Head Motion and Head Gesture Based Robot Control for Tetraplegics: A Usability Study

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***Abstract*—The assistive robot system AMiCUS -Adaptive Head Motion Control for User-friendly Support- has been developed to increase the autonomy of motion impaired people. Especially tetraplegics benefit from collaboration with AMiCUS. The six degrees of freedom robot arm with gripper is controlled with head motion and head gestures only. For validation of the AMiCUS interaction technology and design a usability study with a total number of 30 subjects was conducted. 24 able-bodied subjects of demographically diverse groups and 6 tetraplegics participated in this work. All subjects performed different pick and place tasks by controlling AMiCUS.**

The evaluation of the interaction design was carried out subjectively with a questionnaire as well as objectively by measurement of time needed to complete the control tasks and the error rate of head gestures. The influence of several factors like age, sex, motion impairment and previous experience on head motion based human-robot interaction was analysed. The interaction design has been proven successful in laboratory environment and assessed overall positive by the subjects. Future work will concentrate on the improvement of the head gesture recognition process to increase adaptability and robustness. Furthermore, a next step is the development of an AMiCUS working place for a librarian.

***Index Terms*—assistive technology, head gesture, human-robot interaction, inertial measurement unit, usability study**

I. INTRODUCTION

The incidence of Spinal Cord Injury (SCI) worldwide ranges from 250 000 to 500 000 per year [1]. The damage of the spinal cord is mostly caused by injuries like falls, vehicle accidents and violence. Typical causes for non-traumatic SCI are infections of the spine, diseases of the vessels and tumors. Symptoms of SCI vary depending on location and extent of injury. Therefore, SCI can be classified according to American Spinal Injury Association (ASIA) corresponding to the location of injury in terms of the last intact vertebral segment with additional information about the completeness of neurological deficit.

Tetraplegia is a partial or total paralysis of all four limbs, trunk and pelvic organs [2]. The main cause of tetraplegia are traumatic SCIs with a damage of the cervical segments of the spinal cord [3]. For people suffering from tetraplegia, almost all activities requiring a user interaction are very tedious or even impossible without the help of assistants or assistive devices. A review of several assistive devices, which can be used by tetraplegics is given in [4]. Hands-free assistive devices for tetraplegics can be controlled for example with speech interfaces, chin-joysticks, motion of the eyes, tongue or the head. The usage of gestures provides a further opportunity for hands-free interaction. Gestures are deliberate movements of the body or parts of the body. They can be used as input for control interfaces. Within this work, we focus on head motion and head gesture based control.

Most of recent head motion and head gesture based interfaces are limited to two-dimensional applications as the control of wheelchairs or the control of a mouse cursor in human-computer interaction. Head controlled computer mice are commercial available e.g. the wireless gyroscope mouse Quha Zono [5] or the infrared optical mouse HeadMouse® Nano [6], but also as free downloadable software e.g. Camera Mouse, which uses a standard webcam [7]. Oppenheim et al. capture head gestures with a webcam in order to control switchable software [8]. Further technologies use inertial measurement units (IMUs) to capture the head motion as input of a mouse emulator [9], [10]. As already mentioned, the control of a wheelchair is another frequent application of head motion and head gesture based interfaces with IMUs [11], vision based interfaces [12], [13] or hybrid technologies using camera and IMU [14].

To control complex systems, an interaction design to address more than two degrees of freedom is essential. Fall et al. [15] use several inertial measurement units to capture the position of the head and the shoulders for the control of a robot. In our previous work, Rudigkeit et al. [16] applied a single IMU fixed on a hairband for the control of an assistive robot. This was part of the first version of the AMiCUS assistive robotic system. Human-robot interaction provides the opportunity to create workplaces for tetraplegics, as well as to increase their autonomy in activities of daily living. The potential of semi-autonomous assistive robots for disabled people in activities of daily living is presented by Chen et al. [17]. Hands-free human-robot interaction can even provide an opportunity to (re)integrate disabled people into working life. The robotic system FRIEND supports a person with tetraplegia to retrospectively catalogue books and therefore to work as a librarian [18].

Semi-autonomous robot control combines the advantages of autonomous robots with human superior perception. Autonomous robots offer precision, perseverance, power, high repetition rates and accuracy. In contrast, humans are superior in perception, organizational skills and understanding of new scenes and situations by use of their sensory organs and cognitive reasoning. The abilities of both parts are synergized

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due to cooperation of human and robot in semi-autonomous robots. In unpredictable situations, which are challenging for autonomous robots, the user has the possibility to control the robots movements directly. Moreover, user satisfaction is assessed higher for the ability of direct robot control, than for purely autonomous operation [19].
Within this work, the usability of interaction technology and design for direct control of a robot with head motion and head gestures is tested.

II. Previous Work

The **A**daptive Head **M**ot**i**on **C**ontrol for **U**ser-friendly **S**upport - AMiCUS has been developed in our group for hands-free human-robot interaction [16]. With AMiCUS the end-user controls a semi-autonomous assistive robot intuitively with head motion. The robotic system AMiCUS focuses on the application as assistive system for motion impaired people, who cannot use their upper limbs, e.g. tetraplegics. AMiCUS will be applied in a library working place, where the end-user catalogues books with the help of the assistive system [20]. The application scenario is shown in Fig. 1. It is defined by the semi-autonomous robot which takes a book from a bookshelf, places the book in front of the tetraplegic person and opens the book. The motion impaired person catalogues the book, the robot closes the book and put it away on a bookshelf. Afterwards the actions are repeated in order to catalogue the next book. The end-user initiates the actions and has the possibility to intervene and control the robot directly with head motion. To guarantee the safety of the end-user, the user is placed outside the range of motion of the robot arm and gripper. A safety distance between the maximum range of robot motion and the end-user ensures that the robot never can reach the end-user, even with gripped objects. To avoid uncontrolled movements of the robot, large joint variations are blocked by the AMiCUS software. However, the library scenario will be realised in future work. In this paper the development and test on usability of basic pick and place tasks with the assistive robot system AMiCUS in a laboratory environment is reported.
The process for research and development on AMiCUS is characterized by Technology Readiness Levels (TRLs). These levels specify the maturity of the technology on a scale from 1 to 9 [21]. At the lowest TRL, basic principles are observed and reported. The human head has three degrees of freedom (DOFs) roll φ, pitch ϑ and yaw ψ, while the assistive robot has six DOFs and the gripper provides the seventh DOF. Rudigkeit et al. [16] propose a mapping, which divides robot and gripper movements into four control groups to allow an intuitive head motion based robot control with AMiCUS. This mapping defines the basic interaction technology concept and is based on TRL 2. Analytically recognized head gestures were implemented as interaction elements to switch between control groups. An experimental proof of concept (TRL 3) was performed with ten subjects to evaluate the head gesture based interface in our previous work [22]. Design and redesign cycles of the human-robot interaction including various interaction elements for switching have been performed and tested by a tetraplegic person in the laboratory environment. The next step corresponding to TRL 4 is to test the usability of the proposed interaction design with specified pick and place control tasks. The evaluation of the usability study with 6 tetraplegic persons and 24 persons without motion impairments is presented in this paper. A detailed overview on subjects, AMiCUS hardware and interaction design, experimental setup and the evaluation criteria is given below.

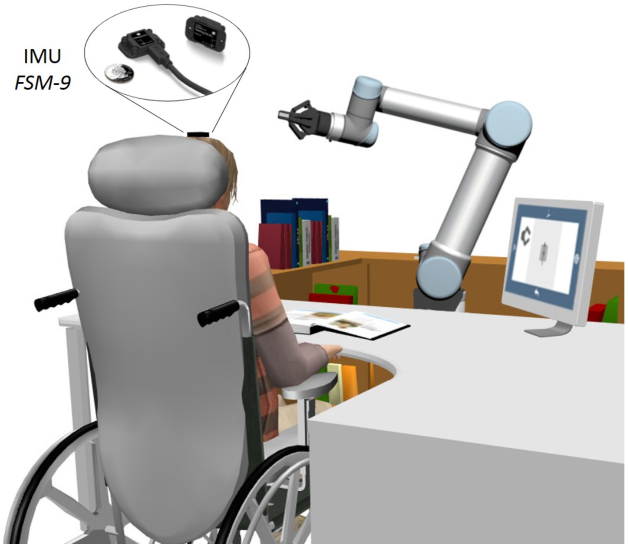


Fig. 1. Application scenario. The assistive robot AMiCUS supports a motion impaired person to work as a librarian. The AMiCUS system is controlled with the end-user's head motion captured by an inertial measurement unit (IMU).

III. Research Goal

This paper presents a test on usability for the assistive robot system AMiCUS in laboratory environment. Pick and place tasks are defined to validate head motion and head gesture based robot control. In future work the AMiCUS system will be applied to a working scenario in a library on the basis of the presented usability evaluation.

IV. Methods

The first design and redesign cycles for the assistive robot system AMiCUS have been carried out with support of a tetraplegic person. She has tested components of the proposed interaction design and the development was adapted according to her inputs. After optimisation of the interaction design, specific pick and place tasks for the usability test presented below have been defined. The pick and place tasks have been chosen to guarantee the best possible access and individual assessment on all degrees of freedom on robot motion. 30 people have been involved in the usability study. The influence of the parameters age, sex, motion impairment and previous experience on the performance of the interaction with AMiCUS was analysed. The ethical committee of the University of Bremen gave its approval to carry out the usability study.

TABLE I
DEMOGRAPHIC PROFILE OF THE SUBJECTS.

ID	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
Age	22	19	24	24	21	21	25	25	24	30	23	24	45	43	67	60	43	57	60	45
Sex	f	f	m	m	m	m	m	f	f	m	f	f	f	m	f	m	m	m	m	m
Previous Experience	-	1h	-	1h	-	1h	-	1h	-	1h	-	1h	-	1h	-	-	1h	-	1h	-
AIS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

ID	21	22	23	24	25	26	27	28	29	30
Age	53	43	48	59	28	46	42	39	27	36
Sex	f	f	f	f	m	m	m	m	m	m
Previous Experience	1h	1h	-	1h	-	-	-	-	-	-
AIS	-	-	-	-	C4 B	C4 A	C3 A	C3 B	C3 A	C3 A

A. *Subjects*

A total number of N=30 subjects, including 24 able-bodied persons and 6 tetraplegics, participated in the usability study. Table I shows the demographic profile of the subjects.

The 24 able-bodied subjects formed two age groups. In one age group, the subjects were supposed to be between 18 and 40 years old, in the other group, they should be older than 40 years. The subjects were recruited with announcements on the university website and in the local newspapers. The age of junior group members ranged from 19 to 30 years (M=23.50, SD=2.75). The senior participants are of age between 43 and 67 years (M=51.92, SD=8.45). In both age groups, an equal number of 6 males and 6 females participated in the study. 12 subjects, 6 subjects of each age group with an equal number of males and females already had experience of about one hour with AMiCUS in a first version graphical user interface.

The tetraplegics age ranged from 28 to 46 years (M=36.33, SD=7.60) and they all were male. All these subjects have been suffering already several years from tetraplegia, caused by traumatic spinal cord injuries. The movement limitations vary across the subjects.

B. *Materials*

1) Hardware: AMiCUS uses the Inertial Measurement Unit FSM-9 by Hillcrest Laboratories [23] to capture users head motion. This nine-axis IMU allows a precise motion measurement due to fusion of the sensor data from three accelerometers, three gyroscopes and three magnetometers. Due to on-board sensor fusion, sensor orientation is available as an output. IMUs are well suited for human-robot interaction, due to their precise motion measurement, small size, energy-efficiency and their self-contained unit.

The end-users head motion is mapped to motion of the robot UR5 by Universal Robots [24] and the adaptive gripper 2-Finger Robotiq 85 [25]. The graphical user interface is shown on a 27-inch screen placed in the back. Several pick and place control tasks were designed and placed on a table in front of the end-user including soft toy cubes and platforms built of LEGO® DUPLO®.

2) Interaction Design: The human head can be moved in three degrees of freedom (DOFs), namely roll φ (lateral flexion), pitch ϑ (flexion/extension) and yaw ψ (rotation). The assistive robot has six DOFs and the gripper has one DOF to be controlled. Based on the control structure presented in our previous work [16], the seven DOFs of robot and gripper are divided into four control groups for intuitive head motion based control (Fig. 2):

1) **Vertical Plane** The gripper is moved in a vertical plane by pitch ϑ and yaw ψ movements of the head
2) **Horizontal Plane** The gripper is moved in a horizontal plane by pitch ϑ and yaw ψ movements of the head
3) **Open/Close Gripper** The gripper is opened and closed by pitch ϑ movements of the head
4) **Orientation** The gripper is rotated according to head orientation (φ, ϑ,ψ)

To switch between the four control groups and to enable and disable robot control, head gestures are performed by roll φ and pitch ϑ movements. Head gestures are conscious movements of the head that differ from the movements for direct robot control. An analytical algorithm [26] is executed to recognize the gestures. The captured data is segmented with activity-based windowing. If the window has a suitable length, a Gaussian function is approximated to the head angle in the dominating DOF. Comparison of the calculated parameters to defined thresholds results in classification of the head gestures. Human-robot interaction is supported with a graphical user interface (GUI), which gives all relevant information to the end-user. The GUI shows the switching options, indicates the chosen robot control group and occurring errors and gives feedback on the current head orientation and gesture performance. Moreover, instructions how to calibrate the neutral position, the gesture parameters and the range of head motion are given during the calibration routines.

To calibrate the neutral position, the end-user holds the head straight with the gaze directed to the centre of the robot and keeps the head stable for two seconds. The neutral position corresponds to the offset, which is compensated in further use. Thus, this calibration is mandatory at the beginning of every use.

Within the optional gesture calibration, the end-user performs each gesture for three times to provide training data for the recognition process. User-dependent thresholds are determined from this data and replace the empirically determined default thresholds.

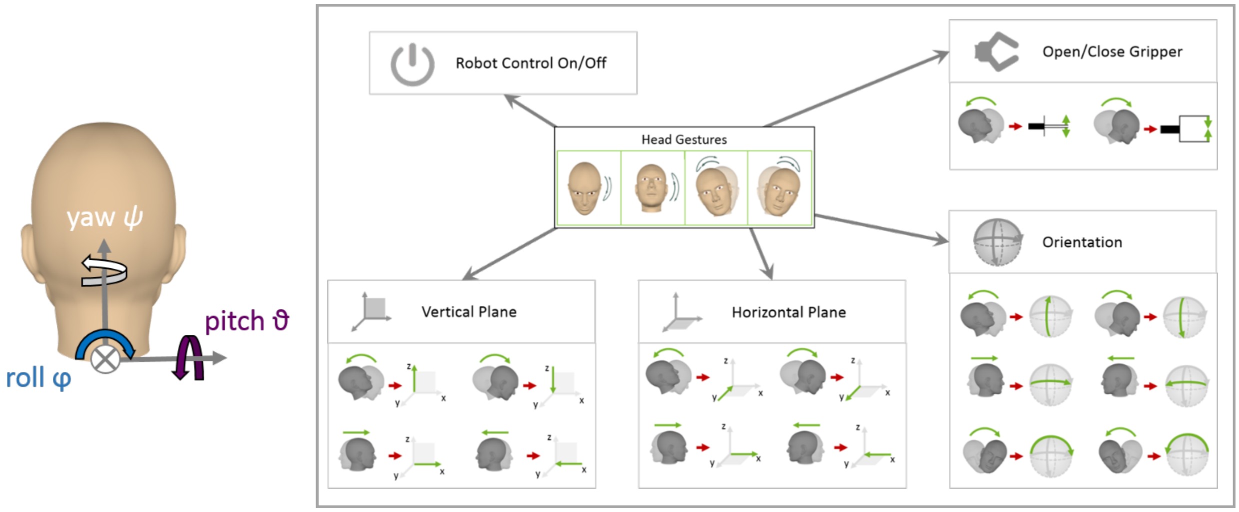


Fig. 2. Interaction design. The human head has three degrees of freedom roll φ, pitch ϑ and yaw ψ. For head motion based control, robot and gripper movements are divided into four control groups. Head gestures are used to switch between the groups and turn robot control on or off.

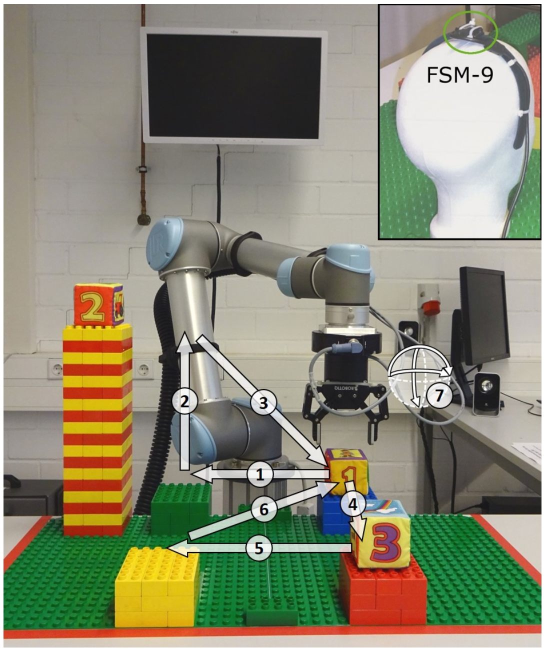


Fig. 3. Experimental setup and procedure of predefined task.

Moreover, the end-user can optionally calibrate the individual range of head motion used for robot control. The end-user moves the head to the maximum head angle in every degree of freedom roll φ, pitch ϑ and yaw ψ, which can be comfortable used for robot control. These maximum head angles are taken into account in the transfer of head motion to robot motion. The head orientation is mapped to the velocity of the robot, as comparison of different control modes pointed out, that velocity control is the preferred choice for this application [27]. Increasing the head angle relative to the neutral position accelerates the robot, decreasing the head angle decelerates the robot. Due to the shape of the used Gompertz function, there is a dead zone around the neutral position, which ensures that small head angles do not result in real robot movements.

3) Experimental Setup: The experimental setup is shown in Fig. 3. The sensor module was mounted on a headset-like carrier worn on top of the head in a way that sensor orientation and head orientation were identically. A calibration procedure for offset compensation was performed. For robot control, the head angle was mapped to the velocity of the robot UR5 and the gripper. Information and feedback on robot control for the end-user is given on a 27-inch screen placed in the back. Different control tasks with soft toy cubes and platforms built of LEGO® DUPLO® were placed on the table in front of the subject. All experimental parts have been supervised during the study and an emergency button was available for the case of unforeseen events.

C. Procedure

Upon arrival, the subjects were introduced to the robot control system AMiCUS and its head gesture based interaction design by a video. The subjects signed an information sheet and a declaration of consent. Afterwards, the subjects performed three experimental parts:

1) **Trial Session** The subjects tested the control of the AMiCUS robot system for about ten minutes. Within this time, they freely controlled the robot in order to explore robot control in the three translational and the three rotational degrees of freedom, as well as manipulation of the gripper. They tested the four head gestures and therefore trained how to switch between different control groups. Each robot control group was entered at least once. Moreover, gesture calibration was performed to determine user-dependent thresholds for gesture recognition.
2) **Predefined Task** The movement sequence of the predefined control task is illustrated in Fig. 3. The subjects were told which gesture they have to perform and how to move the cubes from one platform to another. The first three movements were performed in the *Vertical Plane* and the following three steps were performed in the

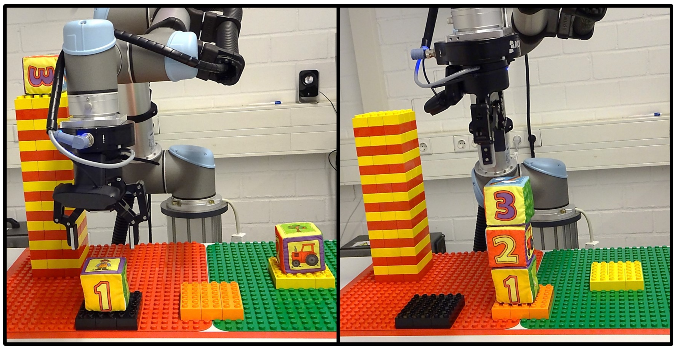


Fig. 4. Complex task. On the left, the initial constellation is shown. The subjects had to stack the cubes as presented in the photo on the right.

Horizontal Plane. Afterwards, three 90-degree rotations were performed. Between the described movements, the cubes were taken from or placed on the platforms. Every step was announced to the subjects.

3) **Complex Task** In the complex task, the subjects had to stack three cubes on top of each other with the numbers from 1 to 3 in the correct position and orientation. The subjects were briefed by a photo with the final cube arrangement. For this task with the setup shown in Fig. 4, the user had to grip, move, rotate and position the cubes by controlling AMiCUS without further instructions. The level of difficulty increased from positioning of cube 1 up to cube 3.

At the end of the experiment, the participants answered a questionnaire about the AMiCUS interaction design.

D. Evaluation Criteria

The interaction design was evaluated objectively as well as subjectively:

- **Objective Evaluation** The time the subjects required to perform the predefined task t_{def} and the time they needed to position the single cubes within the complex task $t_{Cube1-3}$ were measured. The time of the complex task t_{com} describes the time from the beginning of control until cube 3 has been released, no matter if the stack collapsed or all cubes were stacked in the correct orientation. If a subject moved a cube out of range, it has been placed at its previous position. The number of trials, the subjects needed for correct gesture performance and therefore switching between the different control groups were recorded.
- **Subjective Evaluation** For subjective evaluation, the participants assessed the statements of a questionnaire according to the Likert Scale with a value from 1 “I do not agree at all” to 5 “I totally agree”. The questionnaire is composed of a part relating to the graphical user interface, a part concerning gestures and a part regarding robot control in the different control groups. The statements of the questionnaire are listed in Fig. 8.

The Mann-Whitney U test with a significance interval of $p = 0.05$ is used to compare the variables among the different factors age, sex, disability and previous experience. This non-parametric statistical method was chosen because of the small sample size.

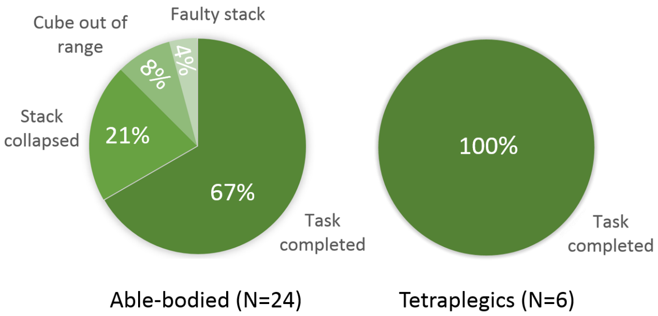


Fig. 5. Completion rate of complex task.

V. RESULTS

A. Completion Rate

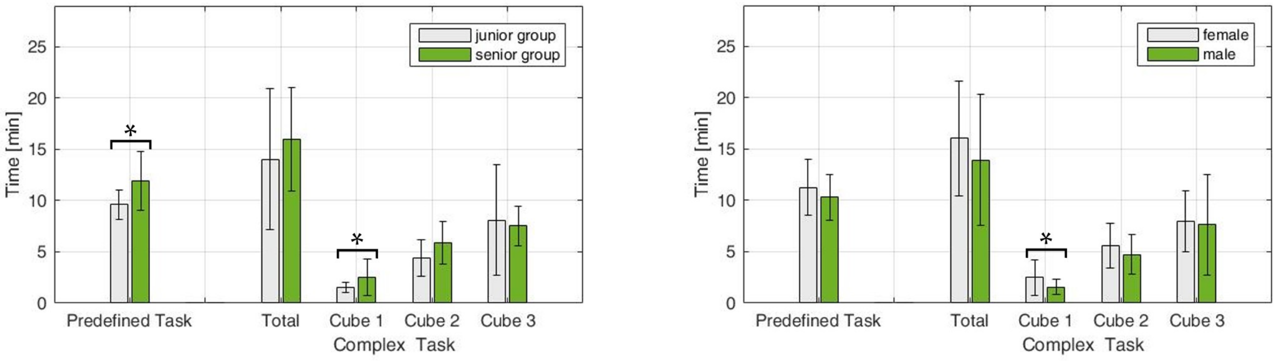
A first remarkable result is that all subjects were able to control the AMiCUS robotic system with head motion and head gestures. All subjects completed the predefined task correctly without any problems. Regarding the complex task, one third of able-bodied subjects did not stack the cubes appropriately, e.g. the stack collapsed or a cube was not stacked in the correct orientation. In comparison, all the tetraplegics subjects completed all tasks exactly as intended (Fig. 5).

B. Time

The time, the subjects needed to complete the predefined control task and to position the single cubes of the complex task were measured. To specify a minimum reference time, an experienced end-user performed the tasks with the result of about t_{def}=6 min to perform the predefined task and about t_{com}=6.5 min to complete the complex task (t_{Cube1}=0.8 min, t_{Cube2}=2.8 min, t_{Cube3}=2.9 min).

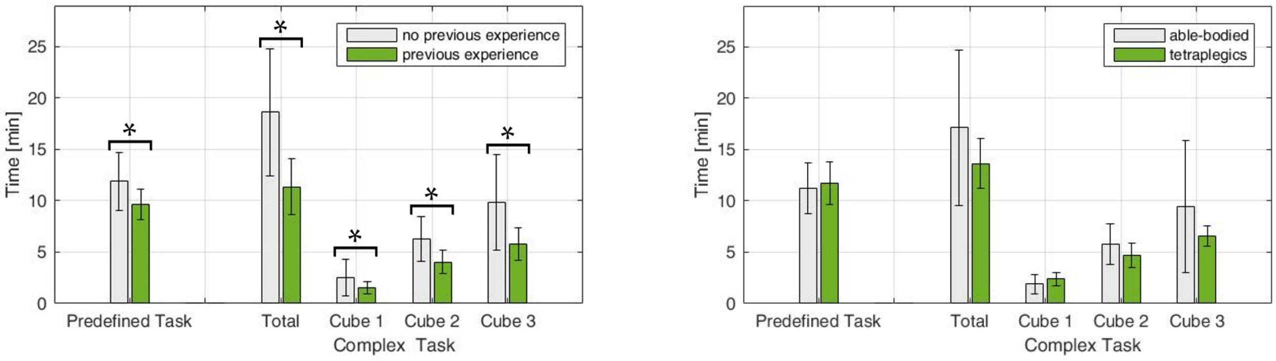
The results of the able-bodied subjects are analysed according to the factors age, sex and previous experience. The able-bodied participants are divided into two age groups. The subjects of the junior group are younger than 40 years, the subjects of the senior group are older than 40 years. Fig. 6a shows the average time and standard deviation needed to perform the different control and subtasks for subjects of the different age groups. With $t_{def-sen}$=11.94 min (SD=2.85) the time given by senior group members is significantly higher than the time of $t_{def-jun}$=9.61 min (SD=1.40), which subjects from the junior group needed to complete the predefined task. The younger subjects are significantly faster in moving and positioning the first cube, but the more complex the task, the smaller the time difference between the two age groups. The standard deviation in time for junior group members strongly increases with complexity of the control task.

Male subjects tend to complete the control tasks faster than female subjects (Fig. 6b). The time difference between female and male subjects for handling the cubes of the complex task is getting smaller from cube 1, which male subjects solved



(a) Time of able-bodied subjects in different age groups

(b) Time of able-bodied subjects of different sex



(c) Time of able-bodied subjects with different previous experience on head motion based robot control

(d) Time of male able-bodied subjects without previous experience and time of tetraplegic subjects

Fig. 6. Average time and standard deviation needed to complete the control tasks. Statistically significant differences concerning the different factors are marked with an asterisk ($*$).

significantly faster, to cube 3 with a negligible time difference. Subjects, who had already previous experience with AMiCUS, completed all control tasks significantly faster than first time users (Fig. 6c). Although the subjects worked with another graphical user interface in their previous experience with AMiCUS, they needed significantly less time to perform all the control tasks.

All tetraplegic participants were males, who did not have previous experience with head motion based robot control. To avoid an influence of the other factors, the factor disability is investigated by comparison of the results of tetraplegic subjects to male able-bodied subjects without previous experience. The results are shown in Fig. 6d. The subjects of both groups performed the predefined task approximately in the same time with t_{def-a}=11.26 min (SD=2.50) needed by the able-bodied subjects and t_{def-t}=11.75 min (SD=2.10) required by the tetraplegics. The able-bodied subjects completed the entire complex task in t_{com-a}=17.14 min (SD=7.54), while the tetraplegics needed t_{com-t}=13.64 min (SD=2.4). Regarding the time needed to position the single cubes 1 to 3, the able-bodied subjects are with a time of $t_{Cube1-a}$=1.90 min (SD=0.95) a little faster in the simplest subtask of positioning cube 1 than the tetraplegics who needed $t_{Cube1-t}$=2.39 min (SD=0.62). The tetraplegics are faster in positioning cube 2 ($t_{Cube2-t}$=4.69 min, SD=1.16) and cube 3 ($t_{Cube3-t}$=6.57 min, SD=1.03) than the able-bodied who solved the subtasks in $t_{Cube2-a}$=5.77 min (SD=2.00) and $t_{Cube3-a}$=9.48 min (SD=6.43). The standard deviation of the time, the able-bodied subjects required for the tasks increased with increasing level of difficulty, while the standard deviation of tetraplegics performance stays low for all tasks.

C. Head Gestures

In total, x=2 117 switching processes have been performed during the control tasks of the study. The number of trials, the subjects needed for correct gesture performance was recorded. The gesture performance of able-bodied subjects is very similar related to subjects age, sex or previous experience, there are no significant differences among these factors.

The average number of trials needed for correct gesture performance by all subjects slightly increased from the predefined task (M=1.44, SD=0.95) to the complex task (M=1.65, SD=1.37).

The tetraplegics performance of the gesture *Nodding Up* with M_t=1.67 trials (SD=1.57) is comparable to the able-bodied average number of M_a=1.55 trials (SD=0.98). Related to the gestures *Nodding Down* (M_a=1.40, SD_a=1.1 vs. M_t=2.15, SD_t=1.42), *Bending Left* (M_a=1.37, SD_a=0.63 vs. M_t=2.21, SD_t=2.82) as well as *Bending Right* (M_a=1.45, SD_a=0.77 vs. M_t=2.04, SD_t=1.95), able-bodied subjects are more successful

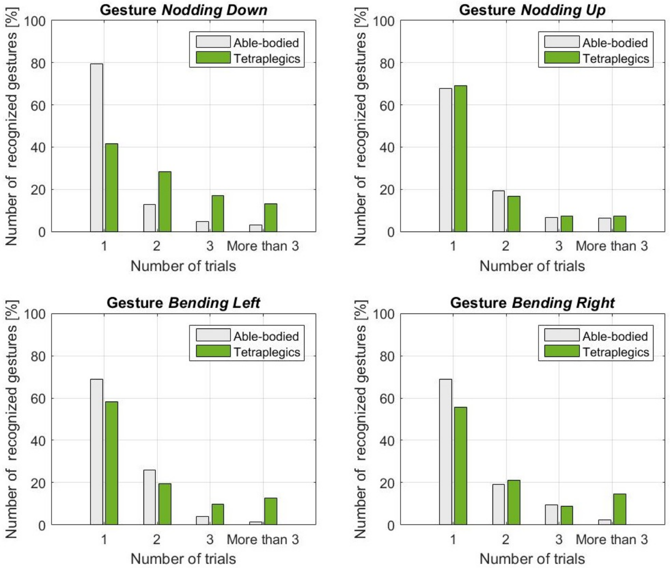


Fig. 7. Relative distribution of recognized head gestures across the number of trials for male able-bodied subjects without previous experience (white) and tetraplegics (green).

in the correct execution of gestures. Fig. 7 shows the distribution of recognized head gestures across the required number of trials for correct gesture performance. A remarkable result on gesture performance is given with the gesture *Nodding Down*. The able-bodied subjects performed this gesture in 79.37% correctly at the first trial whereas the tetraplegics have been successful in 41.51% of the cases at the first trial only.

D. Questionnaire

The subjective evaluation of the AMiCUS interaction design was carried out with a questionnaire (Fig. 8). The rating ranged from 1 “I do not agree at all” to 5 “I totally agree”. The graphical user interface was assessed positive by the subjects (M=4.22, SD=0.92). The performance of all four head gestures and therefore switching between the control groups was rated as easy and as fast (M=4.22, SD=0.91). Changing the position of the robot in the vertical plane (M=4.52, SD=0.71) and opening or closing the gripper (M=4.60, SD=0.72) were rated as most intuitive control groups. The subjects were able to imagine how the robot would move in these control groups, when they would perform certain head movements. Precise grasping is perceived as more challenging (M=3.63, SD=1.30). Moving the robot arm in the horizontal plane was rated as more difficult (M=4.01, SD=0.99) than control in the previous mentioned groups. Gripper rotation is assessed as the most difficult robot movement (M=3.19, SD=1.23).

VI. DISCUSSION

The impact of the factors age, sex, previous experience and motion impairment on robot control with AMiCUS have been analysed in the framework of the usability study. Other factors that could have influenced the users performance, but are not considered in the recent usability study are nervousness, spatial imagination, technical affinity, professional as well as private background of the subjects (e.g. experience with computers, VR games and simulations), interest and motivational factors.

A. Completion Rate

The tetraplegic people performed complex tasks more focused and precise than able-bodied subjects (Fig. 5). It is obvious that they consider the robot system as a challenge to get more autonomy. As the six tetraplegic people suffer from a damage of the spinal cord which was caused by traumatic injuries 6 up to 30 years ago, they are well aware of their options. Since years they are used to personal assistance with up to 9 assistive persons and up to 24 hours. The tetraplegics strongly exploit the remaining mobility of head, eyes and facial expression to communicate. Working together with the robot system without human support represents a real challenge for them. The able-bodied subjects are technique enthusiastic and motivated to take part in the study because of the opportunity to personally test an innovative cooperative robot. However there is a great difference in motivation and life resulting in better performance for the complex tasks for the tetraplegics.

B. Time

As shown in Fig. 6a, the younger subjects completed the control tasks faster, if the actions were announced or the control strategy was obvious. These participants often start moving the robot without further planning how to solve the task. However, the strategy of trial and error took a lot of time in more complex tasks. The older subjects who planned the tasks more adequately made up for the time needed before and are as fast as the younger ones for the most complex task. Especially for the very complex task, the junior members differ much more in time than the senior members (Fig. 6a) which most probably as well results from the trial and error strategy of the juniors.

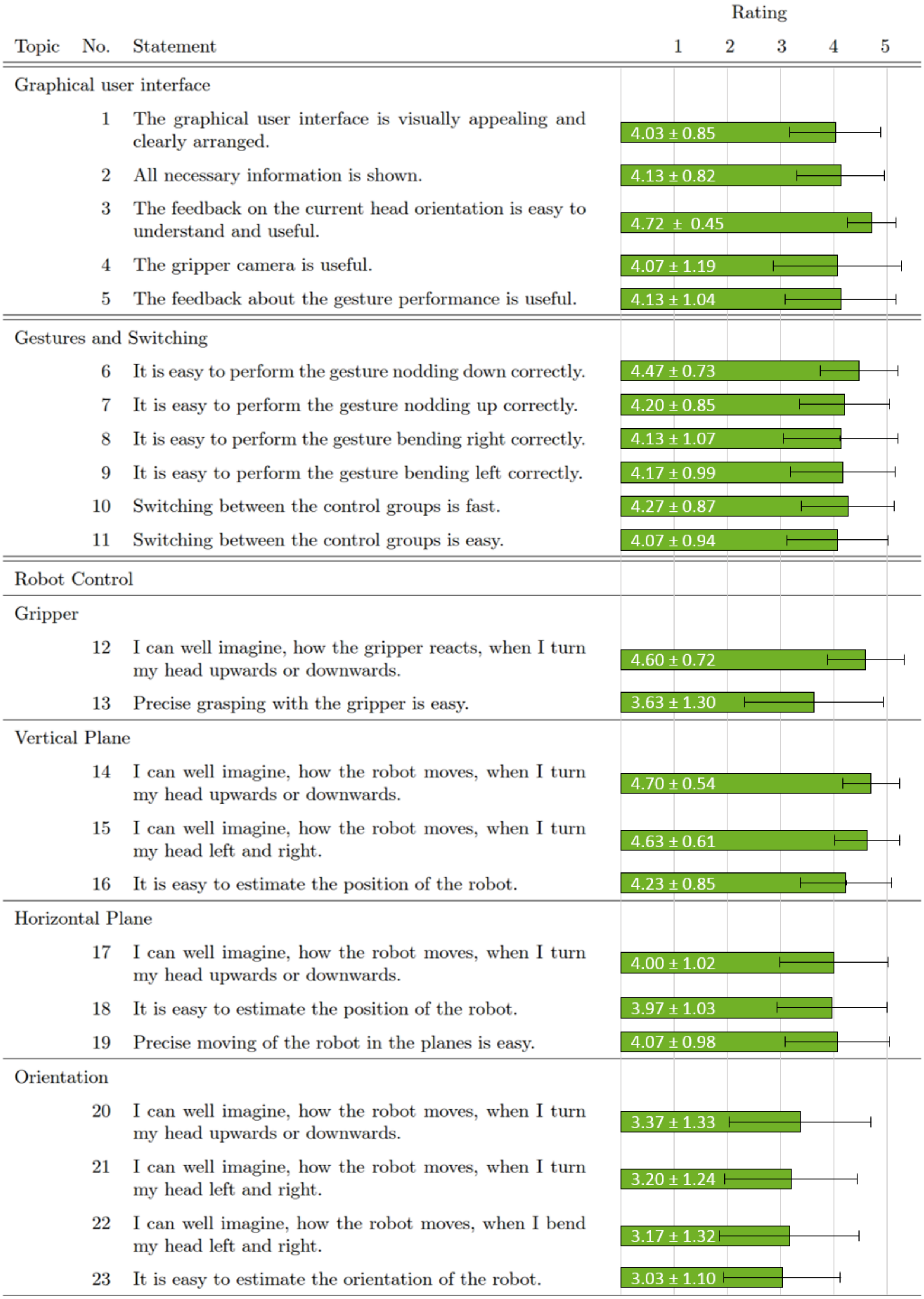
In general, younger and male persons have a higher technology affinity [28], which confirms their faster completion of control tasks (Fig. 6a-6b).

Even after about one hour of previous experience with AMiCUS an enormous learning effect can be seen in Fig. 6c. Despite the previous experience is related to another GUI, the subjects performed all control tasks significantly faster, when they already get used to head motion based control. The handling of the AMiCUS system is very fast to learn.

Tetraplegics are faster than able-bodied persons in the control of AMiCUS for complex tasks (Fig. 6d). As well as their higher completion rate, this result is founded on their motivation. Moreover the tetraplegics planned adequately how to solve the entire complex task before they started robot control.

C. Head Gestures

The objective evaluation points out a high error rate in gesture performance. The analytical gesture recognition prescribes the DOFs and the shape of the head gestures, which does not necessarily correspond to users intuitive head movements. The average number of trials needed for correct gesture performance was very similar for the predefined task and



Topic	No.	Statement	Rating
Graphical user interface			
	1	The graphical user interface is visually appealing and clearly arranged.	4.03 ± 0.85
	2	All necessary information is shown.	4.13 ± 0.82
	3	The feedback on the current head orientation is easy to understand and useful.	4.72 ± 0.45
	4	The gripper camera is useful.	4.07 ± 1.19
	5	The feedback about the gesture performance is useful.	4.13 ± 1.04
Gestures and Switching			
	6	It is easy to perform the gesture nodding down correctly.	4.47 ± 0.73
	7	It is easy to perform the gesture nodding up correctly.	4.20 ± 0.85
	8	It is easy to perform the gesture bending right correctly.	4.13 ± 1.07
	9	It is easy to perform the gesture bending left correctly.	4.17 ± 0.99
	10	Switching between the control groups is fast.	4.27 ± 0.87
	11	Switching between the control groups is easy.	4.07 ± 0.94
Robot Control			
Gripper			
	12	I can well imagine, how the gripper reacts, when I turn my head upwards or downwards.	4.60 ± 0.72
	13	Precise grasping with the gripper is easy.	3.63 ± 1.30
Vertical Plane			
	14	I can well imagine, how the robot moves, when I turn my head upwards or downwards.	4.70 ± 0.54
	15	I can well imagine, how the robot moves, when I turn my head left and right.	4.63 ± 0.61
	16	It is easy to estimate the position of the robot.	4.23 ± 0.85
Horizontal Plane			
	17	I can well imagine, how the robot moves, when I turn my head upwards or downwards.	4.00 ± 1.02
	18	It is easy to estimate the position of the robot.	3.97 ± 1.03
	19	Precise moving of the robot in the planes is easy.	4.07 ± 0.98
Orientation			
	20	I can well imagine, how the robot moves, when I turn my head upwards or downwards.	3.37 ± 1.33
	21	I can well imagine, how the robot moves, when I turn my head left and right.	3.20 ± 1.24
	22	I can well imagine, how the robot moves, when I bend my head left and right.	3.17 ± 1.32
	23	It is easy to estimate the orientation of the robot.	3.03 ± 1.10

Fig. 8. Questionnaire with mean and standard deviation.

the complex task. This indicates that repeated execution of gestures does not lead to a better gesture performance.

For the performance of the different head gestures, the head has to be moved in a specific degree of freedom. The following muscles are primarily used during the required head motion [29]:

- Gesture *Nodding Up*
  Movement: Extension
  Muscle: Mm. suboccipitales; M. sternocleidomastoideus
  Innervation (segments of the spine): N. suboccipitales (C1); N. accessories, Plexus cervicalis (C1-C3)
- Gesture *Nodding Down*
  Movement: Flexion
  Muscles: M. longus capitis; M. longus colli
  Innervation (segments of the spine): Plexus cervicalis (C1-C4); Plexus cervicalis und brachialis (C2-C8)
- Gestures *Bending Left/Right*
  Movement: Lateral Bending
  Muscles: Mm. suboccipitales; M. scalenus anterior; M. scalenus medius; M. scalenus posterior
  Innervation (segments of the spine): N. suboccipitales (C1); Plexus brachialis (C5-C7); Plexus cervicalis und brachialis (C4-C8); Plexus brachialis (C7-C8)

The gesture specific performance of the tetraplegic subjects can be explained by the muscles used for the required head motion and the innervation of the involved muscles. The gesture *Nodding Up* can be executed by able-bodied subjects and tetraplegics in the same manner, as the involved muscles are innervated by spinal nerves above the tetraplegics damage of the spinal cord. In comparison, the tetraplegics are not able to perform the gestures *Nodding Down*, *Bending Left* and *Bending Right* in the same manner as able-bodied subjects due their damage of the spinal cord below the segment C3 or C4.

D. Questionnaire

The assistive robot system AMiCUS was assessed overall positive in the subjective evaluation. All information and all functions needed for intuitive robot control was available on a clearly arranged and visually appealing graphical user interface. Even if the objective evaluation pointed out difficulties with head gestures, the participants subjectively perceived head gesture performance as easy. Control of the translational robot motions as well as opening and closing the gripper with head motion is assessed as very easy. Precise grasping is challenging with the used simple parallel gripper. Therefore, some subjects suggest additional feedback, when an object is firmly gripped. Rotations are more difficult to perform, because the current gripper orientation has to be taken into account and a higher spatial ability is required.

The subjective evaluation shows that AMiCUS allows an intuitive control of robot motion in all six DOFs, as well as gripper manipulation and therefore is well-suited for pick and place tasks.

VII. CONCLUSION AND FUTURE WORK

A. Conclusion

This work presents a fully elaborated, well prepared usability study in terms of subjective as well as objective evaluation with demographically diverse participants.

All subjects were able to control the six degrees of freedom robot and the gripper intuitively with head motions. The performed usability study pointed out that human-robot interaction with AMiCUS is well-suited for pick and place tasks in laboratory environment.

It has been shown that tetraplegic persons were proficient in handling the assistive robot AMiCUS. The AMiCUS system provides an opportunity to increase the autonomy of tetraplegics considerably.

B. Future Work

The head gesture performance and head gesture recognition pointed out a need for optimisation. The currently used analytical algorithm does not take into account individual demands and movement limitations. In future work, AMiCUS will provide a training and classification of individual arbitrary gestures using machine learning algorithms. The end-user will be able to define personal head gestures, which correspond to the individual intuitive head motion.

The successfully evaluation in laboratory environment lays the foundations for the transfer in relevant environment, which is a workplace in a library for motion impaired persons. With a validation in relevant environment, the maturity of the system will reach the next technology readiness level (TRL5).

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