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Understanding the motor learning process in handrim wheelchair propulsio

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GENERAL DISCUSSION

This chapter reflects on the results of the five experimental studies included in this thesis, especially their conceptual contributions to the field of motor learning in handrim wheelchair propulsion as well as their clinical implications. This general discussion will be concluded with a future outlook on research into motor learning in wheelchair propulsion and onto its implementation in clinical practice.

The current thesis aimed to deepen the understanding of the principles that guide the motor learning process during wheelchair propulsion in able-bodied participants and individuals with SCI. We found that introducing variable practice in the early stages of learning to the novel able-bodied participants may have varying results, which depend on the nature of the intervention and introduced task and environmental constraints. When presented with real-time visual feedback on their propulsion technique and instruction to increase variability, participants showed large improvements in propulsion technique and no change in ME (Chapter 2). In contrast, uninstructed variable practice in a free environment resulted in improvements in ME and similar changes in propulsion technique as those found in a 'no practice' control group (Chapter 3). In Chapter 4, the concomitant changes in wheelchair propulsion technique measured on the level on the handrim and shoulder load were investigated following low-intensity propulsion practice. Despite the homogenous direction of change in wheelchair propulsion technique, participants developed varying kinematic solutions to the task, which in turn influenced the outcomes of the musculoskeletal modelling differently. Chapter 5 proved the validity of a wheelchair activity monitor to distinguish between independent wheelchair propulsion and other activities. This allowed the use of the Active8 activity monitor to determine the daily amount of wheelchair propulsion throughout five weeks of active rehabilitation in patients with recent SCI (Chapter 6). The final study, described in Chapter 6, showed that patients with recent SCI did not improve their ME and propulsion technique throughout active rehabilitation, but did increase their work capacity and scores on functional wheelchair skills. Surprisingly, a comparison with a group of experienced wheelchair users revealed little differences between the groups on all above-mentioned parameters, with exception of ME, which was higher in the experienced group after a correction for the relative power output.

EFFECTS OF TWO KINDS OF VARIABLE PRACTICE ON THE MOTOR LEARNING PROCESS

This thesis included two experiments (Chapter 2 and 3) which aimed to explore the effect of practice variability on the motor learning process of wheelchair propulsion in novice able-bodied participants. The choice of variable practice was motivated by the recent findings suggesting that movement variability exhibited during the motor learning process may be a representation of motor exploration which contributes to finding the most optimal task solution [1,2]. The first experiment aimed to increase propulsion variability by means of real-time visual feedback on the individual propulsion technique variables, while propelling on a motor driven treadmill, and found considerable improvements in propulsion technique, but ME remained unchanged throughout the experiment (Chapter 2). The second experiment consisted of uninstructed practice of an inherently variable task, i.e. wheelchair basketball which led to improvements in ME, but little change in propulsion technique (Chapter 3). Keeping in mind that according to a theoretical model proposed by Sparrow and Newell [3], a given task solution is thought to emerge from an interplay between the task, environment and person, it is not very surprising that two kinds of variable practice led to different results. Even though in both cases, the task was to propel the wheelchair, the goals for the participants and the constraints of the tasks were considerably different.

When it comes to the goal of the task and the role of the variability in it, it could be said that while for the participants practicing wheelchair basketball, variability was a mean to achieve a goal, in the feedback-induced variability study, the variability itself was a goal. Wheelchair basketball is an inherently variable task, and is therefore likely to stimulate functional variability. As variability is inherent in the task, the participants possibly learn to be variable implicitly and optimize their energy efficiency in the process. In contrast to that, practicing variability using visual feedback on the propulsion technique variables with an instruction to increase variability is very explicit. The amount of instruction and feedback may have distracted the participants from processing any internal feedback as it would normally take place during the natural learning process. This possibly interrupted the optimization of the energy expenditure. There is a number of reports concerning the superiority of implicit learning over explicit learning in healthy populations [4,5] and there seems to be an agreement that implicit learning may also be advantageous for patient populations [6,7].

Another difference between the two kinds of variable practice that were described in chapters 2 and 3, is the focus of attention during practice. There is considerable evidence that directing attention externally as opposed to internally has a better effect on skill acquisition (for reviews see [8,9]). Focus of attention for individuals playing basketball was outside their body and it was directed towards a ball or avoiding another player. In contrast, the focus for participants who aimed to increase variability by changing their propulsion technique was much more internal. Participants were aware that what they saw on the feedback screen was a direct consequence of their movement, which directed

their attention internally to their own body. Previous research showed that instructions related to the performer's body movements can have a deteriorating effect on learning. In contrast, 'distracting the performers from concentrating on their own movements' and instead 'directing their attention to the effects of those movements on the environment', can enhance motor skill acquisition of complex tasks (for review see [10]).

It could also be that the different effect of the two variable practice studies on the ME was not caused by the choice of a different motor learning principle (explicit vs implicit learning; internal vs external focus of attention), but rather by physiological changes. Change in ME can result from a number of factors, such as improvement in coordination and eliminating unnecessary movements, but also from physical adaptation [11]. The intensity during the practice sessions (power output (W)) of the feedback-induced variability study was closely monitored and remained low. Therefore, it could theoretically not elicit changes in the cardio-respiratory fitness or muscle strength. In contrast, the intensity during wheelchair basketball practice was not registered and could potentially lead to improvements in fitness, especially considering the socially engaging setting which may have increased the motivation of the participants. According to the current guidelines of the American College of Sports Medicine, the participants who practiced basketball did not meet the required frequency of exercise to improve cardiorespiratory fitness [12] or to cause muscle hypertrophy [13,14]. Yet, it should be kept in mind that it cannot be entirely excluded that some physiological improvements, for example on the neuro-coordination level, took place and may have influenced the increase in ME in the group who practiced wheelchair basketball.

Apart from a different effect of the two variable practice studies on ME, they also elicited contrasting results in propulsion technique, which compared to the control group, improved only after the feedback practice. The feedback-induced variability study required the participants to manipulate the value of a certain variable in a prescribed direction, so for example to maximize the contact angle, in the second block of each practice session. Participants achieved this task without difficulties. This probably influenced the large improvements in propulsion technique at the post-test. Visual feedback was shown to be an effective mean to target changes in propulsion technique before [15-17]. Participants in the basketball study did not receive any instruction concerning their propulsion technique. This combined with a fact that the pre- and the post-test took place on a treadmill, so under different constraints than their practice, could have influenced the fact that participants improved their propulsion technique no more than a 'no practice' control group which only performed the pre- and the post-test.

These results showed that the task and environmental constraints can largely influence the motor solution which emerges during the motor learning process in novice able-bodied participants. While ME and propulsion technique showed concomitant improvements during the natural motor learning process, when no instruction or feedback was provided to the able-bodied participants [2,18,19], we found that this relationship does not necessarily holds when participants receive an intervention targeting their propulsion

variability. This does not mean that there is no relationship between ME and propulsion technique, but rather points out that the relationship may be modified under additional constraints. From the physiological and biomechanical point of view, it is believed that lowering push frequency and increasing the contact angle should to some extent lead to a decrease in energy expenditure during wheelchair propulsion [2]. This was confirmed in studies on other cyclical complex motor tasks which found an increase in efficiency concomitant with decreasing movement frequency and increasing movement amplitude [11,20]. It should, however, be kept in mind that changing task constraints by e.g. adding visual feedback to target a certain propulsion technique variable may disturb the optimization of energy efficiency. Similar findings were documented before by de Groot et al, who found that targeting an improvement in fraction effective force with visual feedback was successful in itself, but came at a cost of lower mechanical efficiency [15].

Our findings show that changes in ME and propulsion technique during the motor learning process depend on the chosen task and environmental constraints. Future studies should aim to understand what the exact relationship is between ME and propulsion technique and which factors are potential modifiers for this relationship. Additionally, it is necessary to further explore what kind of intervention could bring the most desirable gain in both, the ME and propulsion technique, and when such intervention should take place. The results of the feedback-induced variability study suggest that confronting unexperienced individuals with quite a constraining and prescriptive intervention in the very early stages of the motor learning process may disrupt the optimization of energy efficiency. We, therefore, suggest that variability should be stimulated implicitly, by choosing an inherently variable task as opposed to explicitly, by providing detailed instruction. Perhaps extending the period of natural learning beyond the pre-test and applying an intervention once the performance stabilizes would contribute to more desirable results. Alternatively, a natural learning protocol could be implemented after the intervention to allow the participants to stabilize their performance.

RELATIONSHIP OF PROPULSION TECHNIQUE AND SHOULDER LOAD

In chapter 4, the concomitant changes in propulsion technique and shoulder load that appeared following 80 min of low-intensity practice in novice-able bodied participants were described. We found that despite uniform changes in propulsion technique measured at the level of the handrim, participants developed various kinematic solutions and exhibited various patterns of glenohumeral reaction force. We also found that extreme values of the push frequency and the contact angle may not be optimal for the shoulder load. This suggests that the recommendation of Clinical Practice Guidelines for Preservation of Upper-Extremity [21], that prescribe lowering the push frequency and increasing the contact angle, may need to be more nuanced. This is in accordance with earlier findings which suggested that altering push frequency or contact angle to extreme values is less effective in lowering overall muscle demand than moderate adjustments in technique [22]. Similar suggestions were made for other propulsion technique variables such as peak force [22] or fraction effective force [23].

It should be kept in mind that there is a mutual dependency among the wheelchair propulsion technique variables, meaning that changing a value of one variable often comes at a cost of another parameter. Like in the example of one participant from Chapter 4 who achieved a push frequency of 21 pushes/min at the post-test. Such extreme value cannot be solely achieved by increasing the contact angle, but must also be accompanied be a significant increase in peak and mean force and the amount of work per push, something that is likely to increase the shoulder load. At this point, it is not possible to say what 'healthy' thresholds are for push frequency, contact angle or any other propulsion variable, beyond which the impact on the shoulder load is negative. It also remains to be determined whether those values are universal or different for various individuals. Future research should attempt to identify the 'healthy' thresholds for the propulsion technique variables in order to find a proper balance between lowering the push frequency and increasing handrim forces during wheelchair propulsion.

A discussion present in wheelchair research, as well as in the wider field of animal biomechanics, is whether the goal of (wheelchair propulsion) practice should be to lower the mean or the peak glenohumeral loads. Even though it can be agreed on that the highest damage comes from high-repetition and high-load tasks, the exact relationship between the dose of mechanical load and tissue response is unknown. In the task of wheelchair propulsion where the number of daily repetitions is counted in thousands, it is crucial to determine how a decrease in mean and peak loads affects the actual damage to the muscle tissue.

Another important finding of Chapter 4 is that participants can exhibit high inter-individual variability in the kinematic solution to the task despite homogenous direction of change in spatio-temporal aspects of propulsion measured at the level of the wheel. It is important to consider this finding when developing the guidelines for preservation of the upper-extremity health and consider the kinematics of the upper extremity and the trunk, instead of only focusing on the forces applied to the handrim. As confirmed by the study in Chapter 4, despite the fact that wheelchair propulsion is a relatively constrained task, as the hand has to follow the trajectory of the handrim, there is still a very high number of movement solutions that a user can exhibit in response to this task.

In conclusion, technique variables measured on the handrim should be used with caution when formulating prescriptive advice aimed at minimizing the shoulder load. The extreme values of propulsion technique may be harmful for the shoulder and it remains to be determined which values of propulsion technique variables should be recommended to the wheelchair users. Moreover, the results suggest that propulsion technique measured at the level of the wheel is not predictive of shoulder load and that information about the kinematics of the movement should also be provided when instructing wheelchair users.

Referring to the constraints-based model [3] and the influence of various factors on the resulting movement, it is important to keep in mind that factors such as wheelchair fitting, personal fitness, especially muscle strength within the shoulder complex, body mass,

wheelchair quality and maintenance and many others can impact both the shoulder load as well as the motor learning process of wheelchair propulsion and its energy efficiency. In future research, it is important to look at the interactions between various parameters during the motor learning process and describe their influence on the shoulder load. Even though it was not the focus of this thesis, pathological scapular orientation and the presence of scapular dyskinesia are thought to be associated with shoulder pain in manual wheelchair users [24] and general population [25,26]. It is advised to look at this aspect in future research in order to determine the influence of scapular pathology on shoulder pain and motor learning process during wheelchair propulsion.

INTER-INDIVIDUAL VARIABILITY: A GREAT CHALLENGE TO RESEARCHERS AND CLINICIANS

Inter-individual variability is something that was particularly visible in chapters 4 and 6, meaning that both able-bodied and individuals with SCI exhibit inter-individual variability on various levels during wheelchair propulsion. Inter-individual variability in task solutions during motor learning was described before in wheelchair literature [2] and during learning a novel discrete motor task [27]. Chapter 6 describes the course of propulsion technique measured at the level of the handrim in patients with recent SCI. On a group level, both ME and propulsion technique did not change across active rehabilitation. It is, however, visible that 2 out of 8 participants developed their technique in a different direction than the rest. Chapter 4 on the other hand, finds unanimous changes in propulsion technique measured at the level of the handrim but various kinematic solutions in able-bodied participants. This showed that inter-individual variability can take place at various levels and homogeneity on one level does not guarantee homogeneity on another one. It is difficult to say what causes an individual to choose a certain task solution. According to the constraint model proposed by Sparrow and Newell [3], all movements emerge from the interaction of three factors; the organism, the environment, and the task being performed. In wheelchair propulsion, this means that the observed movement is a result of an interplay among a large number of factors including: individual physical characteristics, preexisting movement repertoire, talent, the kind of wheelchair and its maintenance, wheelchair-user fitting, and a range of environmental variables such as the rolling surface or presence of obstacles. All these variables and many others could potentially contribute to inter-individual differences in learning trajectories. The presence of those differences constitutes a great challenge for clinical practice which aims to provide evidence-based care. It is not possible at the moment to predict which learning style a person will adapt and more importantly which therapeutic approach will bring the best results. On another note, clinical practice could be advised through systematic monitoring of changes in wheelchair skill and behavior, which with the help of skilled embedded scientists could lead to more optimal outcomes in skill and performance [28].

MOTOR LEARNING IN EARLY SCI REHABILITATION

Chapter 6 in this thesis aimed to describe the motor learning process during active rehabilitation of people with a recent SCI and to compare its outcomes at discharge with an experienced group of wheelchair users with SCI. Despite improvements on the wheelchair circuit and in work capacity, the group with recent SCI did not show improvements in the primary outcome measures of this study, ME and propulsion technique. Based on the results of the studies on able-bodied participants [2,19], we think that the most rapid changes in ME and propulsion technique could have taken place in the days or weeks before the onset of the study. This emphasizes the need to start measuring even earlier during rehabilitation, preferably using non-invasive methods, like wheelchair mounted sensors to quantify the propulsion technique variables and the amount of wheelchair-related activity before the official start of active rehabilitation. It is important to quantify wheelchair activity and performance as soon as possible in order to determine when the rapid phase of skill acquisition takes place and how it progresses in various individuals. Inter-individual differences in early phases of motor learning could explain varying final levels of skill and help to predict individual learning trajectories [29].

We hypothesized that the group with a recent SCI would score worse on all outcome measures at discharge from inpatient rehabilitation compared to the experienced users. However, the differences between the group with a recent SCI and experienced wheelchair users were less pronounced than hypothesized, with the only significant difference found in mechanical efficiency and no difference in propulsion technique, work capacity and on the wheelchair circuit scores. Based on those results it is difficult to make judgements concerning the propulsion technique and ME or say whether those parameters need to be improved in the participants with recent SCI or experienced wheelchair users. This is primarily caused by the fact that there is a limited database of normative values of ME or propulsion technique that could be used to generate individualized advice [28]. The current clinical guidelines [21] for the preservation of the upper-extremity health suggest performing long fluent pushes at low frequency. It was pointed out in Chapter 4 that this advice is insufficient. Its shortcomings are related to the fact that an extremely low push frequency or an extremely high contact angle affect the shoulder load negatively. This combined with the presence of the inter-individuals variability in propulsion technique, makes it clear that there is still a long way to go for the research on wheelchair propulsion before custom advice can be given to individual wheelchair users.

The study with the populations with SCI brought forward an important clinical issue which is critical from the point of the motor learning process but also in the context of overload injury prevention. We found that the group with a recent SCI and the experienced group propelled at the same absolute power output during low-intensity steady state wheelchair propulsion on the treadmill, despite a large, approx. 25 kg difference in body mass between them. We proposed that the significantly lower relative power output in the experienced group, despite the higher body mass, is related to the

state of the wheelchair, as well as the wheelchair-user fitting. It is useful to remember that the group with a recent SCI propelled in non-individualized wheelchairs provided by the rehabilitation center, while the experienced users propelled in their own custom-made wheelchairs. There was a considerable difference in the maintenance of the wheelchairs between the groups with wheelchairs in the experienced group being properly fitted and much better maintained.

Recent studies showed that shoulder pain often develops in the early stages of rehabilitation [30,31]. This finding is not unexpected because active rehabilitation is a period when the body is at its weakest, recovering from an injury, not yet trained for upper extremity exercise, and yet the cumulative loads, also during wheelchair propulsion are quite high [32,33]. This stresses the importance of early provision of well-maintained and properly fitted wheelchairs. Considering the highly repetitive character of wheelchair propulsion and its low mechanical efficiency, it is necessary to take the best possible care for lowering the daily load resulting from an improper wheelchair fitting to prevent musculoskeletal complaints. The finding concerning the large difference in relative power output between the groups also emphasizes how important it is to measure power output in standardized manner during and after rehabilitation. Determining power output, either with a drag test or using the measurement wheels during propulsion, helps to estimate whether the fitting of the wheelchair to the user or the maintenance of the wheelchair are sufficient. It can therefore be used in the prescription and evaluation of the wheelchairs and changes made to the wheelchair-user interface. This advocates again for systematic monitoring of individual wheelchair users already during early rehabilitation, as suggested by de Groot et al. [28].

ACTIVITY MONITORING IN INDIVIDUALS WITH SCI: MULTIPURPOSE MONITORING

The use of activity monitors, which proved to be valid to determine the amount of daily independent wheelchair propulsion (Chapter 5), was a valuable addition to monitoring the motor learning process during active rehabilitation in patients with a recent SCI (Chapter 6). The results showed that the amount of daily activity does not change during the period of 5 weeks of active rehabilitation. Moreover a difference between the weekdays when therapy was scheduled and weekends when patients went home was found. Patients were more active between Monday and Friday, when they actively participated in inpatient rehabilitation.

Monitoring wheelchair activity is very important not only from the point of view of the motor learning process. Systematic monitoring of lifestyle activities can be used as a warning system for the physical over- or underload in the population with SCI. Overload relates to the previously discussed high prevalence of shoulder injuries which take their origin in the repetitive strain imposed on the shoulder during activities of daily living, including wheelchair propulsion. Underload refers to the observation of health behavior, specifically the amount of activities that contribute to energy expenditure and therefore

to the regulation of body mass and cardio-respiratory fitness. As the patients with SCI can only expand their energy with upper-body exercise, the maintenance of a healthy Body Mass Index is difficult and the prevalence of the metabolic syndrome in people with SCI is high [34]. This was visible in Chapter 6, in which the experienced group was on average 25 kg heavier than the patients with a recent injury. Activity monitoring can help to quantify the amount of physical activity in persons with SCI. This information can aid the physicians in constructing individualized advice concerning the balance between the food intake and energy expenditure and thus may help to prevent the metabolic syndrome in individuals with SCI [34].

The activity monitor used in this thesis proved to be valid to differentiate between independent wheelchair propulsion and other activities (Chapter 5). It failed, however, to distinguish various intensities of wheelchair propulsion i.e. maneuvering, normal speed or high speed propulsion. It is important to work on better discriminating abilities of the wheelchair activity monitors. Ideally, the device would be able to recognize the nature and intensity of activates performed in the wheelchair. Such system should be able to distinguish between various tasks, such as wheelchair propulsion, reaching movements, handbiking, transfers, weight-relief lifts etc. This would provide valuable information concerning the motor learning process in wheelchair propulsion, but also the possible origin of shoulder pain and daily energy expenditure in the context of prevention of musculoskeletal overload and overweight.

FUTURE APPROACH TO INVESTIGATING MOTOR LEARNING IN HANDRIM WHEELCHAIR PROPULSION

Results of this thesis contributed to the conceptual knowledge about the motor learning process in wheelchair propulsion. At the same time, they pointed out some of the flaws of the current approach to investigating learning in clinical populations. The complexity of measurements and limited availability of participants call for designing an alternative approach of researching the motor learning process and shoulder pain in individuals with SCI. Especially when considering the presence of inter-individual differences in learning which pose a great challenge to clinicians who aim to provide evidence-based care. Much more associations among various outcomes and better understanding of the dose-response relationship are needed over large groups and longer times to start understanding the role of wheelchair skill and propulsion technique in the context of rehabilitation. Gathering this knowledge systematically and at detailed levels will help to understand the motor learning process in wheelchair propulsion and its dependence on the task, environmental and personal constraints. This may help to create evidence-based individualized therapies for wheelchair-dependent individuals aimed at increasing independence and participation through better skill, less shoulder complaints and the appropriate level of physical activity. Based on the experiences from the last 3 years and previous literature, we will try to propose an ideal setting for researching motor learning in wheelchair propulsion, using the state-of-art technology and considering its

implementation in clinical practice. We would like to stress that this suggestion should not be seen as definitive prescription, but rather provoke a discussion concerning the future of wheelchair-related research.

The implementation of our ideas is strongly reliant on the creation of 'Wheelchair Propulsion Laboratories' [28]. It is important to say that those laboratories would not only serve as research facilities, but rather function as expertise centers generating knowledge for research and clinical purposes. Specifically, in a methodological sense, they would form a large ongoing multi-center trial which would provide standardized data to the researchers and assist clinical decision making for various groups of medical specialists such as rehabilitation physicians or physical and occupational therapists. The implementation of the wheelchair propulsion laboratories would have an overarching goal of providing the best possible, individualized and evidence-based care to wheelchair-dependent individuals.

'Wheelchair Propulsion Laboratories' would be analogous to the gait laboratories, which are very common and can be found in most Dutch rehabilitation wards. The idea for Wheelchair Propulsion Laboratories has been proposed in The Netherlands a few years ago [28], but so far it was not implemented. The study described in Chapter 6 is the first follow-up for this idea since its introduction. Based on the results of a pilot implementation study [28], the greatest barrier to systematic monitoring of the individual wheelchair fitting and learning process in rehabilitation was interpretation of outcomes. The authors suggested that for proper interpretation of individual outcomes, the availability of reference data, smallest detectable differences and visualization of outcomes is crucial. In addition to that, the thesis of Riemer Vegter in 2015 [29], suggested that the use of the newest technological solutions and equipment would be necessary to generate reliable and objective outcome measures. Importantly, the last three years brought a number of technological developments which could make that possible.

A smart use of technology to construct the wheelchair propulsion laboratories is crucial as it may be the key to generating standardized and clinically meaningful outcomes in a reasonable amount of time. Time, space and financial constraints are important to consider as current rehabilitation reality is characterized by high time pressure and motivated by financial incentives. The available technology, which was partly already used in this thesis can help to execute the measurements and gather necessary data. We specifically refer to the use of a wheelchair ergometer, like for example the newly developed ESSEDA (ProCare, Lode, The Netherlands) which allows to perform various testing and training protocols. The great advantage of this wheelchair ergometer is that it can be used to perform a range of tests like those we described in Chapter 6 more efficiently. Another advantage of the standardized testing protocols is the fact that they could be easily implemented in various rehabilitation centers. As a consequence, the acquired multi-center data could be shared, allowing to build large data sets which in turn could be used to construct reference values. This would allow to interpret individual learning trajectories and propose customized therapy.

Next to the use of a wheelchair ergometer, the activity monitors could be implemented as a part of wheelchair propulsion laboratories in order to monitor the daily amount of wheelchair-related activity. The system used in Chapter 4 and 6, showed to be valid to quantify the amount of independent wheelchair propulsion. With the use of technology which is currently in development [35], it will be possible to enrich that information with propulsion technique variables. Moreover, incorporation of GPS data could allow to pinpoint the kinds of environment a participant propelled the wheelchair in. This information could in the future be extended by adding the recognition of the nature and intensity of activities performed in the wheelchair. This would provide very valuable information about the motor learning process, daily physical activity and musculoskeletal overload risk.

In conclusion, the available technology opens up new possibilities to build an efficient multi-center network of wheelchair propulsion laboratories to assist clinicians in providing individualized diagnosis, therapy and wheelchair fitting and to provide a rich source of data from standardized protocols to the research community. Building a comprehensive wheelchair propulsion laboratory should include a database of reference values and visualization software to assist the clinicians in interpreting the acquired results.

LIMITATIONS AND STRENGTHS OF THE THESIS

The strength of this thesis is first and foremost the inclusion of both the able-bodied individuals as well as the clinical population with SCI. Inclusion of both populations allows to observe the motor learning in a homogenous and heterogeneous group. Second of all, we chose for the complex description of the motor learning process and the inclusion of a number of parameters that help to pinpoint where the changes observed during motor learning originate from. Lastly this thesis included a validation and implementation of a customer-grade activity monitor to determine the amount of independent wheelchair propulsion. This is a step towards standardized activity monitoring in individuals with SCI with a goal of observing the motor learning process as well as finding a balance between overload of the musculoskeletal system and insufficient physical activity. Additionally, the implementation of the activity monitor was a step towards field-based, as opposed to lab-based, testing in wheelchair propulsion.

This thesis has some limitations. Because of the limited availability of the patients with SCI and their fragile status, only eight participants could be included in the group with a recent SCI. This combined with the high inter-individual variability in parameters such as lesion level and completeness provided results with limited generalizability. The majority of the measurements included in this thesis was performed with a use of multiple measurement devices which generate data that needs to be post-processed in order to acquire clinically meaningful outcome measures. That makes this kind of measurements in the form presented here not directly suitable for clinical practice which is characterized by severe time constraints. Moreover, a number of important outcome

measures was acquired from the Optipush or Smartwheel measurement wheels. Those wheels or any equivalent ones are not commercially available anymore which poses a serious constraint on the future measurements, especially the determination of shoulder load which requires 3D forces measured on the handrim. Lastly, most tests in this thesis were lab-based. In order to improve the generalizability and ecological validity of the results, we recommend to work on technological solutions that will allow the performance of field-based protocols in combination with lab-based measurements.

CONCLUDING REMARKS

As wheelchair propulsion is a clinically relevant task, this thesis has both theoretical, as well as clinical implications. It should be noted that those perspectives are not separate and have a common overarching goal of increasing the independence and participation of wheelchair-dependent individuals. All findings of this thesis, especially the inter-individual variability among the participants, emphasize the need to rethink the design of research on motor learning process and its implementation in clinical practice. We proposed the implementation of wheelchair propulsion laboratories which would aid the research community by providing large sets of data and assist the clinicians in decision-making processes.

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