempting to explain why statistically significant and statistically non-significant differences were observed when comparing completion times obtained by novice and expert groups in two different complex maneuvers (Maneuvers Sideways and Gets Through Hinged Door), suggesting additional factors in the ability to learn other than those acquired/used during a specific training program [42].

Driving a powered wheelchair using the Tongue Drive System along a lane of 1.2 m width an approximately 50 m length (13 turns and 24 obstacles) by 23 able-bodied and 11 participants with tetraplegia yielded a mean completion time of 207.7 ± 8.2 s (estimated mean speed of 0.24 m/s) and 179.9 ± 24.1 (estimate mean speed of 0.28 m/s) by the fifth and sixth training session, respectively, with a corresponding number of navigation errors of 2.1 ± 2.5 and 1.7 ± 2.0 [19]. The system used a latch control of the wheelchair provided by discrete commands that allowed increase and decrease of predefined wheelchair speed settings of 0.26, 0.35, and 0.44 m/s during forward drive and 0.26 m/s during backward drive. After latching the wheelchair speed on one of these speed levels, right and left commands could be issued to deviate forward and backward drive to left or right when needed. Six participants with tetraplegia completed the same lane in 182.4 ± 22.3 s (estimated mean speed of 0.27 m/s) with 2.6 ± 2.2 errors by the sixth session, controlling the powered wheelchair with their own sip-and-puff home system. According to Table I, estimated mean speed value for ITCI of 0.36 and 0.67 m/s (number of hits 0.25 and 0.33) by the two able-bodied participants and 0.39 and 0.43 m/s (number of hits 0.5 and 3) were obtained by the two participants with tetraplegia during the short-term training.

The quantitative analysis presented above attempted to provide reference numbers for the estimated mean speed values presented in this study. Their relation must be, however, interpreted on a much broader basis including careful consideration of methodological differences and user requirements. For example, we could not find clear explicit information regarding the width of the test lanes and crossing failures for tasks, neither indication of an equivalent path for more complex tasks Maneuvers Sideways and Gets Through Hinged Door [42]. Moreover, statistics of completion times obtained on test lanes of different parameters may not be directly translated in statistics of speed values, considering as well a variable number of participants included in these statistics [19], [42]. Nevertheless, a more thorough review of data reported in other studies [6], [15], [17], [43] for assistive devices for persons with tetraplegia controlling a powered wheelchair, considering reports on able-bodied participants as well, would be required to provide a more appropriate and balanced presentation between quantitative and qualitative estimators.

D. Conclusive remarks

Operation of the ITCI for wheelchair control was demonstrated with two participants with tetraplegia in a short-term training study, including as well two able-bodied participants.

This feasibility study reports comparative quantitative and qualitative data on ITCI and Joystick ability to control a powered wheelchair on a low number of participants within an experimental design of short-term training. Increasing the number of participants, duration, number of trials associated with each speed level of the wheelchair for both systems, defining measures of difficulty for chained paths of various forms, identification of test lanes for validation of maneuverability of the wheelchair driving, and a quantitative evaluation of accuracy must be considered in future studies.

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Eugen R. Lontis received the M.Sc. degree in electronic engineering from the Polytechnic University of Timisoara, Romania, in 1995, and the Ph.D. degree in biomedical engineering from Aalborg University, Denmark, in 2006. He is Associate Professor with the Center for Neuroplasticity and Pain, Department of Health Science and Technology, Aalborg University. His current research interests include neuromodulation and assistive devices for rehabilitation.

Bo Bentsen is Associate Professor at Aalborg University and holds a DDS from The Royal Dental College, Aarhus 1984 and a Ph.D. degree in odontology from Aarhus University, Faculty of Health Sciences 2002. He currently works part time at Aalborg University, Faculty of Medicine, Department of Health Science and Technology, Center for Rehabilitation Robotics. His research has focused on developing and teaching the clinical aspects of the Tongue Computer Interface and the development of a clinical protocol for medical tongue piercing.

Michael Gaihede is Clinical Professor and Chief Physician at the Department of Otolaryngology, Head & Neck Surgery, at Aalborg University Hospital, where clinical experiments with tongue piercings have been performed and refined for optimal safety and function. MG is also involved in audiological, vestibular, and middle ear research together with biomarkers of Head & Neck carcinomas and other fields of research within the medical specialty.

Fin Biering-Sørensen is Clinical Professor at University of Copenhagen and Consultant at Department for Spinal Cord Injuries at Rigshospitalet, Copenhagen, Denmark. Visiting professor at the Spinal Cord Unit, Sunnaas Rehabilitation Hospital, Norway, and Visiting professor at Peking University Third Hospital, Beijing, China. Extensive lecturing worldwide. Supervised more than 20 PhD students. h-index 74, 365 articles in PubMed, 35 book-chapters, 75 proceedings, etc. The research in particular related to individuals with spinal cord injury.

Lotte N. S. Andreasen Struijk received the B.Sc.E.E. degree from the Engineering College of Aarhus, Denmark, in 1993, the M.Sc.E.E. degree from Aalborg University, Denmark, in 1996, and the Ph.D. degree in biomedical engineering from the Center for Sensory-Motor Interaction, Aalborg University, in 2002. She is currently an Associate Professor at the Department of Health Science and Technology, Aalborg University, where she is head of the Center for Rehabilitation Robotics. Her research include exoskeletons, rehabilitation robotics and interfaces for robots and computers based on tongue, brain and muscle signals, and hybrids of these.