Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics
San Antonio, TX, USA - October 2009

Predictive Validity of Wheelchair Driving Behavior for Fine Motor Abilities

Definition of Input Variables for an Adaptive Wheelchair System

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Abstract*—This paper introduces an approach for dynamically adapting the level of automation of a wheelchair system on the basis of the current level of the user's motor abilities. For this purpose, a study is described, during which participants drove through a course consisting of 14 sub-sections. The predictive validity of the participants' wheelchair driving behavior on their precision, tremor, wrist-finger velocity, arm-hand velocity and aiming capability was analyzed. The results demonstrate impressively (1) that some course sections can better be used in order to derive variables allowing a reasoning on the users' motor ability level than other sections and (2) that especially the precision ability can be predicted e.g. on the basis of the distances driven in the forward mode. Implications on how an adaptive assistance system for powered wheelchair could be implemented are discussed as is the impact of such a system on the wheelchair market. *(Abstract)

Keywords*—motor abilities, adaptive automation, assistive technology, human-centered technology *(key words)

I. STATTE OF THE ART

A. *Motivation: Drawbacks of Assistive Technology*

Assistive technologies were developed in order to ease the lives of those with disabilities or serious impairments when executing activities of daily living, to improve their quality of life, and to empower them to live – as far as possible - independently. Examples for such assistive technologies are manually/powered wheelchairs, which should enable mobility-impaired users to move freely. Due to the great variety of remaining skills of wheelchair users, the wheelchair market offers a tremendous amount of different types of manually or electrically powered wheelchairs, so that for each person an optimal wheelchair can be determined and adapted such that the support this person will receive in executing activities of daily living is optimized.

However, practical experience demonstrates serious drawbacks of today's wheelchairs (see e.g., [1], [2], [3], [4]): It takes persons in need months and even years until they learn how to control their wheelchair and efficiently use it in their everyday life. There are also reports about persons, who cannot learn how to use their wheelchair; others lack a sufficient degree of motor skills, physical strength or visual acuity so that they do not benefit from these technologies.

This implies that – although there is a great variety of wheelchair technology to choose from – the perfect match between the skills of a potential wheelchair user and the demands required to operate a wheelchair has not yet been achieved: The demands put on the user when operating an available wheelchair often exceeds his/her skills, which results in long and sometimes even unsuccessful training periods and explains the above mentioned drawbacks of current wheelchair control. One way, which could solve this situation, is based on adaptive automation, which state-of-the-art is introduced in the following.

B. *Human-Centered Technology: Adaptive Automation*

The sophistication of automation systems steadily increased in the past, so that they took over a broad range of activities, which were originally executed by operators of such systems. The practical application of such technology-centered automation systems however revealed drawbacks (see e.g., [5]): The dependability of such human-technology systems did not increase, as expected due to the reduction of the "human factor", but decreased. A number of reasons were discussed, covering for example a reduced situation awareness of the human operator, an incorrect/incomplete mental model about the technical system and a resulting incapability to intervene in a correct and timely manner, if necessary (see e.g., [6]).

As a counter movement, the goal is to develop human-centered technology, which aims at keeping the human operator in the loop of such systems (see e.g., [7], [8]), so that the dependability of the overall human-automation system actually increases.

One way to realize such systems are so-called adaptive automation systems, which use different levels of automation (see e.g., [9]) depending e.g. on the current workload of the operator (see e.g., [10], [11], [12], [13], [14], [15], [16], [17], [18], [19]). The goal of such systems is to balance human performance variations by providing automation when it is necessary (i.e., when it is likely that the operator conducts an error) and by reducing the automation when it is not necessary (i.e., when the operator will most likely not execute an error). For this purpose, input signals (e.g., EEG, ECG), which can be measured from the human operator, were identified being indicative of his/her current state (e.g., state of over-workload); rules were developed of how to process these input signals to derive a meaningful signal and decision rules developed of how the automation system should be reconfigured depending on the meaningful signal in order to optimize performance.

The area of application of such adaptive automation systems is mainly in the field of air traffic control (see e.g., [9], [14]). Approaches of adaptive automation in assistive technology are not known.

II. PROBLEM FORMULATION: DEFINITION OF THE RESEARCH DEFICIT

As the previous section has demonstrated, there is a mismatch between the skills/capabilities of wheelchair users and the demands the technology puts on them. While nowadays, the user has to adapt to the wheelchair system by learning how to control his/her assistive device, the field of adaptive automation offers the technology in order to enable an assistive device to adapt to its user and especially his/her capabilities. This application of adaptive technology in the field of wheelchairs enables to achieve symmetry between the user's capabilities and the demands the technology puts on the user. It yields the possibility to significantly enhance the usability of wheelchairs available on the market. In order to allow the implementation of such an adaptive wheelchair system, (1) input signals have to be identified, which will can be measured by the technical system and which can predict the user's fine motor abilities and (2) rules need to be developed mapping the different motor abilities with different configurations of a wheelchair system, such that the wheelchair takes over the tasks, which are demanding regarding the motor abilities. The research at hand aims at providing an answer to the first question by defining variables which are indicative about a wheelchair user's motor skills.

III. SOLUTION APPROACH

In order to achieve the above defined goal and identify input signals on which basis a wheelchair system could assess the ability of its user to control a powered wheelchair, a study was performed, which is described in the following.

A. Course of the Conducted Study

In order to measure a realistic steering behavior with a wheelchair, the study was conducted in a realistic office environment (see Fig. 1), in which goal positions were inserted, so that the participants had to maneuver through cluttered environments and also drive through free spaces. The goal positions were defined, such that reaching them requires steering behavior which would be necessary if the participants actually worked in this environment. For this purpose, the goal positions were linked to objects distributed in the environment, which are listed in the following:

- Goal Position 1 was a specified position at a wall in a less crowded area,
- Goal Position 2 refers to an office cupboard and the participants had to drive next to it so that they could theoretically open it and withdraw something from it,
- Goal Position 3 was in front of a drawing board,
- Goal Position 4 was a table in a narrow environment reflecting a workplace (leaving the goal position required the participants to turn in a very narrow space/on the spot),
- and, last, Goal Position 5 was next to a printer, which was located on a table.

As this description already shows, driving to these goal positions and maneuvering through the environment evoked critical steering behaviors from the participants. For wheelchair users it is important to master these steering behaviors in order to be able to use their assistive device in everyday life. These critical behaviors are also tested in wheelchair skills tests (see e.g., [20], [21], [22]) and refer to "turning on the spot/very narrow space", "driving straight for a specified distance", "driving around corners in different angles", or "driving besides an object".

Within this environment, a course was defined consisting of different sections. In order to master each section, the participants were asked to drive from a goal position to another one. The order of the sections and a definition of the start and end points of each section are given in Tab. 1.

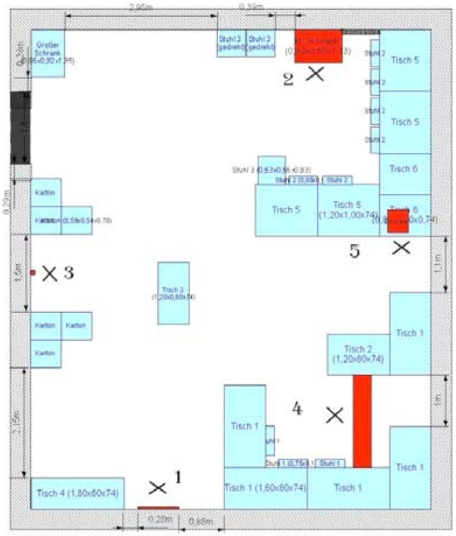

Figure 1. Floor plan of the room in which the study took place and in which the goal positions were inserted, marked with a cross and a number.

In order to drive through this course, the participants used a powered wheelchair from Otto Bock Healthcare GmbH (type B600), which was equipped with (1) a control PC, which was mounted underneath the seat in order to record data and (2) a touch-screen for human-machine communication, which was switched off for the study at hand. The wheelchair was controlled with a standard joystick.

Before the participants drove through the course, they had the chance to practice for an unlimited time with the wheelchair in order to allow skill acquisition to take place before the actual data collection started. This procedure was chosen as no participant had ever depended on a wheelchair. The sample consisted of 23 students of the Universities of

Mannheim and Heidelberg (Germany) (n = 11 were male, n = 12 were female). Their average age was 23.1 years.

TABLE I. DESCRIPTION OF THE COURSE

Section Number	**Way driven**
1	From Goal Position 1 to Goal Position 4
2	From Goal Position 4 to Goal Position 2
3	From Goal Position 2 to Goal Position 5
4	From Goal Position 5 to Goal Position 2
5	From Goal Position 2 to Goal Position 4
6	From Goal Position 4 to Goal Position 3
7	From Goal Position 3 to Goal Position 1
8	From Goal Position 1 to Goal Position 5
9	From Goal Position 5 to Goal Position 3
10	From Goal Position 3 to Goal Position 2
11	From Goal Position 2 to Goal Position 1
12	From Goal Position 1 to Goal Position 5
13	From Goal Position 5 to Goal Position 4
14	From Goal Position 4 to Goal Position 1

As a reward for participation, the participants either received 5 € or a certificate for participation, which is required by some students to complete their degree.

B. Description of the Variables

As mentioned before, an industrial PC was mounted on the wheelchair in order to gather data on how the participants drove through the course. Based on the recorded data, the following variables were calculated and in the following analyses used as independent variables:

- time the wheelchair drove forward in seconds (a forward movement was set when the forward velocity was equal or greater than 0.01 m/s) for each section (TF_1 – TF_14) and for the whole course (TF_TOT)
- time the wheelchair user drove backward in seconds (a backward movement was identified when the backward velocity was equal or lower than -0.01 m/s) for each section (TB_1 – TW_14) and for the whole course (TB_TOT)
- time the wheelchair rotated on the spot in seconds (a rotation on the spot was identified when the forward/backward velocity was smaller than 10% of the maximum forward/backward velocity, i.e., 0.06 m/s and when the rotational velocity was bigger than 10% of the maximum rotational velocity, i.e., 0.08 rad/s) for each section (TR_1 – TR_14) and for the whole course (TR_TOT)
- average velocity when driving forward for each section (VF_1 – VF_14) and for the complete course (VF_TOT)
- average velocity when driving backward for each section (VB_1 to VB_14) and for the whole course (VB_TOT)
- average velocity when rotating for each section (VR_1 – VR_14) and for the whole course (VR_TOT)
- distance driven forward in meters for each section (DV_1 – DV_14) and for the whole course (DV_TOT)
- distance driven backward in meters for each section (DB_1 – DB-14) and for the whole course (DB_TOT)

In order to link the fine motor abilities with the wheelchair variables, the tremor (TR), the precision (PR), the arm-hand velocity (AHV), the wrist-finger velocity (WFV) and the aiming capabilities (AC) were assessed with the second short form of the "Motor Performance Test" [23].

C. Data Analysis

In order to define variables which are based on the wheelchair's movements and which allow an indication about the participants' motor abilities, univariate general linear model analyses were calculated with the wheelchair movement variables as independent variables and the fine motor abilities as dependent variables.

The significant results regarding the connections between the motor abilities and the times driven forward, backward and rotating are summarized in Tab. 2.

TABLE II. RESULTS OF THE UNIVARIATE ANALYSES TESTING THE EFFECT OF THE PSYCHOMOTOR ABILITIES ON THE TIME VARIABLES

Indep. variable	**Dep. variable**	**Value of the test statistic**	***p***	***f²***
TF_TOT	PR	F(1, 20) = 5.24	0.03*	0.21^{1}
TF_1	PR	F(1, 20) = 5.98	0.03*	0.23^{1}
TR_1	AC	F(1, 21) = 9.35	0.01**	0.31^{1}
TF_3	PR	F(1, 20) = 10.14	0.01**	0.34^{2}
TB_3	AC	F(1, 21) = 17.18	0.00**	0.45^{2}
TF_5	PR	F(1, 20) = 7.34	0.01**	0.27^{1}
TF_9	PR	F(1, 20) = 4.39	0.05*	0.18^{1}
TR_9	WFV	F(1, 19) = 4.59	0.05*	0.19^{1}
TR-11	WFV	F(1, 19) = 5.45	0.03*	0.22^{1}

** $p < .01$, * $p < .05$. ^{1} medium-sized effect, ^{2} large effects according to [24].

As these results demonstrate, especially the time driven forward in Section 1, 3, 5 and 9 are indicative for the participants' precision. The direction of the effects were analyzed on the basis of bivariate correlations, which indicated that the better the times were, the bigger were the precision abilities of the participants. The participants' aiming capabilities could be predicted by the participants' times driven backward in Section 3. The aiming capacity could also be predicted by the times used for rotating in Section 1: The participants had lower aiming capabilities if they required longer for rotating. The time required for rotating especially of the Sections 9 and 11 were significant predictors for the wrist-finger speed. The direction of the effect was the same as for the aiming capability: The participants with longer durations demonstrated higher wrist-finger velocities.

The significant results regarding the univariate general linear model analyses conducted to test the predictability of the psychomotor abilities on the basis of the wheelchair velocities, are summarized in Table 3.

These results demonstrate the following patterns:

- Precision could be predicted especially by the velocities driven forward and especially in the Sections 1, 3 and 5, but also by the average velocity driven backward during Section 12. The participants using greater forward velocities yielded better results in precision; however, the participants using greater backward velocities yielded worse results regarding their precision ability.
- The arm-hand velocity could significantly be predicted by the participants' average velocity when driving forward and backward in Section 1 and 8, when rotating in Section 1 and 6. The correlational patterns demonstrate that the participants, who have received better values with regard to their arm-hand velocities, have gained faster average velocities when driving forward, slower average velocities when driving backward and faster velocities for rotating.

- In addition, the aiming capacity could be determined on the basis of the average velocity driven backward in Section 3 and the total average velocity when rotating for the complete course and in Section 4. The correlational patterns demonstrate that the participants with better aiming capabilities yielded greater average velocities when rotating and lower average velocities when driving backward.
- Last, the tremor could significantly be predicted by the average velocity when rotating on the spot in Section 4 and 9. The correlational patterns show different directions of this effect: While participants with greater tremor had lower average velocities in Section 4; they had greater average velocities in Section 9.

TABLE III. RESULTS OF THE UNIVARIATE ANALYSES TESTING THE EFFECT OF THE PSYCHOMOTOR ABILITIES ON THE VELOCITY VARIABLES

Indep. Variable	**Dep. Variable**	**Value of the test statistic**	***p***	***f^2***
VF_1	PR AHV	F(1, 19) = 5.05 F(1, 21) = 4.22	0.04* 0.05*	0.21^1 0.17^1
VB_1	AHV	F(1, 20) = 4.45	0.05*	0.19^1
VR_1	AHV	F(1, 19) = 4.19	0.05*	0.18^1
VF_3	PR	F(1, 20) = 4.34	0.05*	0.18^1
VB_3	AC	F(1, 21) = 63.84	0.00**	0.75^2
VR_4	TR AC	F(1, 20) = 5.32 F(1, 19) = 6.86	0.03* 0.02*	0.21^1 0.27^1
VF_5	PR	F(1, 20) = 7.52	0.01*	0.27^1
VR_6	AHV	F(1, 19) = 10.87	0.00**	0.36^2
VF_8	AHV	F(1, 21) = 6.29	0.02*	0.25^1
VB_8	AHV	F(1, 21) = 4.53	0.00*	0.18^1
VR_9	TR	F(1, 19) = 4.19	0.05*	0.18^1
VB_12	PR	F(1, 21) = 8.68	0.01**	0.29^1
VR_TOT	AC	F(1, 21) = 4.60	0.04*	0.18^1

** $p < .01$, * $p < .05$. ^{1} medium-sized effect, ^{2} large effects according to [24].

As a last step, the results regarding the univariate general linear model analyses testing which wheelchair variables could predict the psychomotor abilities, are summarized in Table 4 and described in the following:

- Precision could be predicted on the basis of the distances driven forward in Section 1, 3, and 7 and of the distances driven backward in Section 3 and 13. The directions of the effects are two-fold: On the one hand, the participants with greater precision abilities drove shorter distances in the forward mode in Section 1, 3 and 7 and in the backward mode in Section 13. On the other hand, the participants with greater precision abilities drove longer distances in the backward mode in Section 3.
- Aiming capacity could be significantly predicted by the distance driven forward in Section 1, 2 and 3 and by the distances driven backward in Section 3 and 9. The correlations between the aiming capacities and the distances driven in the forward mode are positive, which means that the participants with greater aiming capabilities drove longer distances. The correlations between the aiming capabilities are negative, which means that the persons with greater aiming capabilities drover shorter distances in the backward mode.
- The participants' tremor could significantly be predicted by the distance driven forward in Section 2, 3, 10, and 12, the distances driven backward in Section 3 and 12. The correlations show a two-fold picture: The participants with greater tremor abilities yielded shorter distances driven in the forward mode in Section 2, 3, 10 and 12 and in the backward mode in Section 12; while the participants with greater tremor, yielded longer distances driven in the backward mode in Section 3.
- The participants' arm-hand velocity could significantly be predicted on the basis of the distances driven forward and backward in Section 6. The correlational patterns demonstrate that participants with greater arm-hand velocities drove longer distances both in the backward and forward mode in Section 6.
- Last, the participants' wrist-finger velocity could be predicted by the distances the participants drove backward in Section 11 and 12. The correlations demonstrate that the participants with greater wrist-finger velocities yielded greater distance values in both sections.

TABLE IV. RESULTS OF THE UNIVARIATE ANALYSES TESTING THE EFFECT OF THE PSYCHOMOTOR ABILITIES ON THE DISTANCE VARIABLES

Indep. Variable	**Dep. Variable**	**Value of the test statistic**	***p***	***f^2***
DF_1	PR AC	F(1, 21) = 7.08 F(1, 21) = 5.84	0.02* 0.03*	0.25^{1} 0.22^1
DF_2	TR AC	F(1, 20) = 5.79 F(1, 21) = 5.16	0.02* 0.03*	0.23^1 0.20^1
DF_3	TR AC PR	F(1, 20) = 5.14 F(1, 21) = 17.95 F(1, 21) = 3.97	0.04* 0.00** 0.05	0.20^1 0.46^2 0.16^1
DB_3	PR TR AC	F(1, 21) = 5.36 F(1, 21) = 4.02 F(1, 21) = 12.75	0.03* 0.05* 0.00**	0.20^1 0.16^1 0.38^2
DF_6	AHV	F(1, 21) = 5.42	0.03*	0.21^1
DB_6	AHV	F(1, 20) = 10.44	0.00**	0.34^2
DF_7	PR	F(1, 20) = 3.58	0.03*	0.22^1
DB_9	AC	F(1, 18) = 13.49	0.00**	0.43^2
DF_10	TR	F(1, 20) = 6.79	0.02*	0.20^1
DB_11	WFV	F(1, 18) = 7.01	0.01**	0.30^1
DF_12	TR	F(1, 20) = 5.04	0.04*	0.20^1
DB_12	TR	F(1, 21) = 9.32	0.01**	0.31^1
DB_13	PR WFV	F(1, 18) = 6.62 F(1, 18) = 5.89	0.02* 0.03*	0.28^1 0.25^1

** $p < .01$, * $p < .05$.. ^{1} medium-sized effect, ^{2} large effects according to [24].

As the description of these results has already demonstrated, some of the psychomotor abilities can better be predicted by the driven times, velocities and distances than others: The radar diagrams given in Fig. 2 clearly demonstrate that precision can be predicted best, i.e. by the biggest number of wheelchair variables. In contrast, there are only four significant predicts for the wrist finger speed.

The radar diagrams also show important differences in the strengths of the effects:

- For the aiming capacity, the best predictor is the velocity driven backward in Section 3; the worst, but still significant predictor is the velocity used for rotation during the complete course.
- The best predictor for the precision is the time driven forward in Section 3; the worst significant predictor is the distance driven forward in Section 3.
- Regarding the tremor, the distance driven backward in Section 12 is the most important predictor; the least impact has the distance driven backward in Section 3.
- The most important predictor for the time required for rotation in Section 9 and the time required to rotate in

Section 11 has the smallest impact on the wrist-finger speed.

- Last, the predictive validity for the arm-hand velocity is greatest for the average velocity to rotate in Section 6 and smallest for the average velocity to drive forward in Section 1.

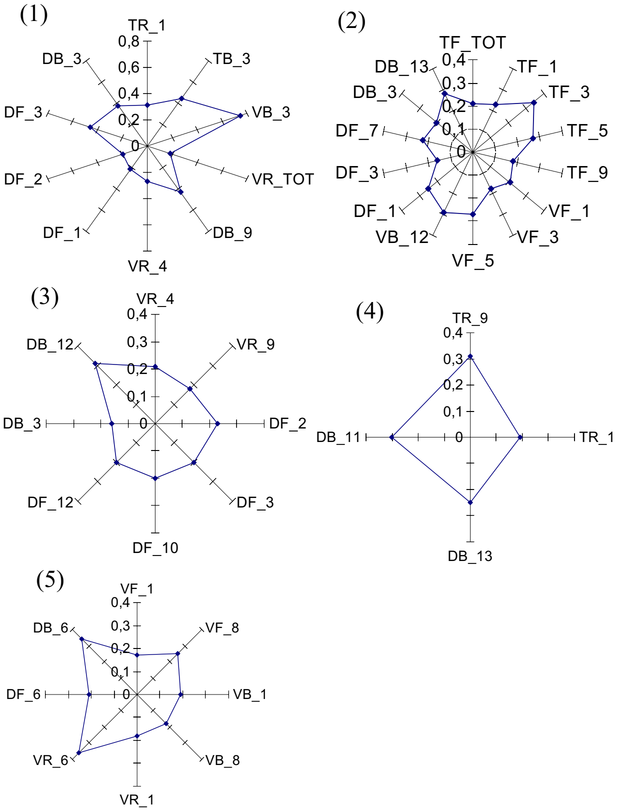

Figure 2. Radar diagrams showing the wheelchair variables significantly predicting (1) aiming capacity, (2) precision, (3) tremor, (4) wrist-finger-speed, and (5) arm-hand velocity with greater numbers indicating greater effect sizes.

When comparing the predictive validity of the various sections on the psychomotor abilities, the following patterns attract attention:

- The time variables only allow conclusions regarding the motor abilities "aiming", "precision" and the "wrist-finger velocity".
- The wheelchair velocity variables do not allow conclusions regarding the participants' wrist-finger velocity.
- The distances driven allow judging on all measured psychomotor abilities, which are aiming capacity, precision, tremor, arm-finger velocity and wrist-finger velocity.

In addition, some sections give better indications about the psychomotor abilities:

- The data derived from concluding Section 3 gives the biggest scope to judge on aiming, precision and tremor.
- Section 1 allows drawing conclusions on aiming, precision, and the arm-finger finger speed.
- To judge on the wrist-finger speed, Section 9, 12, and 13 can be used.
- The variables derived from the complete course only allow drawing conclusions with regard to the person's aiming and precision capabilities.

How these results and the underlying knowledge can be used in order to develop an assistance system for adaptive wheelchair control, is introduced in the following section.

IV. IMPLICATIONS FOR ADAPTIVE WHEELCHAIR CONTROL

This definition (1) of highly predictive sections and (2) of wheelchair motion variables which enable to predict especially the participants' precision, aiming capability, wrist-finger velocity, arm-hand velocity and tremor enables to build a model which output is the ideal configuration of the wheelchair system such that the possibility of an accident is minimized.

For this purpose, an a-posteriori analysis of the past behavior of the wheelchair could be conducted to identify meaningful sections (e.g., a section, which resembles Section 3). On that basis, the variables identified in this section (e.g., time driven forward) as predictive for the motor abilities (e.g., precision) can be calculated and fed, for example, into a Bayesian Network (such as introduced in [25]) or an Artificial Neural Network (as discussed in [26]), which have both demonstrated their adequacy for reasoning on human abilities. The resulting classification of the users' capability can then be used for reasoning on a configuration of the system, which – on the one hand – optimizes the safe navigation of the wheelchair user and – on the other hand – allows him/her training the remaining abilities if the current motor skills enable him/her a safe navigation.

V. DISCUSSION AND FUTURE WORK

The paper at hand first of all expands the concept of adaptive automation, which has mainly been applied to the field of air traffic control, in two aspects: First of all, it extends it to the field of assistive devices and more specifically to assistance systems for powered wheelchair control. Second, it defines another variable, which can significantly influence human performance and which can be used as a reference variable for adaptive automation. As the individual differences in the human motor abilities do not have a significant effect on performance differences on highly cognitive tasks (such as in the field of air traffic control), studies have demonstrated that in the field of wheelchair control, these differences are crucial for safely and efficiently using the assistive device in the everyday life ([1][2][3][4]). Hence, adapting the level of automation to the current motor abilities of the wheelchair user might have a significant impact on the wheelchair market: It might increase the usability of today's wheelchairs; it might reduce the number of accidents, which happen with powered wheelchairs; it might enable people to use a wheelchair and gain independence, who nowadays cannot operate a powered wheelchair due to lacking motor skills.

In order to be able to build such an adaptive wheelchair system, this paper aimed at defining variables, on which basis an assistance system for powered wheelchair control could measure and assess the current level of the motor abilities of a user. For this purpose, a study was conducted, during which the participants drove through a course and during which major variables reflecting the wheelchair movement were collected. In order to calculate the predictive validity of these variables, the participants' motor abilities and more specifically their precision, tremor, aiming capabilities, wrist-finger velocity, and arm-hand velocity were assessed with traditional tests. On the basis of univariate general linear model analyses, it was demonstrated that especially the precision of the participants could be predicted. The greatest predictive validities were reflected in the wheelchair movement data derived from Section 3, which covers turning on the spot, turning right twice and driving straight ahead along a table for a short distance. It was discussed how this knowledge could be used for an assistance system: An online assessment could take place by identifying such routes, measuring the described variables and feeding it, for example, in a Bayesian Network, reflecting the described structure.

Future work will aim at implementing an assistance system for powered wheelchair control, which can measure the psychomotor abilities of its user, at developing rules, on which basis the most appropriate configuration of a complex system can be identified for a given level of psychomotor abilities and at evaluating the resulting system with regard to user acceptance, dependability, and user satisfaction.

REFERENCES

[1] D. M. Bailey and T. DeFelice, "Evaluating movement for switch use in an adult with severe physical and cognitive impairments", American Journal of Occupational Therapy, vol. 45(1), pp. 76-79, 1991.

[2] H. Bateni and B. E. Maki, "Assistive devices for balance and mobility: Benefits, demands, and adverse consequences", Arch. Phys. Med. Rehab., vol. 86(5), pp. 134-145, 2005.

[3] J. Chase and D. M. Bailey, "Evaluating the potential for powered mobility", American Journal of Occupational Therapy, vol. 44(12), pp. 76-79, 1990.

[4] L. Fehr, W. E. Langbein and S. B. Skaar, "Adequacy of powered wheelchair control interfaces for persons with severe disabilities: A clinical survey", Journal of Rehabilitation Research & Development, vol. 37(3), pp. 353-360, 2000.

[5] N. B. Sarter, D. D. Woods and C. E. Billings, "Automation Surprises". In G. Salvendy (Ed.), Handbook of Human Factors & Ergonomics (2nd ed.). New York: Wiley, 1997.

[6] S. Norman, C. E. Billings, D. Nagel, D., E. Palmer, E. L. Wiener and D. D. Woods, "Aircraft automation philosophy: A source document", Moffett Field, CA: NASA Ames Research Center, 1988.

[7] C. J. Kessel and C. D. Wickens, „The transfer of failure-detection skills between monitoring and controlling dynamic systems", Human Factors, vol. 24(1), pp. 49-60, 1982.

[8] L. R. Young, "On adaptive manual control", Ergonomics, vol. 12(4), pp. 635-675, 1969.

[9] D. B. Kaber and M. R. Endsley, "The combined effect of level of automation and adaptive automation on human performance with complex, dynamic control systems". In Proc. of the 41st Annual Meeting of the Human Factors and Ergonomics Society (pp. 205-209). Human Factors and Ergonomics Society: Santa Monica, CA, 1997.

[10] G. M. Corso and M. M. Moloney, "Human performance, dynamic function allocation and transfer of training", In Koubek & Karwowski (Eds.), Manufacturing Agility and Hybrid Automation-I. Proceedings of the 5th International Conference on Human Aspects of Advanced Manufacturing. Louisville, KY: IEA Press, 1996.

[11] P. A. Hancock and M. H. Chignell, "Mental workload dynamics in adaptive interface design", IEEE Transactions on Systems, Man, and Cybernetics, vol. 18, pp. 647-658, 1988.

[12] P. A. Hancock, M. H. Chignell and A. Lowenthal, "An adaptive human-machine system", IEEE Transactions on Systems, Man, and Cybernetics, vol. 15, pp. 627-629, 1985.

[13] T. Inagaki., "Adaptive automation: Sharing and trading of control", In E. Hollnagel (Ed.), Handbook of cognitive task design (pp. 147-169). Mahwah, N. J.: Lawrence Erlbaum Associates, 2003.

[14] D. B. Kaber and M. R. Endsley, "The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task", Theoretical Issues in Ergonomics Science, vol. 5(2), pp. 113-153, 2004.

[15] R. Parasuraman, "Effects of adaptive function allocation on human performance", In D. J. Garland & J. A. Wise (Eds.), Human factors and advanced aviation technologies (pp. 147-157). Daytona Beach, FL: Embry-Riddle Aeronautical University Press, 1993.

[16] R. Parasuraman, T. Bahri, J. E. Deaton, J. G. Morrison and M. Barnes, "Theory and design of adaptive automation in adaptive systems" (Progress Report No. NAWCADWAR-92033-60). Warminster, PA: Naval Air Warfare Centre, Aircraft Division, 1992.

[17] W. B. Rouse, "Adaptive aiding for human/computer control", Human Factors, vol. 30, pp. 431-443, 1988.

[18] M. W. Scerbo, "Theoretical perspectives on adaptive automation", In R. Parasuraman & M. Mouloua (Eds.), Automation and human performance: Theory and applications (pp. 37-63). Hillsdale, N. J.: Lawrence Erlbaum Associates, 1996.

[19] M. W. Scerbo, "Adaptive automation". In W. Karwowski (Ed.), International encyclopedia of ergonomics and human factors (pp. 1077-1079). London: Taylor and Francis, Inc., 2001.

[20] O. J. Kilkens, M. W. Post, A. J. Dallmeijer, H. A. Seelen, and L. H. Van der Woude, "Wheelchair skills tests: A systematic review", Clinical Rehabilitation, vol. 17, pp. 418-430. 2003.

[21] O. J. Kilkens, M. W. Post, A. J. Dallmeijer, F. W. Van Asbeck and L. H. Van der Woude, "Relationship between manual wheelchair skill performance and participation of persons with spinal cord injuries 1 year after discharge from inpatient rehabilitation", Journal of Rehabilitation Research & Development, vol. 42(3), pp. 65-74, 2005.

[22] R. L. Kirby, "Wheelchair Skills Program", available at www.wheelchairskillsprogram.ca, 2005.

[23] W. Neuwirth and M. Benesch, "Motorische Leistungsserie", Schuhfried, Mölding. 2004.

[24] J. Cohen, "Statistical power analysis for the behavioral sciences", Hillsdale, NJ: Lawrence Erlbaum Associates, 1988.

[25] M. Jipp, E. Badreddin, C. Abkai, and J. Hesser, „Individual ability-based system configuration – Cognitive profiling with bayesian networks". Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics, vol. 1, pp. 3359-3364, 2008.

[26] A. Wagner, C. Bartolein, M. Jipp, and E. Badreddin, "Assessment of the user's dependability-relevant abilities for enhanced human-technology interaction". Proceedings of the Annual Meeting of the Human Factors and Ergonomics Society, vol. 52, pp. 980-984, 2008.