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Analysis of Stress and Strain in Head Based Control of Cooperative Robots through Tetraplegics

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Abstract**—**Industrial robots as part of highly automated manufacturing are recently developed to cooperative (light-weight) robots. This offers the opportunity of using them as assistance robots and to improve the participation in professional life of disabled or handicapped people such as tetraplegics. Robots under development are located within a cooperation area together with the working person at the same workplace. This cooperation area is an area where the robot and the working person can perform tasks at the same time. Thus, working people and robots are operating in the immediate proximity. Considering the physical restrictions and the limited mobility of tetraplegics, a hands-free robot control could be an appropriate approach for a cooperative assistance robot. To meet these requirements, the research project MeRoSy (human-robot synergy) develops methods for cooperative assistance robots based on the measurement of head movements of the working person. One research objective is to improve the participation in professional life of people with disabilities and, in particular, mobility impaired persons (e.g. wheelchair users or tetraplegics), whose participation in a self-determined working life is denied. This raises the research question, how a human-robot cooperation workplace can be designed for hands-free robot control. Here, the example of a library scenario is demonstrated. In this paper, an empirical study that focuses on the impact of head movement related stress is presented. 12 test subjects with tetraplegia participated in the study. Tetraplegia also known as quadriplegia is the worst type of spinal cord injury. In the experiment, three various basic head movements were examined. Data of the head posture were collected by a motion capture system; muscle activity was measured via surface electromyography and the subjective mental stress was assessed via a mental effort questionnaire. The muscle activity was measured for the sternocleidomastoid (SCM), the upper trapezius (UT) or trapezius pars descendens, and the splenius capitis (SPL) muscle. For this purpose, six non-invasive surface electromyography sensors were mounted on the head and neck area. An analysis of variance shows differentiated muscular strains depending on the type of head movement. Systematically investigating the influence of different basic head movements on the resulting strain is an important issue to relate the research results to other scenarios. At the end of this paper, a conclusion will be drawn and an outlook of future work will be presented.

Keywords**—**Assistance robot, human-robot-interaction, motion capture, stress-strain-concept, surface electromyography, tetraplegia.

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I. INTRODUCTION

EACH year at least 250.000 people worldwide suffer a spinal cord injury. The most common causes of a spinal cord injury are traffic accidents (50%) and falls (24%). But also sport accidents (6%) or extreme sport accidents (3%) are causes for spinal cord injuries (17% other causes). Subsequently, 53% of the affected suffered from paraplegia and 47% from tetraplegia [1], [2]. According to the International Classification of Diseases (ICD-10), tetraplegia can be assigned to the category of G82.5 [3].

Tetraplegia is caused by a damage of the spinal cord at the height of the C1 – Th1. Thereby the seventh cervical vertebrae (or further up) is damaged in such a way that the complete body from the neck down is paralyzed or partly paralyzed. Depending on the severity and level of injury, tetraplegia results into functional loss in the neck, trunk, and upper and lower limbs. For instance, affected people with complete C1 – C3 injuries cannot breathe independently, so that they will require the assistance of a ventilator to breathe. Affected people with complete C5 injuries can control their shoulders or rather their upper arms but not their wrists or hands. Furthermore, affected people with complete C6 injuries lose their hand and finger functions. Finally, affected people with complete C7 – Th1 can control their upper limbs, but have problems to move their hands or fingers [4].

After a spinal cord injury, the affected person needs to be treated in specialized hospitals with 24-hour care. Those trauma centers have the required know-how in both acute surgical and medical management to assure the first aid of injured people. The early stages of recovery and mobilization take place in specialized rehabilitation centers. Depending on the severity and level of injury, three rehabilitative efforts are focused on: Pulmonary management, mobilization (as refers to skin protection, spasticity, and thromboembolic phenomena), and neurogenic bowel or rather bladder care. Even conversation with the patient is an important factor of recovery in the case of a damage of the spinal cord. The patients should be prepared regarding to impairments that indicate eventual disabilities. Rehabilitation patients need a disease-specific care to optimize their quality of life, support their independence, and reintegrate into community. Rehabilitation centers offer a multidisciplinary team including i.e. physical medicine and rehabilitation physicians, various therapists, rehabilitation nurses, psychologists, and social workers to provide the required measures for an effective rehabilitation [5].

Subsequently, the next challenge is to reintegrate people with spinal paralysis into private and professional life as well as into society. A key factor of reintegration is a personal assistance helping tetraplegics perform basic activities essential for living in the community (e.g. dressing, bathing, toileting, and housekeeping) [6]. Another important factor is to enable tetraplegics leading a self-determined life. For this purpose, technical aids and assistive technologies can be used. Therefore, technical aids and assistive technologies are essential for facilitating a successful reintegration [7]. Although technical aids and assistance technologies cannot replace personal assistance service, they might promote the participation of tetraplegics in the community and in particular in working life. Depending on the level and severity of injury, tetraplegics can reach a certain degree of independence in their daily life, and especially in their mobility. A suitable wheelchair is an essential factor for the inclusion in society. For instance, people with a low-level of tetraplegia can use a manual wheelchair (e.g. traditionally controlled by joysticks) [7]. Additionally, tetraplegics with loss of hand functions can compensate these functions with helpful adaptive technical aids. Simple utensils like flatware with a yoke for people with grip impairment enable tetraplegics to grasp their fork, spoon or knife [8]. Such aids can support tetraplegics to regain at least part of their independence. But especially in the case of affected persons with a high level of tetraplegia, useable assistive technologies and wheelchairs are needed, which take into account that input sources as hand gestures are limited. Nevertheless, there are many innovative wheelchairs and assistive technologies for disabled persons which can be operated by various sorts of user inputs. In this case, a special human computer interface is needed, for instance using head movements, facial expression or voice in order to control the wheelchair or an assistive technology [9], [10]. Recent wheelchairs and assistive technologies can also be controlled by tongue motion [11], chin steering [12], eye-gaze [13], or brain-computer-interface [14]. Assistive technologies can support greater independence for tetraplegics by enabling them to perform tasks they were not able to perform before. A review of numerous assistive technologies is given by Lobo-Prat et al. [15]. To improve the quality of life for people with limited hand functions recent development tends to focus on manipulation-based assistive robotics. These robots can replace hand functions like holding or gripping (e.g. [16], [17]. Those advanced assistive technologies can be controlled, for example, by hand interface, by hands-free interface like eye, tongue, head and speech, by brain computer interface, or finally hybrid control interface (a combination of different interface modalities). Hands-free input devices like head interface are mainly used to control electric wheelchairs. Those control interfaces are restricted to the control of two degrees of freedom (DOFs) [15], [18].

In the research project MeRoSy (human-robot synergy), an approach of a head based controlled assistive robot for people with disabilities (in particular mobility impaired persons) is introduced. This project researches, develops and implements methods of machine learning and adaptation for cooperation assistance robots based on the measurement of head movements of the working person with a total number of seven degrees of freedom. An essential issue for research is how a human-robot cooperation workplace can be designed suitable for a human-centered, ergonomic hands-free robot control. The most important objective here is to develop a suitable interaction design, which arranges the three natural movements of human head ("role", "pitch" and "yaw"). These natural movements are used to create an intuitive head motion based control. In order to realize such an intuitive design an adaptive head motion control for user-friendly support (AMiCUS) was developed. With AMiCUS, the user can control a robot arm and a gripper intuitively via head motion. To measure the head motion of the working person an inertial measurement unit (IMU) is used. The IMU is composed of a high performance fully calibrated 9-axis IMU, which allows a precise motion measurement due to fusion of the sensor data from three accelerometers, three gyroscopes and three magnetometers. An onboard sensor fusion shows the output of the IMU as sensor orientation [19]-[22]. This interaction design has not only the potential of being more intuitive than other interface designs, but also offers the advantage that the user can control the robot hands-free. Subsequently, this design meets the special requirements of the target group of tetraplegics. The robot arm and gripper provides an opportunity for tetraplegics whose upper extremity functions are limited to manipulate their physical environment. But a direct manipulation of the physical environment and a self-determined participation in society, especially in working life, is only possible to a limited extent. A solution approach is realized by a graphical user interface (GUI). The GUI displays the robot and gripper movements, which are divided into four control groups ("Vertical Plane", "Horizontal Plane", "Orientation" and "Open/Close Gripper"). Here, head movements are used to switch between the groups or to turn the robot on or off. One objective of MeRoSy is the usability of a human-robot-cooperation workplace for tetraplegics. In the research project the example of a library scenario is explored. Here, the participants move the end effector of a robot through a head based control system and grab a book with a gripper attached to this end effector [19]-[21], [23].

In the following, the perspective of human ergonomics with analysis of stress and strain in head based control of a cooperative assistant robot through tetraplegics is considered. For this purpose, the impact of head movement related stress was measured with 12 test subjects in an empirical study. In the experiment, three different basic head movements each with two characteristics (flexion/extension, rotation left/right, lateral flexion left/right) were investigated. Data of the head posture were received by a motion capture system, muscle activity was measured via surface electromyography (sEMG) and the subjective mental stress was assessed via Rating Scale Mental Effort (RSME) [24]. Furthermore, a Thinking Aloud protocol was made during a free task in the experiment to implement comments of the subjects into the development of a user-centered design of the software. Like this, thoughts and wishes of a potential target group shall be integrated into the process of development to fit their requirements. In addition, a subsequent interview was carried out to derive design recommendations and improvement suggestions from the target group. This is very important for the design process, since potential users know their requirements best and might mention aspects not having been considered so far. When realizing a task-centered design, work tasks should be analyzed and modelled and the requirements of these tasks regarding the system should be emphasized. To design software as ergonomically as possible, DIN EN ISO 9241-110 sets seven dialogue principles. The results of this study are later discussed with respect to ergonomic design recommendations regarding the design of the human-robot workplaces and the human-robot cooperation.

II. LITERATURE REVIEW

A. The Stress-Strain-Concept

According to Rohmert et al.'s [25] stress-strain concept, it is necessary to assess both the stress and the strain, which in this study are caused by the head based control of a robot arm. With regard to the cause-effect principle, stress is commonly referred to as the cause, while strain is mostly called the effect. But strain is not only an effect or a consequence of stress. The same amount of stress can cause a different amount of strain in different individuals. Some people might be more resistant to stress and therefore show lower reactions to strain [26]. The relation between the amount of stress and the amount of strain is determined by the performance of the individual [27]. In this study, the physical stress is represented by the basic head movements (flexion/extension, lateral flexion, rotation of the head) while the physical strain is represented by the muscular activity of the neck muscles during these movements. Only when measuring both the participants' stress and strain, a proper evaluation of the results is possible and corresponding design recommendations can be derived for the robot control concept.

According to the human factors/ergonomics (HFE) concept, three key elements can be considered when designing systems with people [28]. First of all, the HFE takes a systems approach. This means that interacting components like the characteristics of humans and the characteristics of their environment are both taken into account on different levels (from micro to macro level). Secondly, HFE focuses on an individual's performance and well-being as an outcome of the systems design, which leads to the last characteristic of the HFE: It is design driven [28]. Just like the HFE concept, this paper concentrates on (1) the design and (2) the evaluation of the robot arm as well as the human-robot cooperation, taking into account both performance (e.g. efficiency, productivity, reliability etc.) and well-being (e.g. health, safety, learning etc.) of the individual as well as usability criteria. In this way, new design recommendations can be derived to further improve the human-robot cooperation and the working environment for disabled people.

B. Measurement of Stress

The robot arm was controlled via IMU that captures the users head motion. The nine-axis IMU allows a precise motion measurement due to fusion of the sensor data from three accelerometers, three gyroscopes and three magnetometers [22]. Using an IMU for the control of the robot arm offers the advantage of real-time capability. Furthermore, the IMU sensor is lightweight, small and low-priced and therefore very economical. But though the IMU can be used to capture the users' motion, the objective stress of the subjects was separately measured by an infrared tracking system which recorded the degree to which the different head movements were executed. This decision was based firstly on the very high accuracy of the infrared cameras and secondly on the knowledge of possible problems with the occurring IMU sensors. Bolink et al. [29] report that in various studies they investigated, measurement errors exceeded a maximum of 5°, which is critical for an appropriate interpretation of the results. In these studies, movements in the leg area were investigated. But especially in the neck area the maximum movement range is way smaller which makes a measurement error of 5° even more critical. Furthermore, according to Lebel et al. [30], perturbations in the magnetic environment around the sensor can affect the ability of the algorithm to differentiate between the actual motion and a change in environment. They report that studies have also shown that the type, the direction and the velocity of the motion performed, as well as the distance of the sensors from the center of rotation, all contribute to the orientation accuracy behavior. Similarly, Ligorio and Sabatini [31] mention different error sources (e. g. measurement noise, bias, calibration errors) which might lead to drifting integration errors which grow unbounded with time and may also depend on how the IMU moves in the 3D space. Additionally, ferrous objects produce small-scale magnetic field variations, which might cause a distortion. Especially in indoor environments sources of magnetic interference are often present and can include common items just like monitors [32]. Ligorio and Sabatini [31] give the advice to avoid those parts within the workspace that are most interfering, which of course is not always possible. Due to these difficulties a motion capture system was consulted to ensure reliable results in assessing the objective stress. Optical motion capture systems like those manufactured by Vicon offer an exceptional accuracy and extremely fast update rates [33].

C. Measurement of Strain

The decision to use sEMG and the corresponding muscles to assess the objective strain was based on a previous literature review which investigated possible fields where robots with head based control might be used. In the context of human-machine interaction, the authors carried out a systematic research for literature in the databases Pubmed and Web of Science, inter alia with the aim to provide an overview on how different neck movements affect a person's stress and strain [18].

The research study showed that sEMG is a very common method for assessing the physical strain, which is the muscular activity of the neck. Following Day [34], the advantage of sEMG is that since it is non-invasive it can also be used by personnel other than medical doctors. Furthermore, there is only minimal risk to the subject compared to invasive EMG. When using sEMG, it is important to ensure that the electrodes cover the active muscle area properly to allow reliable results. Therefore, it should be avoided to use muscles, which are hard to access (e. g. which are deeper under the skin or covered by another muscle) [18]. In the neck and shoulder area, Nelles et al. identified two muscles being used frequently in studies dealing with strain of the neck: The trapezius pars descendens and the SCM muscle. The latter muscle has got two functions. The unilateral function is the lateral flexion of the head to the ipsilateral and the rotation of the head to the contralateral side. The bilateral function is the dorsal extension of the head. The trapezius pars descendens functions to lift the scapula diagonally upwards to turn it outwards. Furthermore, it bends the head to the ipsilateral and turns it to the contralateral side [35]. Next to the trapezius pars descendens and the SCM, the SPL muscle was selected for the current study. The SPL is essential for head rotation. Almost all of this muscle lies underneath the trapezius and SCM muscles, except for a rectangular area on the lateral portion of the neck, where it is the most superficial muscle [36]. When measuring the activity of the SPL, it should be considered that there is only a small area where it is not covered by the other two muscles and it is important to find the right position for the electrodes. But on the other hand, it is advantageous that this muscle is so superficial.

Besides the assessment of objective sizes like the subject’s stress and strain, the subjective mental effort respectively strain was quantified via RSME. Mental strain is referred to as the psychophysical effects, which are caused by activities with affect-free information processing [37]. The assessment should ensure that, next to the physical aspects, participants are not overstrained by the mental aspects like the understanding of the robot control system or the tasks. Furthermore, it is assumed that there is a relation between mental strain and the muscle activity [38], so that with increasing mental strain the muscle activity grows as well. This effect was shown for the trapezius muscle by Lundberg et al. [39].

D. Hypothesis

The following hypotheses could be derived from the previous explanations:

H_1: Regarding the mobility of the subjects, significant differences are expected between the three head movements flexion/extension, rotation and lateral flexion, whereby least mobility is assumed for lateral flexion and highest mobility for head rotation. This is expected because in the everyday life turning one’s head and nodding are more common gestures than bending the head.

H_2: In terms of the muscular strain, significant differences between the three head movements are assumed as well. Here, the highest muscle activity is expected for lateral flexion, followed by head rotation and flexion/extension. This expectation is accompanied by the assumption that in the everyday life nodding is a more frequently used gesture than rotating or bending the head.

H_3: For the different muscles no significant differences in the muscle activity are expected. Rather, an interaction between the initialization movements and the muscle activity of the different muscles is assumed. Based on the functions of the different muscles explained before, it is expected that during lateral flexion the SCM and during head rotation the SPL are stressed the most. For the trapezius no significant differences in the muscle activity between the initialization movements are expected.

In the following, these hypotheses are examined and subsequently discussed in terms of research and future implications.

III. METHODS

Before initiation of the empirical user study, an ethics approval was submitted to the ethics committee at the Faculty of Medicine of RWTH Aachen University. According to a vote by the ethics committee (reference number EK 013/16), there are no reservations to be raised against the research project from an ethical and professional regulations point of view.

A. Subjects

Twelve subjects between the age of 16 and 53 (M = 36, SD = 11.45) with tetraplegia, including 11 males and 1 female, participated in this study. The subjects were all examined at the hospital “BG Klinikum Hamburg” between 18.04.2016 and 22.04.2016. Five of the subjects were paralyzed below C3, respectively two below C4 and C3/4 and respectively one below C2/3, C4/5 and C6/7. The average body weight, height and body mass index (BMI) of the subjects were 74.36 kg (SD = 18.24 kg), 183.58 mm (SD = 10.28 mm) and 22 (SD = 3.9). Seven subjects had a normal vision (score of 1 in Landolt C eye chart) and four subjects with limited vision (score of 0.5) participated. One subject declined the participation in the vision test. Furthermore, eight subjects with normal color vision participated, while four failed the color vision test. Before the study began, all the subjects signed an informed consent form providing information about the procedure and the purpose of the study as well as the benefits it offers and the risks it contains. For the participation the subjects received 30 €.

B. Apparatus and Materials

Motion Capture

Head movements were recorded via a motion capture system by Vicon [40]. This system contains four cameras of the Vicon Bonita 10 model emitting and recording infrared light, marker spheres which reflect infrared light and the software Nexus 2.1.1. The cameras were adapted to the test design by adjusting the intensity with which the cameras emit the infrared light to the conditions of the laboratory as well as the experimental setup and by setting it in the corresponding software. Furthermore, zoom, focus of the camera and focus of the aperture were set mechanically at the cameras to adjust them to the experimental design. The cameras record with 100 Hz, hence 100 frames per second, to capture the trajectories of the markers and therefore the head movements of the subjects. For the experiment at least three markers were needed to create a spatial element, i.e. a segment. Every marker must be captured by three of the cameras at the same time to determine its exact position in the room. Additionally, they should be positioned in a way that they do not disturb the subject during the experimental task and cannot be covered by other parts of the body. To display the head movements via the software, three markers were positioned on a hairband on top of the head (on the right, on the left, in the middle). To relate these markers with the sitting posture, three additional markers were positioned in the shoulder area: two of them each on the left and right on top of the shoulders and one centered on the spine, Fig. 1. Since five of the subjects owned a wheelchair with high backrest, here the markers were placed on the backrest. The markers are grey each with a diameter of 9.5 mm.

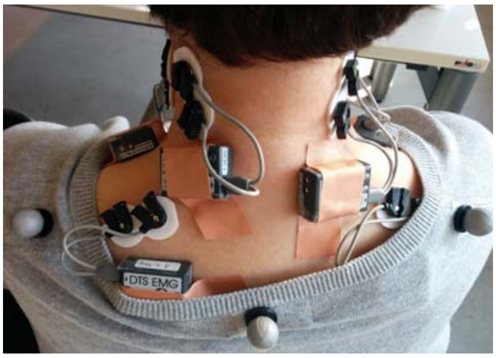

Fig. 1 Subject preparation, motion capture marker, sEMG electrodes and transmitters

sEMG

The muscular strain of the neck was measured via sEMG, using a system by Noraxon [41]. This system contains a TeleMyo DTS Belt Receiver, eight DTS EMG transmitters, the software MyoResearch XP 1.07 Clinical Edition and the adhesive disposable dual electrodes. The electrodes have an adhesive surface of 4 cm x 2.2 cm, while the single gel areas have a diameter of 1 cm. There is a distance of 1.75 cm between the electrodes. A wet gel containing Ag/AgCl (silver/silver chloride) was used as electrode gel. Both the adhesive and the gel are hypoallergenic. To attach the sensors there are buttons at the electrodes. On these buttons the sensors can be fixed with brackets, Fig. 1. On the bottom of the sensors there are the reference electrodes which need to be attached parallely to the measured muscles. Additionally, a preamplifier with a high pass filter to filter the frequencies below 10 Hz (± 10 %), a low-pass filter with 500 Hz and an A-D converter with a 16 bit resolution and a sampling frequency of 3000 samples per second and channel was used. With the TeleMyo DTS Belt-Receiver by NORAXON with USB port the signals of up to eight sensors are transmitted wirelessly via radio. The recorded data was processed and analyzed using the software MyoResearch XP 1.07 Clinical Edition. To assess the participants strain during the experimental task the activity of the trapezius pars descendens muscle, the SCM muscle and the SPL muscle was measured. The muscle activity was measured for both the right and the left side of the body, so that six transmitters were used. Before the electrodes have been placed, hair was removed via disposable razors and the skin was cleaned with the abrasive paste Everi by Spes Medica.

RSME, Thinking Aloud and Interview

To measure the participants' mental strain during the main task, RSME was used. The participants rated their subjective mental strain on selecting a value on the scale ranging from 0 (absolutely no effort) to 150 (intolerable effort).

During the complex task the Thinking Aloud method was applied to assess the thoughts, feelings and intentions of the learning users. A protocol was made to note the subjects' comments as well as discrepancies during the task. For testing in ergonomic terms, the DIN EN ISO 9241 "Ergonomics of human-system-interaction – Part 110: Dialogue principles" was taken as a basis [42]. These notes are classified according to the dialogue principles suitability for the task, self-descriptiveness, conformity with user expectations, suitability for learning, controllability, error tolerance and suitability for individualization.

After the experimental task a semi-structured interview was carried out, discussing the physical strain caused by the head-based control, the initial contact with the human-robot cooperation workplace, the experimental tasks, the control of the robot arm, the usability of the user interface as well as the design of dialogue and potential application scenarios in the professional and private context.

C. Robot and Head Movement Based Robot Control

Robot

In the study, a UR5 robot by Universal Robots was used, Fig. 2. The six-axis robot arm has a working radius of 850 mm and a maximum load of 5 kg. Its range of motion is ± 360 ° and all its joints reach an angular velocity of 180 °/s. Due to its six rotating joints the robot arm provides six degrees of freedom. In addition to the six degrees of freedom another one results through the possibility of opening and closing the gripper of the robot arm [43].

IMU

The hands-free head movement based robot control was realized by an IMU sensor FSM-9 by Hillcrest that is capturing the participants' head movements [22]. The IMU contains a data processor, three acceleration sensors, three gyroscope sensors, and three magnetic field sensors, which measure the head movement. The sensor was attached on the participants' heads via hairband.

By modelling the cervical spine as ball joint three degrees of freedom of the human head are represented: roll ϕ (flexion/extension), pitch ϑ (rotation clockwise/counter-clockwise) and yaw ψ (lateral flexion left/right). The user controls the robot arm in device-dependent world coordinate system (x, y, z). The seven degrees of freedom of the robot (with gripper) are transferred on the basis of a control paradigm to the three degrees of freedom of the human head by means of four control groups (horizontal plane, vertical plane, orientation in space, gripper) [21].

Fig. 2 Experimental setup, UR5 robot with gripper, screen, hairband with IMU, and motion capture cameras

GUI: Cursor/Gesture Robot Control

Switching between the four control groups takes place via a GUI displayed on a 27" screen slightly on the right hand side behind the robot, positioned on a table. Depending on the individual needs and abilities of the participants, two different types of control concepts for the robot arm were tested.

With the cursor control concept users can switch between the different groups via a cursor (analogous to the control with a mouse cursor). At first the overview menu for the cursor control system appears. Via head movements the cursor can be directed to the desired control group. By head rotation, the symbol is drawn to the right and then back to its starting position. Now the group is selected and the robot mode menu appears. Within this menu the selected group and the camera image are presented. To switch back to the overview menu an interactive gesture (flexion/extension) must be executed [19]-[21].

With the gesture control concept users can switch between the different groups via interacting gestures (flexion/extension gesture, lateral flexion left gesture, lateral flexion right gesture). The gripper is selected by a symbol top left within the white field. The other three groups and the exit symbol are arranged on the grey frame and can be selected via interactive gestures (flexion/extension, lateral flexion). During control mode a camera image of the gripper is presented within the white field [19]-[21].

In both concepts, robot control takes place via head movement relative to a pre-calibrated default resting position. For both control systems there is a light grey field illustrating the neutral zone of the robot. As long as the cursor/arrow is placed within the zone, the robot does not move. If the head is moved too fast or if gestures are executed outside the neutral zone, the robot stops. The further the cursor/arrow is moved away from the neutral zone, the faster the robot moves [19]-[21].

D.Procedure

Before the experiment began, a demographic questionnaire, a color vision test and a Landolt C eye chart was carried out. Afterwards the subject was brought to the robot workplace, where a short introductory video was presented, explaining the workplace and the concept of the robot control system. Then, the sEMG sensors and the motion capture markers were attached and the initialization of the head movements was carried out both for the motion capture and the sEMG system. Here, the subject performed four initial sub tasks as follows: first, the subject was asked to keep the head in resting position, then to nod (flexion/extension), to rotate (rotation) and finally to bend (lateral flexion) their head repeatedly. Every movement was carried out for ten seconds and between the different ones EMG time stamps were set to later assign the data correctly. Then, the main task began. A video was presented explaining the type of control concept (cursor or gesture) suitable for the individual subject. Afterwards, the subject could test the control concept and its different sub control groups. Again, a short video was presented, showing the upcoming tasks in 6-fold speed. When the robot was calibrated, the recording of the motion capture and the sEMG system was started. The subject carried out the tasks given by the examiner. After each releasing and gripping of the respective cube and after the successful performance of the gesture to leave the control group, the subject was asked to name the current RSME value. Furthermore, a marker for the sEMG data was set. After the main task was finished, the workplace was redesigned for the complex task. This time was used as a short resting period for the subject.

The complex task started with the calibration of the robot control system as well. During the task a Thinking Aloud protocol was filled with comments by the subject and problems with the control system. Furthermore, the time needed to place each cube was noted. At the end of the task the RSME was asked. After the experiment, a semi-structured interview was carried out. Then, the EMG sensors were removed.

E. Design and Statistical Analysis

The dependent variables within the statistical analysis are the data of the head posture recorded via motion capture system, the data of the muscle activity measured by sEMG and the subjective assessment of the participants' mental load via RSME scale. Independent variables are the three head movements with respectively two characteristics (flexion/ extension, rotation left/right, lateral flexion left/right). Due to high complexity, in the present paper only sEMG and Motion Capture data measured during the initialization were analyzed. sEMG data from two subjects were completely excluded. Furthermore, eight extreme statistical outliers were excluded.

IV. RESULTS

The data received from the motion capture and sEMG systems were analyzed with IBM SPSS Statistics Version 21.0 via Univariate Analysis of Variance (ANOVA) with repeated measures. *p* values < 0.05 were accepted as significant.

A. Stress – Motion Capture

Regarding the default resting position, for each subject a mean was calculated from the data recorded during the initialization. These values were then averaged over all subjects.

In terms of the three head movements, for each subject a mean was calculated from the various repetitions during the initialization. These values were then standardized by means of the resting position and averaged over all subjects. Mean default resting positions and mobility regarding the three head movements are represented in Table I.

TABLE I
MEAN RESTING POSITION (°), MEAN MOBILITY (°) AND STANDARD DEVIATION (°) FOR THE THREE HEAD MOVEMENTS DURING THE INITIALIZATION

Head posture	Mean (°)	SD (°)
Default resting position		
Flexion	-22.87	26.91
Rotation	1.51	2.24
Lateral flexion	4.42	6.49
Mobility		
Flexion	10.48	7.42
Extension	10.90	7.33
Rotation left	28.01	17.88
Rotation right	28.62	14.12
Lateral flexion left	15.23	10.25
Lateral flexion right	17.64	11.53

Regarding the mobility, a significant difference between the initialization movements was found ($F(5, 54) = 4.526$, $p < .005$, $\eta^2 = .295$). A post hoc test according to Bonferroni was carried out, showing significant differences between the following initialization movements: flexion and rotation to the left ($p < .05$), flexion and rotation to the right ($p < .05$), extension and rotation to the left ($p < .05$), extension and rotation to the right ($p < .05$).

B. Strain – sEMG

The mean muscle activity for each muscle during initialization is represented in Table II.

TABLE II
MEAN MUSCLE ACTIVITY (µV) AND STANDARD ERROR (µV) OF THE DIFFERENT MUSCLES FOR THE INITIALIZATION MOVEMENTS

Muscle	Mean (µV)	SE (µV)
Left UT	2.46	1.34
Right UT	2.23	1.36
Left SCM	7.28	1.30
Right SCM	2.91	1.34
Left SPL	4.22	1.32
Right SPL	10.25	1.30

In terms of the muscular strain during the initialization, a highly significant main effect for the different muscles has been shown ($F(5, 190) = 6.339$, $p < .001$, $\eta^2 = .143$). A post hoc test according to Bonferroni revealed that only the difference between the left trapezius and the right SPL was significant ($p < .001$). Regarding the flexion/extension during the initialization, the mean muscle activity was 1.61 µV (SE: 0.93 µV). For rotation, it was 6.23 µV (SE: 0.93 µV) and for lateral flexion 6.97 µV (SE: 0.96 µV). A highly significant difference between the initialization movements could be observed ($F(2, 190) = 9.674$, $p < .001$, $\eta^2 = .092$). Again, a post hoc test according to Bonferroni was carried out. The results show a significant difference between flexion/ extension and rotation ($p < .01$) as well as between flexion/ extension and lateral flexion ($p < .001$). No significant difference between rotation and lateral flexion could be noticed. Furthermore, there was no significant interaction between the two factors muscles and initialization movements. The mean muscle activity of the six different muscles for each initialization movement is shown in Table III.

TABLE III
MEAN MUSCLE ACTIVITY OF THE SIX MUSCLES DURING THE DIFFERENT INITIALIZATION MOVEMENTS

Initialization movement	Muscle	Mean muscle activity (µV)	SE (µV)
Flexion/extension	Left UT	1.27	2.25
	Right UT	1.03	2.35
	Left SCM	1.93	2.25
	Right SCM	-0.28	2.25
	Left SPL	0.12	2.25
	Right SPL	5.59	2.25
Rotation	Left UT	3.23	2.25
	Right UT	3.72	2.25
	Left SCM	7.94	2.25
	Right SCM	2.38	2.35
	Left SPL	7.03	2.35
	Right SPL	13.07	2.25
Lateral flexion	Left UT	2.87	2.46
	Right UT	1.93	2.46
	Left SCM	11.95	2.25
	Right SCM	6.63	2.35
	Left SPL	5.51	2.25
	Right SPL	12.91	2.25

C. Mental Load – RSME

Regarding the RSME values, for each subject a mean was calculated from the values asked during the main task. The mean RSME value (scale range from 0 to 150) over all subjects for the gesture control system was 26.99 (SD = 10.25), while the mean RSME value for the cursor control system was 34.61 (SD = 18.89). No significant difference between the two types of control systems was determined, regarding the RSME values.

D. Interview

Physical Strain

4 out of 11 subjects perceived pain or tension in the neck and shoulder area. Subjects mentioned the sitting position or the execution of the gestures as a cause for the former. In this context, 8 out of 11 subjects perceived some head movements as more difficult than others. 3 out of 11 felt that the

flexion/extension became more strenuous over time. 4 out of 11 felt similarly in terms of the lateral flexion.

First Encounter

Almost all of the subjects (8 out of 11) felt the first encounter with the workplace as positive and did not feel uncertain or anxious (9 out of 11) at the beginning of the experiment. The two subjects who felt uncertain reported that during the experiment, the uncertainty declined.

Complexity of the Tasks

Nearly all of the subjects (10 out of 11) perceived some tasks to be more difficult than others. Furthermore, many subjects (8 out of 11) had difficulties with the orientation within the space coordinates xyz (multidimensional thinking). Therefore, especially the rotation of the end effector and the robot arm in space was problematic. Since the third cube in the main task had to be rotated to be placed correctly, this cube was the one with the most difficulties.

Control System

Only one of the subjects felt the control system to be difficult, while nine rated it to be medium difficult. All in all, the movements of the robot were rated as fluent and ideally adjusted (8 out of 11). Four subjects mentioned it to be too slowly. The movements of the gripper were evaluated as rather jerky (4 out of 11) or too fast (4 out of 11).

Usability

5 out of 11 subjects tested the cursor control system during the experiment. Here, three of the subjects mentioned the neutral area, in which the arrow to control the robot can be held, to be very helpful. The structure of the menu options was mainly felt as clear and understandable (3 out of 5).

6 out of 11 subjects tested the gesture control system. 5 of the subjects mentioned it to be very interfering that the symbols were constantly rearranged. Three subjects agreed with the design of the menu.

Regarding the monitor, 6 out of 11 subjects felt its position to be adequate. Five subjects mentioned that they would have to shift their focus permanently between robot and monitor, while one subject complained that the monitor would obscure the view on the robot. The following improvement suggestions were made: place the monitor above (2), in front (2) or diagonally behind the robot (1); place the monitor centrally (5) or closer to the user (2); attach the monitor to the robot (2).

Potential Application Areas

6 out of 11 subjects could imagine professional application areas beyond the experimental scenario. The following areas were mentioned in which a robot could be used: manufacturing, medicine, laboratory, library, technological workplace, crane operator. Two subjects explicitly mentioned that they could imagine the robot to support disabled people at their workplace.

8 out of 11 subjects could imagine situations for a private application of the robot. Most of them (7 out of 11) mentioned the gripping of objects, furthermore subjects spoke about operating devices like television or radio (2), fetching or moving objects (2), using the robot in a playful context (1).

7 out of 11 subjects could not imagine using the robot in a professional or private context in its current state of development. Three would like to test it at home and four would like to use it in a creative or playful way. The most important factor that is still not given is that the robot needs to be mobile to be a real assistance for disabled people at home. This means it should be lighter and smaller to better stow it. Finally, the subjects agreed that the robot so far is no replacement for personal assistance.

E. Thinking Aloud

The subjects' comments and problems during the complex task were noted and afterwards assigned to the seven dialogue principles (Table IV).

TABLE IV
THINKING ALOUD NOTES DURING THE COMPLEX TASK, ASSIGNED TO THE SEVEN DIALOGUE PRINCIPLES.

Dialogue principles	Thinking Aloud
Suitability for the task	Difficulties with third cube, since it needs to be rotated (gesture: 1, cursor: 1)
Self-descriptiveness	Problems with the understanding of the menu options or different control levels (gesture: 4, cursor: 2)
Controllability	Sensor disturbed by ferrous parts (of wheelchair) at 4 subjects, making control very difficult
Conformity with user expectations	Difficulties controlling robot in direction intended (gesture: 2, cursor: 3); rotation not intuitive (gesture: 5, cursor: 3); control of gripper not intuitive (gesture: 2, cursor: 3)
Error tolerance	Problems with calibration and correct execution of gestures (gesture: 9, cursor: 7)
Suitability for individualization	Whether control is possible depends on type of wheelchair (no ferrous parts)
Suitability for learning	Sometimes external aid necessary (gesture: 3, cursor: 5)

V. DISCUSSION

In the present study, a hands-free head movement based robot control was tested and evaluated by twelve tetraplegics. The aim was to derive design recommendations for the ergonomic use of such a control system at workplaces for disabled people. For that purpose, the subjects' stress was measured via motion capture, while strain in the neck area was assessed through sEMG.

The first hypothesis stated that significant differences in terms of mobility would be found between the three head movements flexion/extension, rotation and lateral flexion, whereby least mobility was assumed for lateral flexion and highest mobility for head rotation. Here, the assumptions were only partly supported by the results. Although significant differences between head rotation and flexion/extension were found, flexion/extension turned out to show the least range of motion, followed by lateral flexion. Head rotation indeed showed the highest mobility, probably because it is frequently used in everyday life to explore the environment around. Since this does not only demand to turn the head left or right, but also to look backwards, it makes a high range of motion necessary. It was further expected that flexion/extension shows a higher range of motion than lateral flexion, since nodding in the everyday life is frequently used as an interactive gesture. This assumption could not be supported by the results. This might be because nodding in the everyday interaction mostly consists of quick and short movements, explaining why a high range of motion may not be given.

Regarding the motion capture procedure, in this study it can be criticized that the reference markers sometimes were not placed on the shoulders of the subjects as planned. Due to some specialized wheelchairs sometimes the reference markers needed to be placed on the backrest of the wheelchair. Therefore, the relation between the markers on the head and the reference markers in the shoulder area was different for some subjects, causing a lack in standardization. In that context, the high standard deviations are very conspicuous. On the other hand they might indicate the high variability of the head movements between the subjects.

Now, a high mobility does not mean that an individual shall execute a movement to the maximum point, especially not over a long time and with many repetitions. To therefore better evaluate the suitability of the head movements, the muscle activity was measured as well to draw a relation between a user's stress and strain. In terms of the muscular strain, the highest muscle activity was expected for lateral flexion, followed by head rotation and flexion/extension (H_2). The results mainly support these assumptions. Significant differences between the initialization movements were found regarding the muscle activity, whereby muscles during flexion/extension showed to be significantly less active than during rotation and lateral flexion. As expected, flexion/ extension showed the least muscle activity (1.61 μV) followed by head rotation (6.23 μV) and lateral flexion (6.97 μV). Only the difference between rotation and lateral flexion is not significant. Though rotation and lateral flexion show a higher range of motion in general, at the same time these movements cause higher strain in the individuals. It is possible that subjects are more used to head flexion and extension since in the everyday life this is an interactive gesture which is frequently used. Therefore, muscles might be better trained for flexion/extension than for rotation or lateral flexion. These findings demonstrate the importance of Rohmert's stress-strain concept [25], saying that it is important to assess both a person's stress and strain, since a user's performance depends on the relation between stress and strain [27]. An implication for practice therefore is that users should stay in a comfortable range of motion during the calibration of movements, not calibrating to the maximum range of motion. In that way, the user's muscles are not fully stretched.

A general point that needs to be critically discussed is the lack of sEMG normalization via maximal voluntary isometric contractions (MVIC). In the present study, sEMG data was normalized with the help of the values during the default resting position. Due to the physical restrictions of the subjects by tetraplegia, no maximum force test was performed. Though, to be able to generalize the results and compare the data between the different subjects MVICs are required since the maximum contraction can vary from subject to subject and muscle to muscle, so that the gained value needs to be compared to the maximum value [44].

The third hypothesis stated that for the different muscles no significant difference in the muscle activity would be found. Rather, a relation between the initialization movements and the muscle activity of the different muscles was expected based on the functions of the different muscles. This hypothesis was only partly supported by the results. Although a significant main effect for the factor muscles was found, a post hoc comparison revealed that only the left trapezius and the right SPL differed significantly in terms of the muscle activity. Against the expectations, no significant interaction between the factors muscles and initialization movements took place. Based on the functions of the different muscles explained in the introduction, it was expected that during lateral flexion the SCM muscle and during head rotation the SPL muscle were stressed the most. For the trapezius no significant differences in the muscle activity between the initialization movements were expected. At this point, it should be mentioned that the correct positioning of the EMG electrodes is a major challenge. As explained in the introduction, when using sEMG it should be ensured to choose muscles that are easy to access. This is given for both the SCM and the UT. But as mentioned by Benhamou et al. [36] there is only a small rectangular area of the SPL that is not covered by the other two muscles. The authors criticize that this area is difficult to find, so that electrodes might measure the activity of adjacent muscles as well, making a distinction impossible. But when considering the means in Table III, during head rotation the left and right SPL show the highest values together with the left SCM. During lateral flexion highest values were obtained by the left and right SCM together with the right SPL. So, with a few exceptions, at least a trend is observable. It is very probable that with a bigger sample and a resulting higher power the results will be clearer, so that it is not a problem of method but of sample size. Furthermore, it is not unusual that adjacent muscles are active together with the muscle mainly responsible for a certain movement. For example, in a magnetic resonance imaging study by Conley et al. [45], the SPL ipsilateral to the rotation was identified as the primary muscle used for rotation. But the results also showed that it was involved in the extension of the head. Another finding of the study was the contribution of the contralateral SCM to head rotation. Additionally, it was one of the muscles being extensively used during head flexion and lateral flexion. So even in a MRI study it could be shown that adjacent muscles are commonly active at certain movements of the head and it is nearly impossible to completely separate them from each other.

Regarding the experimental tasks, it was very conspicuous that nearly all of the subjects had difficulties with the orientation group which was needed for tasks in which the robot end effector or the gripper had to be rotated. This could be noticed both during the main and the complex task. This indicates that perspective adoption during rotation is problematic, which might be caused by the three degrees of freedom. Subjects were uncertain which of the three head movements corresponded to the robot end effector or gripper movements. Especially during the complex task without instructions subjects controlled the robot arm into the wrong direction, not only in the orientation mode. And even the gripper sometimes was closed instead of opened or opposite. It can be assumed that users have to practice the robot control system more often to get an understanding of the relation between head and robot movement.

Besides the objective measures and observations a Thinking Aloud protocol was made during the complex task to implement comments of the subjects into the development of a user-centered design of the software. Like this, thoughts and wishes of a potential target group shall be integrated into the process of development to fit the users' requirements. Furthermore, a subsequent interview was carried out to derive design recommendations and improvement suggestions from the target group. This is very important for the design process, since potential users know their requirements best and might mention aspects not having been considered so far. As revealed by the interview, some subjects perceived a tension in the neck and shoulder area caused by the permanent execution of the head movements. Especially flexion/ extension and lateral flexion were perceived as strenuous over time. It is no surprise that these movements were named since they dealt to move the robot forwards, backwards and sidewards, which is demanded in most of the tasks. A solution for this problem might be to implement more rest breaks between the different tasks, which is important for the working context, especially when considering an eight-hour working day. It was very positive that almost all of the subjects perceived the first encounter with the robot workplace as positive. This indicates that the design of the robot fits the expectations of the subjects and does not provoke uncertainty. This is very important in terms of ethical aspects, since an individual should feel safe when working together with a robot [23]. Following Kuz et al. [46], the field of human-robot interaction should focus on the concept of anthropomorphism, which is the simulation of human characteristics by non-human agents such as robots. In this way a higher level of safety and user acceptance can be achieved [47]. In that context, speed and fluency of the robot movements play an important role for the users' trust in the robot. Fluent movements in an accurate speed remind the user of a human being rather than jerky and fast movements. In general, subjects perceived the movements of the robot as fluent and ideally adjusted and rather a little too slowly. However, the movements of the gripper were rated as too fast and jerky. As explained before, fast and jerky movements might frighten the user, especially when they are not expected. In this respect the so called neutral area was developed, in which the head movements would not cause any movement of the robot. This area shall give room for users to have a short break or selecting a new group via gestures without provoking an unintended movement of the robot. In the interview most subjects testing the cursor control concept explicitly mentioned the neutral area to be very helpful. However, it should be assumed that when using the gesture control concept the neutral area is more relevant since the groups have to be selected via gestures during control mode. Here, many subjects got outside the neutral area during the execution of gestures, indicating that the neutral area for this control concept might be too small and should be bigger in size. During the interview, subjects were also asked whether the position of the monitor was adequate. While half of the subjects agreed with the position rightside behind the robot, the other half criticized that they would have to shift their focus permanently between robot and monitor. Most of the subjects therefore recommended placing the monitor more centrally. This should definitively be respected for future implementations, since in the working context the robot and the task have to be in the center of focus at all times.

In the experiment, two control concepts were tested to later be evaluated and compared. Subjects testing the cursor control concept perceived the menu as very clear and understandable. Subjects testing the gesture control concept mentioned it to be very interfering that the symbols were constantly rearranged. Here, the symbol selected was always exchanged by the symbol of the last group that was used, so that no permanent arrangement of the symbols was given. The symbol for the intended group therefore had to be searched on the menu each time a new mode was desired. From the Thinking Aloud protocol also emerges that some subjects had difficulties selecting the right symbol for the intended movement. A general explanation could be that the subjects did not understand the meaning of the symbols right away. But it is very conspicuous that this happened twice as often for the gesture control concept than the cursor control concept, making it plausible that symbols in the gesture control concept were selected based on their former position which changed during the experiment. Therefore, one implementation for the design of the gesture control concept is to arrange a permanent position for the symbols of the different groups. Though, an advantage of the gesture control concept is that groups can be changed more quickly, because users do not have to switch to an overview menu like in the cursor control concept. To furthermore evaluate how mentally stressful the two control concepts were the subjects' mental load was measured via RSME. This should indicate whether the designs demanded a high mental effort, for example to understand and select the right groups or to control the robot and gripper to the right direction. Though the mean RSME value from subjects testing the gesture control concept was smaller (26.99) than the one from subjects testing the cursor control concept (34.61), no significant difference was found due to a high standard deviation. This shows that both control concepts are comparable regarding the mental effort they cause. The values can be verbalized from "A bit hard to do" to "Fairly hard to do", which is an acceptable area. Furthermore the high standard deviation shows the variability and individuality of perceived mental effort.

Since the robot may be used both in a professional and private context in the future, in the interview subjects were asked whether they could imagine concrete workplaces or situations in which the robot could be used. More than half of the subjects could imagine professional application areas like in the manufacturing, medicine or laboratory. Especially in such workplaces like in the manufacturing, where many monotone tasks have to be carried out and dangerous machines have to be operated or workplaces in a laboratory, where there is worked with toxic substances, workers need to be supported and their workload reduced. Furthermore, the head based control might allow disabled people to remain in their working life. But besides the application in professional areas, most of the subjects could also think of situations in their private lives, where the robot would be helpful. Most activities they imagined concerned the gripping and moving of objects. Being able to use the robot to compensate the paralysis of the arms offers people suffering from tetraplegia or other disabilities the freedom to act when intended and gives back some independency. But though the subjects in general named various workplaces and situations where the robot might be used, most of them could not imagine using the robot in its current state of development. The idea of a head based control is plausible for most subjects, but the robot currently is too big and heavy. According to the subjects, the robot has to be lighter and smaller to make it mobile and to be able to stow it at home. Finally, they agreed that the robot so far is no replacement for a personal assistance.

VI. CONCLUSION

The present study is one of the first studies in the context of human-machine interaction testing a head-based control of a robot with people suffering from tetraplegia. Though some methodological problems need to be criticized, like the lack of an adequate normalization of the sEMG data via MVIC or the inconsistent placing of the reference markers for the motion capture system, this study delivers first insights in design requirements for the use of a head-based control system at a robot workplace (for disabled people). All in all, it should be said that the robot and its head-based control system are on a high state of development already. Though, the current state is insufficient for a private or professional application. The robot so far is too big and heavy, making it immobile. Since for most of the subjects mobility – especially in terms of private assistance – is very important, this should be considered for future development. Furthermore, the designs of the robot control concepts both have their advantages and disadvantages. A solution here would be to combine the strengths of both designs and therefore create a better one with a higher usability. Another aim should be to eliminate the problem of sensor drifting due to ferrous parts to allow subjects with special equipment at their wheelchairs to control the robot without disturbances.

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REFERENCES

[1] Wings for Life. Rückenmarksverletzung. (accessed 18.10.2016) Available at.: http://www.wingsforlife.com/de/querschnittslaehmung/.

[2] World Health Organization. Spinal cord injury. Fact sheet N°384. November 2013. (accessed 18.10.2016) Available at: http://www.who.int/mediacentre/factsheets/fs384/en/.

[3] International Classification of Diseases, 10th Revision. G82.5 – Quadriplegia. Last Updated: Oct 01, 2016. (accessed 18.10.2016) Available at: http://icd10coded.com/cm/ch6/G80-G83/G82/

[4] J. Bickenbach et al., International perspectives on spinal cord injury, World Health Organization & The International Spinal Cord Society, Malta: WHO, 2013, pp. 68–72.

[5] N. L. Mazwi, K. Adeletti, and R. E. Hirschberg, “Traumatic Spinal Cord Injury: Recovery, Rehabilitation, and Prognosis,” Current Trauma Reports, vol. 1, issue 3, Sept. 2015, pp. 182–192.

[6] M. P. LaPlante, H. S. Kaye, T. Kang, and C. Harrington, “Unmet need for personal assistance services: estimating the shortfall in hours of help and adverse consequences,” Journal of Gerontology: Social Sciences, vol. 59B, No. 2, 2004, pp. 98–108

[7] L. Floris, C. Dif, and M. A. Le Mouel, “The tetraplegic patient and the environment," in: Surgical rehabilitation of the upper limb in tetraplegia, London: W.B. Saunders, 2002, pp. 45–55.

[8] Dinging with Dignity. Flatware for the Grip Impaired. (accessed 18.10.2016) Available at: www.diningwithdignity.com.

[9] D. A. Craig, and H. T. Nguyen, “Wireless real-time head movement system using a personal digital assistant (PDA) for control of a power wheelchair”, IEEE, Jan. 2006, pp. 772-775 (27th Annual Conference on Engineering in Medicine and Biology).

[10] T. Guerreiro, and J. Jorge, “Assistive technologies for spinal cord injured individuals: Electromyographic mobile accessibility,” Proceedings of GW, 2007 (7th International Workshop on Gesture in Human-Computer Interaction and Simulation).

[11] J. Kim, H. Park, J. Bruce, D. Rowles, J. Holbrook, B. Nardone, D. P. West, L. Laumann, E. J. Roth, and M. Ghovanloo, “Assessment of the tongue-drive system using a computer, a smartphone, and a powered-wheelchair by people with tetraplegia,” IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 24, Issue 1, Jan. 2016, pp. 68-78.

[12] S. Guo, R. A. Cooper, M. L. Boninger, A. Kwarciak, and B. Ammer, “Development of power wheelchair chin-operated force-sensing joystick,” Engineering in Medicine and Biology, vol. 3, Oct. 2002, pp. 2373-2374 (24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society EMBS/BMES Conference, 2002, Proceedings of the Second Joint).

[13] M. A. Eid, N. Giakoumidis, and A. El Saddik, A., “A Novel Eye-Gaze-Controlled Wheelchair System for Navigating Unknown Environments: Case Study With a Person With ALS,” IEEE, vol. 4, 28. Jan. 2016, pp. 558–573.

[14] C. Mandel, T. Lüth, T. Laue, T. Röfer, A. Gräser, & B. Krieg-Brückner (2009, October). Navigating a smart wheelchair with a brain-computer interface interpreting steady-state visual evoked potentials. In 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 1118-1125). IEEE

[15] J. Lobo-Prat, P. N. Kooren, A. H. Stienen, J. L. Herder, B. F. Koopman, and P. H. Veltink, „Non-invasive control interfaces for intention detection in active movement-assistive devices,” Journal of neuroengineering and rehabilitation, vol. 11, No. 2, 2014.

[16] A. Cunningham, W. Keddy-Hector, U. Sinha, D. Whalen, D. Kruse, J. Braasch, and J. T.Wen, “Jamster: A mobile dual-arm assistive robot with jamboxx control,” IEEE, Oct. 07, 2014, pp. 509-514 (IEEE 10th International Conference on Automation Science and Engineering, 2014).

[17] C. Leroux, I. Laffont, N. Biard, S. Schmutz, J. F. Desert, G. Chalubert, and Y. Measson, „Robot grasping of unknown objects, description and validation of the function with quadriplegic people," IEEE, Jan. 14, 2008, pp. 35–42 (IEEE 10th International Conference on Rehabilitation Robotics, 2007).

[18] J. Nelles, S. Kohns, J. Spies, C. Brandl, A. Mertens and C. M. Schlick, "Analysis of Stress and Strain in Head Based Control of Collaborative Robots – A Literature Review," in Advances in Physical Ergonomics and Human Factors, International Publishing: Springer, 2016, pp. 727-737.

[19] N. Rudigkeit, M. Gebhard, and A. Gräser, "Towards a user-friendly AHRS-based human-machine interface for a semi-autonomous robot," IEE, Sept. 04, 2014 (IEEE/RSJ International Conference on Intelligent Robots and Systems, Workshop on Assistive Robotics for Individuals with Disabilities: HRI Issues and Beyond, 2014.

[20] N. Rudigkeit, M. Gebhard, & A. Gräser (2015). An analytical approach for head gesture recognition with motion sensors. In IEEE Ninth International Conference on Sensing Technology (pp. 720-725).

[21] A. Jackowski, M. Gebhard, & A. Gräser, (2016, May). A novel head gesture based interface for hands-free control of a robot. In Medical Measurements and Applications (MeMeA), 2016 IEEE International Symposium on (pp. 1-6). IEEE.

[22] Hillcrestlabs Experts in Motion. FSM-9. (accessed 18.10.2016) Available at: http://hillcrestlabs.com/product/fsm-9/

[23] J. Nelles, J., C. Bröhl, J. Spies, C. Brandl, A. Mertens, C. M. Schlick, „ELSI-Fragestellungen im Kontext der Mensch-Roboter-Kollaboration," in Arbeit in komplexen Systemen. Digital, vernetzt, human?! Bericht zum 62. Arbeitswissenschaftlichen, Kongress vom 03. - 05. März 2016, Gesellschaft für Arbeitswissenschaft e.V. (GfA), GfA-Press: Dortmund, 2016, pp. 1-6.

[24] F. R. H. Zijlstra, (1993). Efficiency in work behaviour: A design approach for modern tools. TU Delft, Delft University of Technology.

[25] W. Rohmert, & J. Rutenfranz (1975). Arbeitswissenschaftliche Beurteilung der Belastung und Beanspruchung an unterschiedlichen industriellen Arbeitsplätzen. Bonn: Bundesminister für Arbeit und Sozialordnung.

[26] W. Rohmert (1984). Das Belastungs-Beanspruchungs-Konzept. Zeitschrift für Arbeitswissenschaft, 38 (4), 193-200.

[27] W. Rohmert, & H. Luczak (1973). Zur ergonomischen Beurteilung informatorischer Arbeit. Internationale Zeitschrift für angewandte Physiologie einschließlich Arbeitsphysiologie, 31, 209-229.

[28] J. Dul, R. Bruder, P. Buckle, P. Carayon, P. Falzon, W. S. Marras, J. R. Wilson, & B. van der Doelen (2012). A strategy for human factors/ergonomics: developing the discipline and profession. Ergonomics, 55(4), 377-395.

[29] S. A. A. N. Bolink, H. Naisas, R. Senden, H. Essers, I. C. Heyligers, K. Meijer, & B. Grimm (2015). Validity of an inertial measurement unit to assess pelvic orientation angles during gait, sit–stand transfers and step-up transfers: Comparison with an optoelectronic motion capture system. Medical Engineering and Physics, 000, 1-7.

[30] K. Lebel, P. Boissy, H. Nguyen, & C. Duval (2016). Autonomous Quality Control of Joint Orientation Measured with Inertial Sensors. Sensors, 16 (7), doi: 10.3390/s16071037.

[31] G. Ligorio & A. M. Sabatini (2016) Dealing with Magnetic Disturbances in Human Motion Capture: A Survey of Techniques. Micromachines, 7, 43.

[32] E. R. Bachmann, X. Yun, & A. Brumfield (2007). Limitations of Attitude Estimation Algorithms for Inertial/Magnetic Sensor Modules. IEEE Robotics & Automation Magazine, 14, 76-87.

[33] D. Vlasic, R. Adelsberger, G. Vannucci, J. Barnwell, M. Gross, W. Matusik, & J. Popović (2007). Practical Motion Capture in Everyday Surroundings. ACM Transactions on Graphics, 26 (3), doi: 10.1145/1239451.1239486.

[34] S. Day (2002). Important Factors in Surface EMG Measurement. Calgary: Bortec Biomedical Ltd.

[35] M. Schünke, E. Schulte, & U. Schumacher (2007). PROMETHEUS Lernatlas der Anatomie. Allgemeine Anatomie und Bewegungssystem. Stuttgart, New York: Thieme Verlag.

[36] M. A. M. Benhamou, M. Revel, & C. Vallee (1995). Surface electrodes are not appropriate to record selective myoelectric activity of splenius capitis muscle in humans. Experimental Brain Research, 105, 432-438.

[37] F. Klimmer, J. Rutenfranz, & W. Rohmert (1979). Untersuchungen über physiologische und biochemische Indikatoren zur Differenzierung zwischen mentaler und emotionaler Beanspruchung bei psychischen Leistungen. International Archives of Occupational and Environmental Health, 44, 149-163.

[38] G. Sjøgaard, U. Lundberg, & R. Kadefors (2000). The role of muscle activity and mental load in the development of pain and degenerative processes at the muscle cell level during computer work. European Journal of Applied Physiology, 83, 99-105.

[39] U. Lundberg, R. Kadefors, B. Melin, G. Palmerud, P. Hassmén, M. Engström, & I. E. Dohns (1994). Psychophysiological Stress and EMG Activity of the Trapezius Muscle. International Journal of Behavioral Medicine, 1 (4), 354-370.

[40] Vicon. (accessed 09.12.2016) Available at: https://www.vicon.com/

[41] Noraxon. (accessed 09.12.2016) Available at: http://www.noraxon.com/products/emg-electromyography/

[42] DIN EN ISO 9241-110 (2008). Ergonomie der Mensch-System-Interaktion–Teil 110: Grundsätze der Dialoggestaltung (ISO 9241-110: 2006); Deutsche Fassung EN ISO 9241-110: 2006.

[43] Universal Robots (2015): UR 5 Technische Spezifikationen, (accessed 30.11.16) available at: http://www.universal-robots.com/de/produkte/ur5-roboter/

[44] A. Burden (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. Journal of Electromyography and Kinesiology, 20, 1023-1035.

[45] M. S. Conley, R. A. Meyer, J. J. Bloomberg, D. L. Feeback, & G. A. Dudley (1995). Noninvasive Analysis of Human Neck Muscle Function. Spine, 20 (23), 2505-2512.

[46] S. Kuz, H. Petruck, M. Heisterüber, H. Patel, B. Schumann, C. M. Schlick, & F. Binkofski (2015). Mirror neurons and human-robot interaction in assembly cells. Procedia Manufacturing 3, 402-408.

[47] B. R. Duffy (2003). Anthropomorphism and the social robot. Robotics and Autonomous Systems, 42, 177-190.