

UNDERSTANDING THE MOTOR LEARNING PROCESS IN HANDRIM WHEELCHAIR PROPULSION

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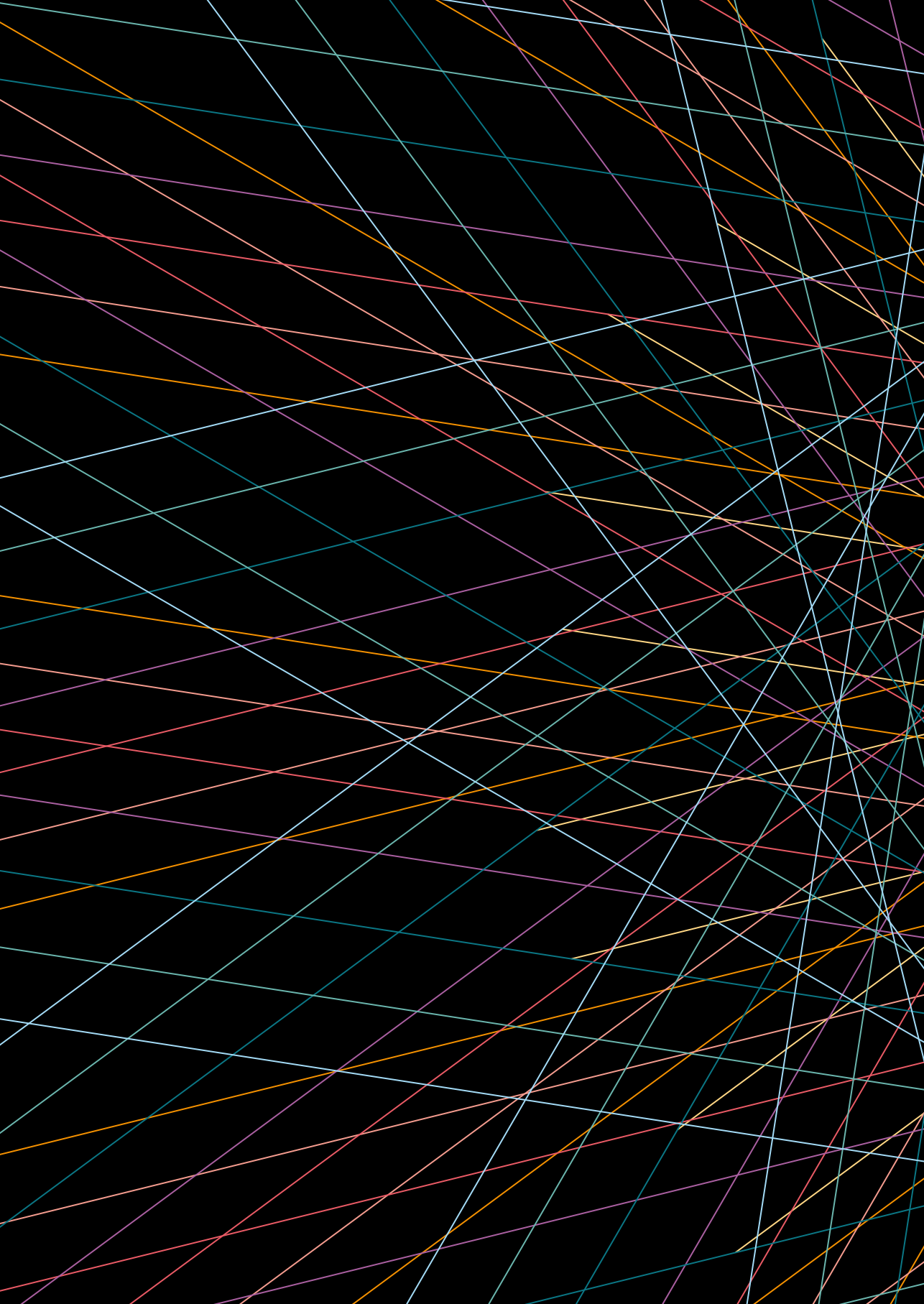
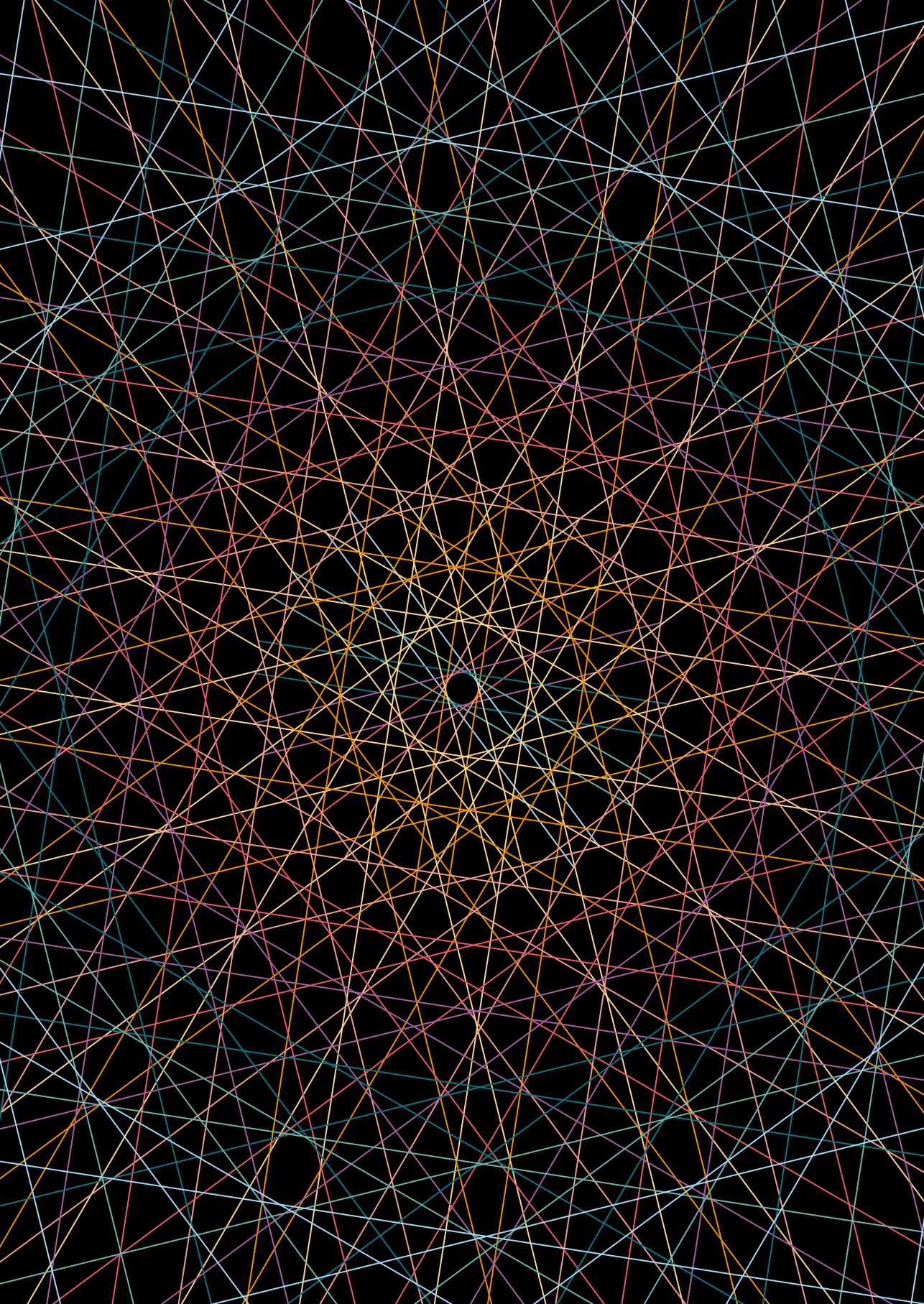
Marika T. Leving





Understanding the motor learning process in handrim wheelchair propulsion

Marika T. Leving

Colophon

The experiments described in chapter 2, 3, 4 and 5 were conducted in the Center for Human Movement Sciences, University Medical Center Groningen, the Netherlands. The experiments described in chapter 6 and a part of the experiment described in Chapter 3 were conducted in the Center for Rehabilitation, University Medical Center Groningen, the Netherlands.

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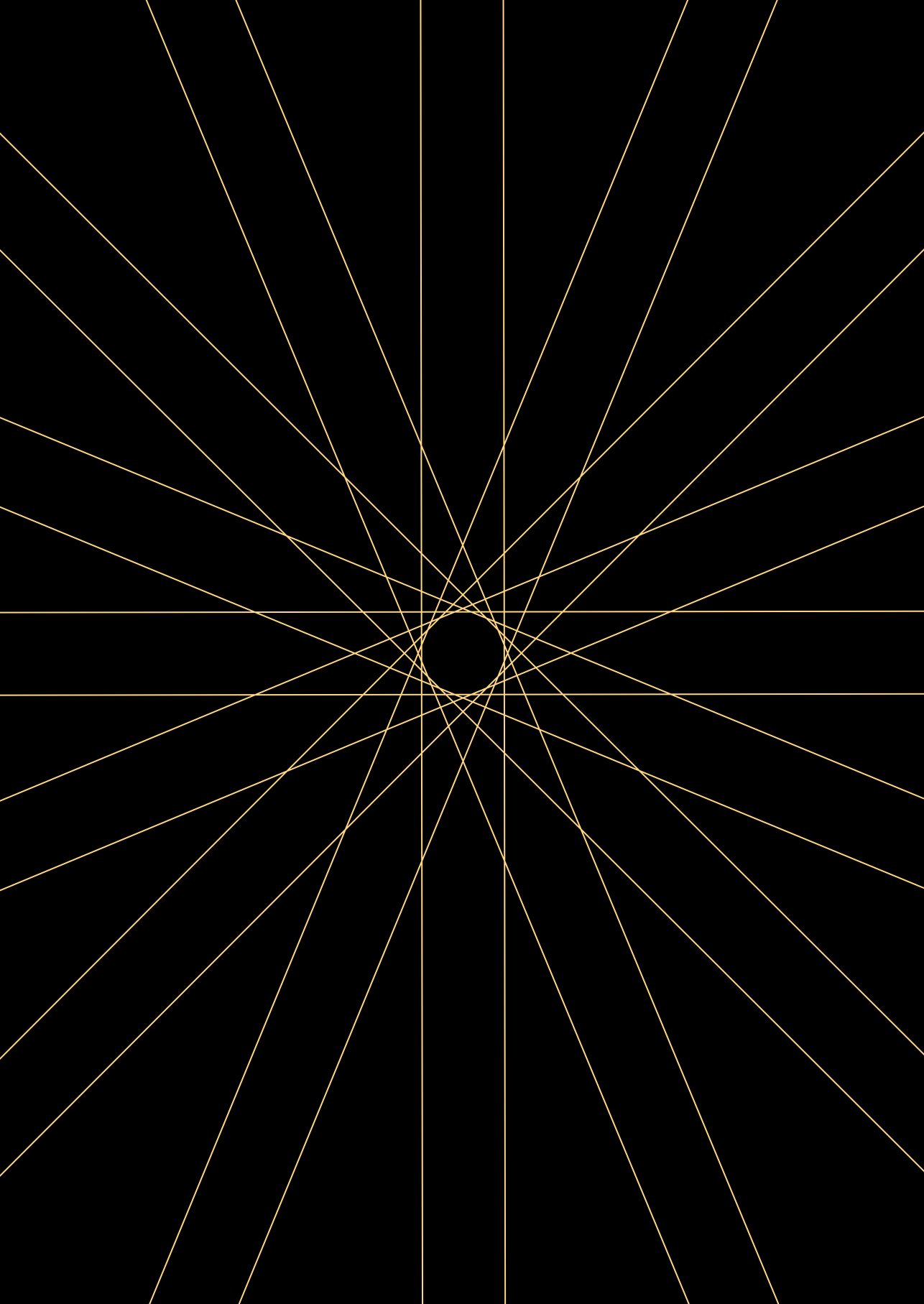

1

INTRODUCTION

BACKGROUND AND RELEVANCE

Motor learning is defined as 'a set of processes associated with practice or experience leading to relatively permanent changes in the capability for responding' [1]. It is a demonstration of an amazing property of our body and mind to observe and interpret the environment in order to perfect our actions. While some motor skills like skiing or playing a violin may not be vital for most, there is a range of skills, like walking, that have the ability of defining our way of life. When the ability of walking is lost due to trauma or a disease, a new skill of wheelchair propulsion needs to be learned. This skill, if perfected, can be the key to independence [2,3] and when neglected, be a sentence to social isolation [3,4].

Approximately 1% of the World population i.e. about 65 million people depend on a wheelchair for their mobility [5]. In that group, nearly 90% is assumed to use a handrim wheelchair [6]. Becoming wheelchair dependent has a profound effect on all domains of human functioning. The model of the International Classification of Functioning, Disability and Health [7] adapted for a population of wheelchair users with a spinal cord injury (SCI) [8] represents the impact of this disability on three domains: Body function and structure, Activities and Participation (Figure 1). This model also indicates the interrelations between the three mentioned domains, as well as their dependence on the external and personal factors. The main goal of rehabilitation is improving participation. While it is important to realize that there are various ways to influence participation according to the ICF model, this thesis will focus on the level most inherently representative of the motor learning process: Activities, as well as the Body functions and structures as prerequisites of being able to perform various Activities, which are in turn required for successful participation.

The domain of Activities, here especially focused on the broadly defined wheelchair skill, is central to the ICF model and will also be central in this thesis. Wheelchair skill is a complex multilayered phenomenon which cannot be measured with a single test. In this thesis being skilled in the wheelchair is defined as: being able to efficiently perform all daily wheelchair-related activities, including wheelchair propulsion. As such, wheelchair skill has multiple ingredients including: mechanical efficiency, propulsion technique and level of functional wheelchair skills e.g. negotiating a threshold or performing a transfer or a wheelie. It could be argued that mechanical efficiency (ME; ratio of power output and energy expenditure) and propulsion technique (spatio-temporal variables measured at the level of the handrim) belong in the domain of Body functions and structures, since both are parameters extracted from physiological or biomechanical data. However, in contrast to e.g. peak oxygen consumption, mechanical efficiency and propulsion technique do not describe a function of a specific bodily structure, but instead describe an activity. Moreover they represent a dynamic and multilevel process of motor learning and complex optimization of function on a higher level than just that of a single body structure. Additionally, the efficiency of walking was also previously described under the domain of Activities [9]. Wheelchair skill is a very modifiable domain and some of its ingredients, such as the functional wheelchair skills can be used to target improvements

in participation in socially-valued activities such as work, sports, family [2,10]. This is confirmed by various studies which showed that high level of functional wheelchair skill corresponds to higher independence, self-efficacy, participation and quality of life [2,3]. In contrast, low levels of wheelchair skill relate to social isolation and dependence on others [3,4].

The focus of this thesis is a description of the outcomes of the motor learning process of handrim wheelchair skill taking place under the influence of various interventions or during regular rehabilitation. Understanding the motor learning process in a fully novel skill such as wheelchair propulsion, and factors that may influence it, will allow to understand human motor learning and optimization and help to design future evidence-based interventions targeting the improvement in wheelchair skill. Higher wheelchair skill proficiency facilitates mobility and independence, which are the prerequisites of social participation.

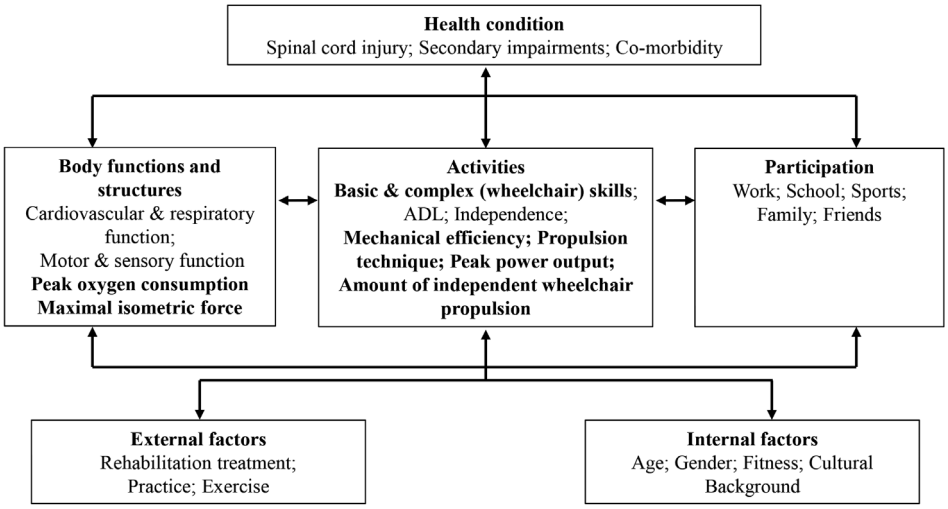

Figure 1. ICF model [7], as applied to persons with a spinal cord injury [8] and supplemented with the outcome measures of this thesis (in bold).

MOTOR LEARNING PROCESS AND WHEELCHAIR SKILL

Interpreting the outcomes of the motor learning process in wheelchair propulsion can sometimes be challenging because of the complexity of the process and a number of variables that influence it. According to the constraint-based model proposed by Sparrow and Newell [11], all movements emerge from an interaction of three factors; the organism, the environment, and the task being performed (Figure 2). In wheelchair propulsion, this means that the observed movement is a result of an interplay among a large number of factors including: personal characteristics such as demographic features, talent or preexisting movement repertoire; task characteristics, specifically the

user-wheelchair interface, and environmental constraints such as obstacles or uneven terrain. A frequently used approach of studying the individual motor learning trajectories in wheelchair propulsion is to keep the constraints of the task and the environment constant throughout practice and observe the changes in movement efficiency as well as the emergent movement pattern. In wheelchair propulsion, those changes can be quantified using mechanical efficiency and wheelchair propulsion technique.

Mechanical efficiency and propulsion technique are very well established outcomes in wheelchair literature. Apart from their role in ergonomic optimization of the wheelchair-user interface, they were used to describe motor learning [12-16] and physical adaptation [17,18] in novice [14,16] and experienced [19] wheelchair users. Also in this thesis they are used as primary outcomes of motor learning process in wheelchair propulsion. Mechanical efficiency is an outcome measure which quantifies the optimization of energy consumption in the human system needed to perform a submaximal steady-state cyclic task. Mechanical efficiency is expected to increase, across the motor learning process, as mastering a task results in more optimal kinematics and kinetics which in turn leads to lower energy expenditure [13]. In wheelchair propulsion, improvements in ME are thought to be related to the physiological adaptation or changes in coordination and movement pattern taking place during practice. To quantify the latter, it is useful to look at the changes in wheelchair propulsion technique. Measuring torques and forces applied to the handrim allows to quantify temporal and spatial kinetic changes in the movement and coordination pattern of upper extremities.

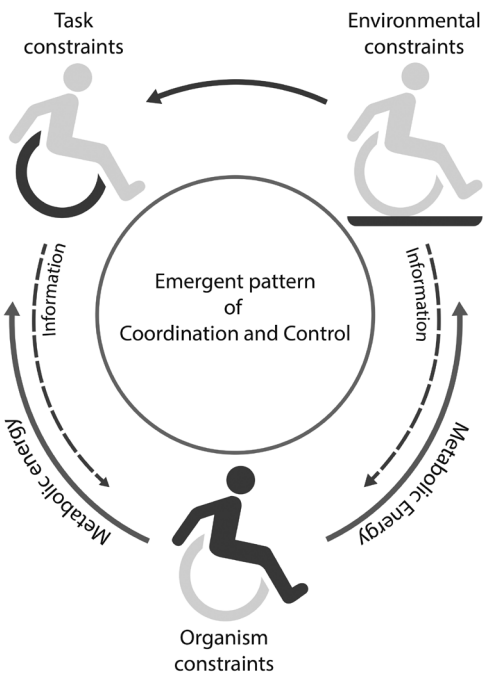

Figure 2. According to the constraint-based framework, all movements occur as a result of an interplay among three factors; the organism, the environment, and the task being performed [11]. Figure reproduced with permission [15].

EXISTING STUDIES ON MOTOR LEARNING IN HANDRIM WHEELCHAIR PROPULSION – SHORT SYNOPSIS

Able-bodied population

When it comes to longitudinal observations, the natural motor learning of wheelchair propulsion is predominantly well documented in able-bodied individuals. Next to the changes in mechanical efficiency and propulsion technique during the very early stages of motor learning process (first 12 minutes, [13], also longer experiments, reaching 1470 min distributed over seven weeks, have been conducted [20]. All those studies, independently of practice dose, found that both mechanical efficiency and propulsion technique improve during the natural learning process (practice without feedback or instruction) of wheelchair propulsion in able-bodied participants. The exact changes in technique include a decrease in push frequency, an increase of the contact angle of the hand on the handrim and decrease in braking moment. A study using multi-level modeling showed that those changes in propulsion technique are related to the improvements in mechanical efficiency [13]. Recent findings offer a new perspective on the motor learning process and propose that movement variability is an important factor during wheelchair propulsion [14,21-23]. The variability is operationalized as intra-individual stroke-to-stroke variations in propulsion technique (e.g. alternating short and long pushes, varying push frequency). A study documenting early stages of a natural motor learning process showed that novice able-bodied participants who show higher propulsion variability, learn faster and exhibit better propulsion technique and mechanical efficiency than those who are less variable [13]. Variability was also found to enhance motor learning in studies on other motor tasks, such as reaching [24]. Variability is thought to enhance learning because it is a representation of task exploration within a motor system. Increased exploration is thought to result in finding a better task solution. Since naturally occurring variability seems to benefit the motor learning process of wheelchair propulsion it is interesting to see whether increasing variability in early stages of learning causes similar or even better learning effects. So far, the effect of variability-inducing intervention on the early stages of learning process in wheelchair propulsion is unknown.

Population with SCI

While researching healthy participants provides valuable information about early stages of motor learning in a homogenous population, direct translation of those findings into the patient populations is not possible, because of their injury-related constraints which may influence the results of the motor learning process such as sitting balance, pain or distorted muscle function. That is why the early motor learning process needs to be documented in patients who became dependent on a handrim wheelchair, such as people with a SCI. Moreover, it is interesting to study the difference between recent and experienced wheelchair users with a SCI. The population with SCI is heterogeneous when it comes to personal factors presented in the ICF model, such as age, gender but also lesion-specific characteristics, like lesion level and completeness. Even though those personal factors will not be the focus of this thesis, it is important to realize that they largely determine the function of a person after a SCI and may also influence the motor

learning process. When it comes to the longitudinal observation of the motor learning process during SCI rehabilitation, the knowledge in this area is still incomplete. While a very large study, including 8 rehabilitation centers in the Netherlands showed that ME, level of functional wheelchair skills (wheelchair circuit) and wheelchair work capacity improved between the beginning of active rehabilitation, 3 months later and at discharge [19,25], no information about the course of propulsion technique in between this period is available. Additionally this study was performed more than 10 years ago and it is questionable whether results still hold since the reality of rehabilitation, such as the length of stay, changed drastically in the last decade [26]. Considering the relationship of ME and propulsion technique found in the able-bodied studies [13], as well as suggested relationships of technique with shoulder pain [27-29], it is very important to look at this factor from the early stages of active SCI rehabilitation as well. Another factor that was not yet documented in relation to the motor learning process is the amount of practice during rehabilitation. Motor learning is dependent on practice dose, i.e. frequency, duration, intensity and form. Quantifying amount of independent wheelchair propulsion throughout rehabilitation is important as more practice could relate to better propulsion technique and subsequently higher ME. It is therefore important to validate and implement an activity monitor which can continuously be used across weeks of active rehabilitation to quantify the amount of daily wheelchair practice.

During active rehabilitation, next to undergoing a motor learning process, patients are expected to improve their physical capacity. It is important to realize that the processes of learning and physiological adaptation are not totally separate. There is a possible link between physiological variables such as muscle force and cardio-respiratory fitness, which are likely to improve during rehabilitation, and the outcomes of the motor learning process. It is reasonable to assume that an increase in muscle mass and improvement in neuromuscular coordination may influence the total amount of force and its timing and application when propelling a wheelchair and therefore affect both mechanical efficiency and propulsion technique as well as the functional wheelchair skills. Moreover, improvements in cardio-respiratory fitness could influence the total energy needed to propel a wheelchair at a submaximal intensity, affecting ME. Therefore, in order to be able to indicate whether potential changes in wheelchair skill during active rehabilitation in patients with SCI result from the motor learning process or physiological adaptation, it is necessary to study the change in ME and propulsion technique during low-intensity steady state propulsion, but also to include wheelchair work capacity.

SHOULDER LOAD DURING WHEELCHAIR PROPULSION

While the motor learning process, operationalized as changes in mechanical efficiency and propulsion technique, will be the main focus of this thesis, we will also pay attention to a very clinically relevant outcome, shoulder pain. The reported incidence of pain within the shoulder complex in wheelchair users ranges from 32% to 78% [30,31], making it the most common musculoskeletal complaint within the upper-extremity in

this group. The anatomy of the upper-extremities, specifically the relatively small muscle mass and high glenohumeral joint mobility, makes the shoulder complex vulnerable to overuse injuries [32]. Shoulder load and propulsion technique are thought to be linked as wheelchair propulsion is a highly repetitive task, where the same motion is performed approximately 2700 times per day [29]. The accumulation of the submaximal loads often leads to repetitive strain injuries. Since optimizing wheelchair propulsion technique is suggested to be one of the ways to minimize the load on the shoulder, it is very important to look at the relationship between those two variables. This is especially important in the early stages of learning when propulsion technique changes rapidly [13,33] and shoulder load is often developed [34]. So far, changes over time (pre-post design) in both propulsion technique and shoulder load were only investigated in the very initial stages of learning (first 12 min, [27]). It is of interest to see whether the effects found in this very short-term study would remain valid in longer studies on the motor learning process.

AIM AND OUTLINE OF THIS THESIS

This thesis attempts to widen the understanding of the motor learning process in handrim wheelchair propulsion, with special consideration for shoulder load and factors associated with it. We will extend on studies with able-bodied participants by investigating the effect of variability-inducing practice on the motor learning process. We hypothesize that increasing practice variability will benefit the motor learning process of wheelchair propulsion and contribute to an increase in ME and propulsion technique at a submaximal steady-state intensity. Subsequently, we will perform an important step aimed at describing the natural motor learning process in patients with recent SCI during active rehabilitation and compare their outcomes with experienced wheelchair users with SCI. We hypothesize that the group with recent SCI will improve ME and propulsion technique, as well as functional wheelchair skills and wheelchair work capacity between the beginning of active rehabilitation and discharge from inpatient care. Moreover, we expect the experienced wheelchair users to have a better propulsion technique, higher mechanical efficiency, achieve better results during the peak test and show better skill and higher strength than the group with recent SCI.

Chapters 2 and 3 examine the influence of various forms of variable practice on the motor learning process of handrim wheelchair propulsion in able-bodied participants. **Chapter 2** aims to increase the variability of practice by providing real-time visual feedback on the propulsion technique in a controlled lab-based environment. In contrast, **Chapter 3** introduces uninstructed variable practice in a free environment to a group of novel wheelchair users. **Chapter 4**, re-evaluates a part of the data of the participants from Chapter 2 to analyze the concomitant changes in wheelchair propulsion technique and shoulder load in order to explore whether certain changes in technique may relate to a decrease in shoulder load. **Chapter 5** is a preparatory experiment aiming to validate an activity monitor which will be able to quantify the daily amount of independent wheelchair propulsion in patients with recent SCI during active rehabilitation. **Chapter 6**

observes the natural motor learning process in patients with recent SCI who undergo inpatient rehabilitation. Their outcomes will be compared to a group of experienced community-dwelling wheelchair users with SCI. This study has an observational character and takes place within 'care as usual', introducing regular measurement moments, but not intervening in the regular rehabilitation schedule. **Chapter 7** provides a general discussion of the findings of this thesis, discussing their implications for clinical practice, as well as for future studies to further develop knowledge about the motor learning process in handrim wheelchair propulsion.

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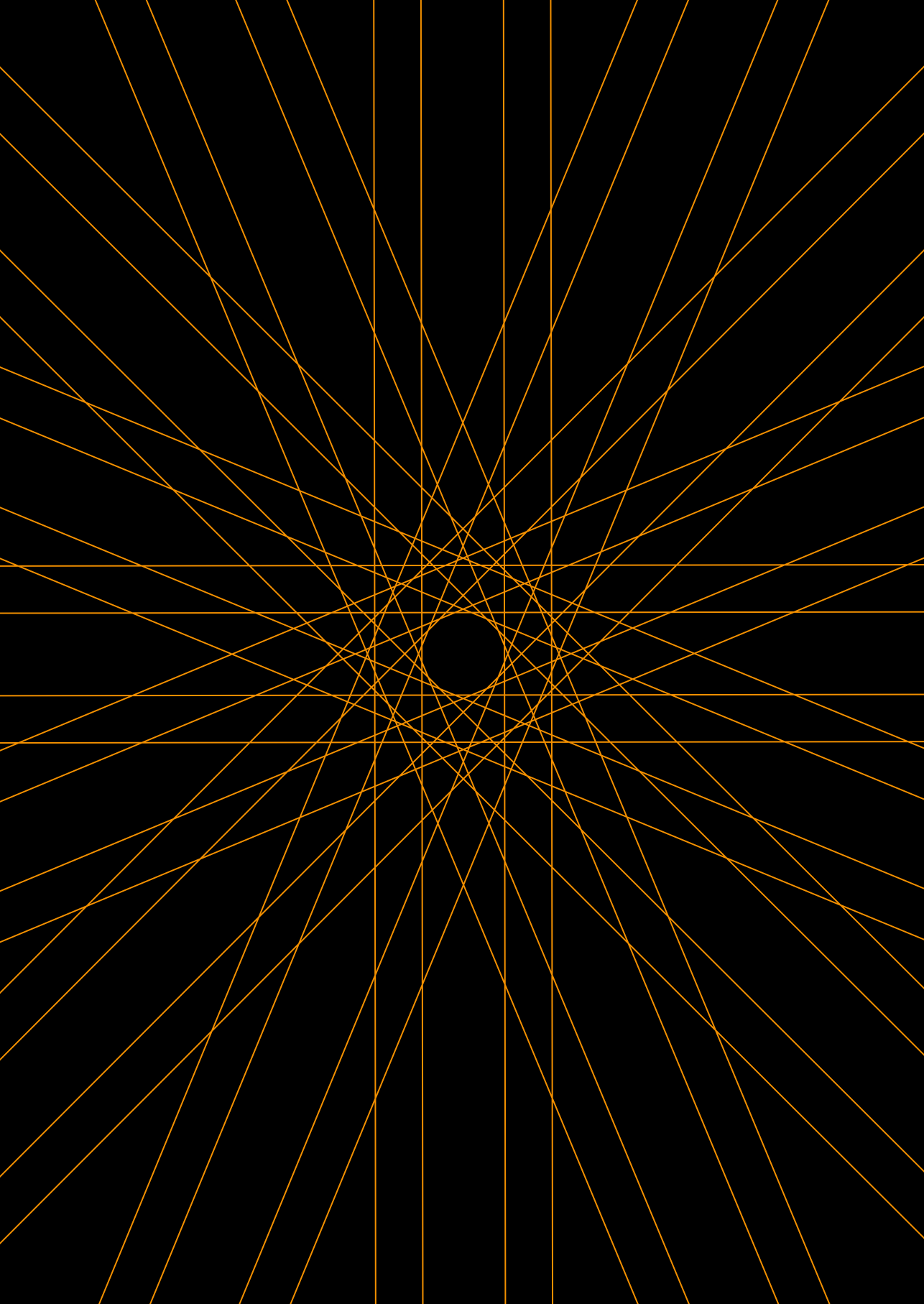

2

EFFECTS OF VISUAL FEEDBACK-INDUCED VARIABILITY ON MOTOR LEARNING OF HANDRIM WHEELCHAIR PROPULSION

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ABSTRACT

Background: It has been suggested that a higher intra-individual variability benefits the motor learning of wheelchair propulsion. The present study evaluated whether feedback-induced variability on wheelchair propulsion technique variables would also enhance the motor learning process. Learning was operationalized as an improvement in mechanical efficiency and propulsion technique, which are thought to be closely related during the learning process.

Methods: 17 Participants received visual feedback-based practice (feedback group) and 15 participants received regular practice (natural learning group). Both groups received equal practice dose of 80 min, over 3 weeks, at 0.24 W/kg at a treadmill speed of 1.11 m/s. To compare both groups the pre- and post-test were performed without feedback. The feedback group received real-time visual feedback on seven propulsion variables with instruction to manipulate the presented variable to achieve the highest possible variability (1st 4-min block) and optimize it in the prescribed direction (2nd 4-min block). To increase motor exploration the participants were unaware of the exact variable they received feedback on. Energy consumption and the propulsion technique variables with their respective coefficient of variation were calculated to evaluate the amount of intra-individual variability.

Results: The feedback group, which practiced with higher intra-individual variability, improved the propulsion technique between pre- and post-test to the same extent as the natural learning group. Mechanical efficiency improved between pre- and post-test in the natural learning group but remained unchanged in the feedback group.

Conclusion: These results suggest that feedback-induced variability inhibited the improvement in mechanical efficiency. Moreover, since both groups improved propulsion technique but only the natural learning group improved mechanical efficiency, it can be concluded that the improvement in mechanical efficiency and propulsion technique do not always appear simultaneously during the motor learning process. Their relationship is most likely modified by other factors such as the amount of the intra-individual variability.

INTRODUCTION

Wheelchair propulsion brings mobility to people with lower-limb disabilities and empowers active community participation [1]. However, wheelchair propulsion is not present in the skill repertoire of most people and often has to be learned in the early stages of the rehabilitation process after disease or injury. Due to the load on the shoulder complex, manual wheelchair propulsion is considered to be a straining form of ambulation and is often associated with overuse injuries of the shoulder [2-5]. The goal of wheelchair propulsion training is to facilitate the motor learning process of this cyclical motor skill, with special consideration for injury prevention.

Motor learning of a cyclical skill, such as wheelchair propulsion, can be seen as an adaptation of the human motor system, which emerges from the interaction between different constraints, and possibly leads to a decrease in energy expenditure [6-9]. Under standardized steady-state submaximal conditions the effect of motor learning in wheelchair propulsion can thus be quantified as a decrease in the energy expenditure and therefore increase in mechanical efficiency, i.e. the ratio of external power output and energy expenditure. On a group level, mechanical efficiency increases during motor learning of wheelchair propulsion [10-13]. However, a recent study reported individual differences in the learning rate of acquiring the new skill of wheelchair propulsion [13]. Concomitant with these differences, a higher within-person (intra-individual) variability of the propulsion technique parameters was shown for the group that increased more in mechanical efficiency, compared to the group that increased less in mechanical efficiency. Therefore it was suggested that this intra-individual variability might have been a property that enhanced the motor learning process [13].

Fundamental motor control studies established that intra-individual variability is not just the product of noise, but that it may facilitate the motor learning process as it improves motor exploration and learner's adaptability [14, 15]. Recent findings suggest that especially task-relevant variability, and not total variability, is crucial to the performance [16]. In wheelchair propulsion task-relevant variability is expected to be the variability in propulsion technique variables that have previously been associated with mechanical efficiency [12].

With respect to task-relevant variability in wheelchair training, propulsion technique variables such as push frequency, contact angle and braking moment have been shown to be directly related to mechanical efficiency [12]. In addition, it was shown that change within these and other propulsion variables such as fraction effective force, peak force, push distance and smoothness can be targeted by providing visual feedback on these parameters [17-21]. Combining the above findings with the notion of explorative learning, we suggest that providing participants with extra means of exploration through visual feedback on task-relevant propulsion variables will enhance the motor learning process.

Therefore, the current experiment aims to assess if learners, who actively explore their motor space using visual feedback on propulsion technique variables as guidance, learn more than learners who do not receive any feedback and therefore undergo a natural learning process. We hypothesize that feedback-induced variability will enhance the motor learning process (operationalized as improvement in mechanical efficiency and propulsion technique) in the feedback group more than the natural learning practice. To evaluate the effectiveness of the proposed motor learning training it was chosen to include able-bodied participants who are naïve to wheelchair propulsion. The inclusion of able-bodied participants with similar age and lack of wheelchair experience eliminates potential confounders resulting from trauma or disease, which are often present in the wheelchair-dependent population: e.g. lack of sitting balance or presence of pain. Therefore, the inclusion of able-bodied participants ensures a homogenous group, which will allow to more accurately isolate the effect of feedback-induced variability on the motor learning process.

METHODS

Participants and Ethics Statement

Thirty-two men participated voluntarily in this study. To compare with earlier research in our laboratory only male subjects were selected. The average age of the participants in the feedback group was 22.9 ± 2.9 years and in the natural learning group 22.8 ± 3.9 years. The average mass of the participants in the feedback group was 82.4 ± 12.5 kg and in the natural learning group 83.4 ± 10.4 kg. The average height of the participants in the feedback group was 1.86 ± 0.05 m and in the natural learning group 1.87 ± 0.08 m. All participants signed an informed consent before the onset of the experiment, following detailed verbal and written information about the character of the study. The protocol of the study was approved by the Local Ethics Committee, of the Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, The Netherlands. Criteria for inclusion were: being able-bodied and having no previous experience with wheelchair propulsion. The exclusion criterion was: presence of severe medical conditions that could influence parameters measured in the present study, including any musculoskeletal complaints, especially involving the shoulder complex and upper extremities.

Experimental Setup

All measurements were performed in an experimental handrim wheelchair (Double Performance BV, Gouda,The Netherlands) placed on a 2.4 m long and 1.2 m wide level motor-driven treadmill(Forcelink b.v, Culemborg The Netherlands). The wheelchair remained unchanged throughout the experiment and for all participants. The aspects concerning the wheelchair-user interface such as seat height, torso height and distance between acromion and axle position were not included in the current study. Tire pressure of the rear wheels was set at 600 kPa during all practice and test sessions. Treadmill velocity was set at 1.11 m/s and power output at 0.24 W/kg body mass throughout the 80

min experiment. The extra resistance needed to maintain the power output was calculated for each participant individually, based on the data acquired from a drag test prior to experimentation (Fig. 1A). The drag test, developed by the technical workshop of the Faculty of Human Movement Sciences at the VU University in Amsterdam, measures the rolling resistance, which together with the velocity determines the power output [22, 23]. The extra resistance was added using a pulley system [24] (Fig. 1B). The experimental setup is presented in Fig. 2.

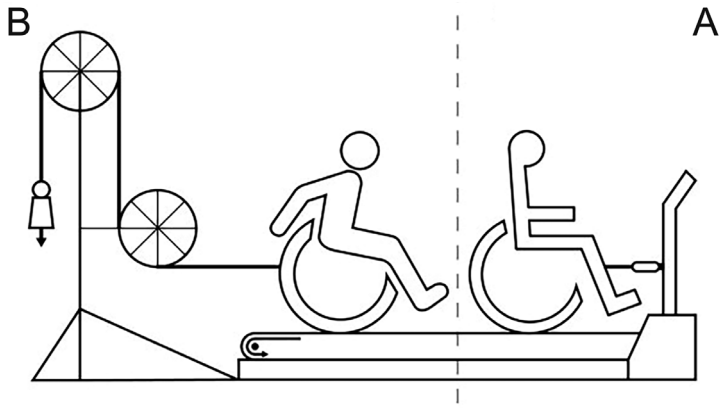

Figure 1. (A) The extra resistance needed to maintain the power output was calculated for each participant individually based on the data acquired from a drag test. (B) Power output was set using the pulley system (figure from Vegter et al. [25]).

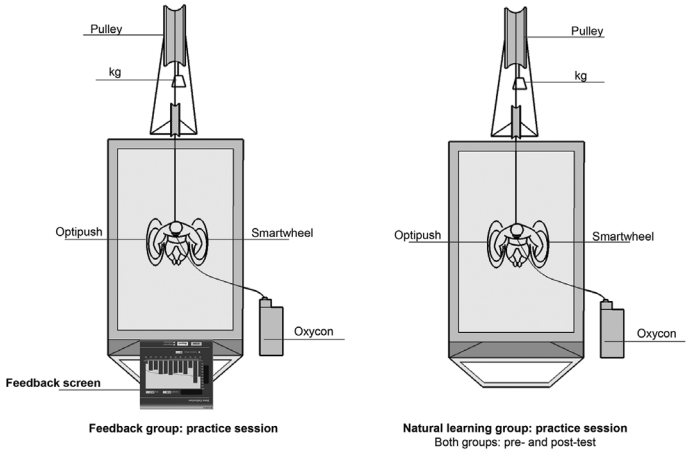

Figure 2. The experimental setup. The setup during practice sessions for the feedback (left side) and the natural learning group (right side). The setup presented on the right side of the figure was also utilized during the pre- and post-test in both groups.

Procedure and feedback-induced variability

17 Participants received visual feedback-based practice (feedback group) and 15 participants received regular practice with no feedback or instruction (natural learning group). Both groups received the same practice dose of 80-min spread over a period of 3 weeks (Fig. 3). This protocol duration was chosen since previous research showed that it allows for observing significant changes in mechanical efficiency and propulsion technique [10, 12, 13]. The 80 min dose consisted of a 12 min (3 x 4min, with bouts of 2-min rest between the exercise blocks) pre- and post-test and 7 sessions of 8 min (2 x 4min, with 2-min rest between the exercise blocks) of submaximal handrim wheelchair practice on a motor-driven treadmill. The pre- and post-test were performed without any feedback in both groups (Fig. 3).

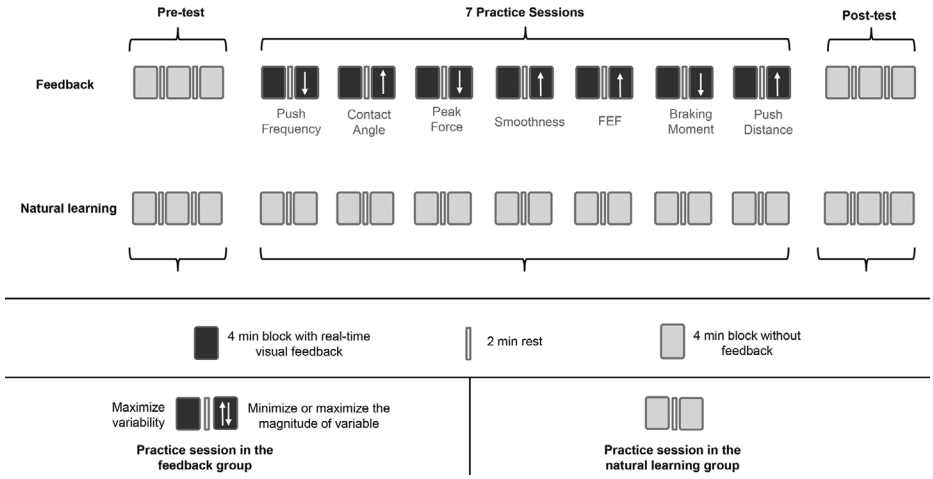

Figure 3. Study protocol for the feedback and the natural learning group. Pre- and posttest consisted of 3 x 4 min blocks each. Seven practice sessions consisted of 2 x 4 min each. A different propulsion variable at each practice session was presented in the form of real-time visual feedback to the participants in the feedback group. The order of the propulsion variables was counterbalanced over the participants. Participants in the natural learning group practiced without feedback. Last minute of each exercise block was used in the analysis.

Counterbalanced over the participants, the feedback group received real-time visual feedback (Fig. 4) on seven different propulsion variables (2 x 4min/variable): push frequency, braking moment, contact angle, peak force, push distance, smoothness and fraction effective force (Table 1). The vision ability of the participants in the feedback group was checked by asking the participant to read the average value of the propulsion technique variable (Fig. 4), which was presented on the feedback screen, while seating in a wheelchair in the front, middle and at the end section of the treadmill. Visual feedback was provided using software of the instrumented wheel Optipush (MAX Mobility, LLC, Antioch, TN, USA). The visual feedback was presented real-time on a 22" computer screen. The value of the variable is displayed once the start and the end of a cycle is calculated. This provides a slight delay in the feedback. Each propulsion variable was

presented to the participants on a 22 inch screen in the form of a bar graph displaying the magnitude of the variable push-by-push. Participants were informed that they could alter the height of the bars by changing their propulsion technique. To increase motor exploration and intra-individual variability, the participants didn't know which variable they were practicing on during a given practice session. Descriptions or names of any of the seven propulsion variables were not provided before or during the experiment. Participants had to discover their solutions and options themselves. However, participants did receive feedback on the screen about their performance and were encouraged to manipulate the unknown variable to achieve the highest possible variability (1st 4-min block) and to optimize it in the prescribed direction (2nd 4-min block). Before each block, the participants were asked to explain the task in their own words to make sure that they understand the instruction and know how to correctly perform the task. No target line was displayed for the propulsion variables to guide the participants. This way, each participant was given the freedom of exploration without providing additional task constraints.

Motor learning

Mechanical efficiency

Oxygen uptake (VO2) and respiratory exchange ratio (RER) during steady-state wheelchair propulsion were continuously determined breath-by-breath using Oxycon Pro-Delta (Jaeger, Hoechberg, Germany), which was calibrated before each measurement occasion using Jaeger 5 l syringe, room air and a calibration gas mixture.

Mechanical efficiency was calculated over the last minute of each 4-min block. The equation used to calculate mechanical efficiency was: $ME = PO \times E^{-1} \times 100\%$, where PO is a power output and E is the energy expenditure, calculated according to:

PO (W) =T (torque (Nm)) x Av (Angular velocity (rad/s))

E (W) = (4940 x RER + 16040) x VO_2 (l/min) / 60, where RER and VO_2 are the average values over the last minute of each exercise block [26]. The last minute was chosen to make sure that steady-state propulsion was reached [27]. RER used to calculate the energy expenditure, can only be used as an estimation of the substrate utilization if the participant propels the wheelchair at the steady-state submaximal intensity.

Propulsion technique variables

The absolute values of the propulsion technique variables (Table 1) were used to evaluate the effect of practice on the propulsion technique. Applied forces and torques on the hand rim were continuously measured throughout the whole experiment. Software of the instrumented wheel Optipush (MAX Mobility, LLC, Antioch, TN, USA), which measures 3-dimensional forces and torques that a user applies to the handrim, was used to gather data from the right wheel. The data from the left side was collected using a Smartwheel instrumented wheel (Three Rivers Holdings, Mesa, AZ, USA) and could be used to replace missing Optipush data, since the two measurement wheels have high consistency which allows the data to be used interchangeably [25]. The data from the right side was used

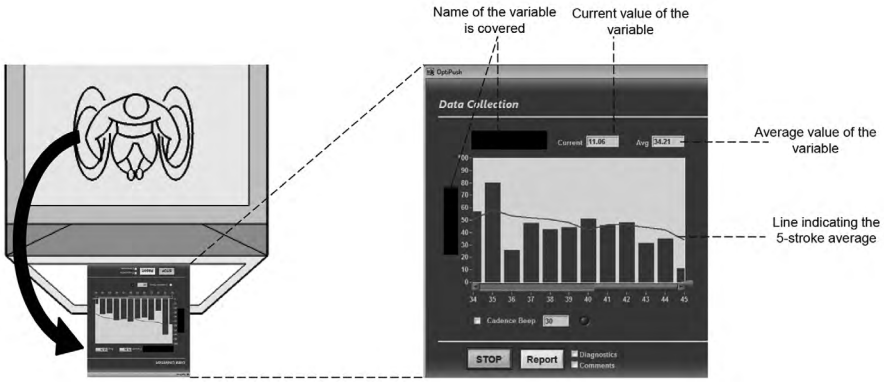

Figure 4. Real-time visual feedback screen. Participants in the feedback group received real-time visual feedback on different propulsion variables at each practice session. The black arrow on the left side indicates that forces and torques applied by a person to the handrim were calculated into specific propulsion technique variables and presented real-time on the feedback screen in the form of a bar graph. Participants were informed that they could alter the height of the bars by changing their propulsion technique. The task in the first out of two blocks was to vary the height of the bars on the screen. In the second block the height had to be either minimized or maximized, depending on the propulsion variable.

Table 1. The propulsion variables. The variables were used in the form of visual feedback to increase the intra-individual variability and as outcome variables to compare the change in propulsion technique between the groups. All variables except cadence were calculated as an average value of all pushes performed during last minute of each practice block. Equations from Vegter et al [12, 25].

Propulsion variable	Unit	Description	Equation	Direction of the manipulation[a]
Push frequency	push/ minute	The number of pushes performed during one minute	$N_{pushes}/\Delta t$	Minimize
Braking moment	Nm	The braking moment applied to the handrim with each push. The sum of braking moment exerted on the handrim during coupling and decoupling of the hand	$\Sigma_{end}(i)_{:start}(i+1)\ (Tz \cdot \Delta\emptyset)$	Minimize
Contact Angle	degrees (°)	The angle measured along the handrim, where subject's hand maintained contact with the handrim during each push	$\emptyset_{end}(i).\emptyset_{start}(i)$	Maximize
Smoothness	no unit[b]	The ratio of mean to peak force per push	$Mean_{(start:end)}\ (Fx^2+ Fy^2+ Fz^2)^{0,5}/Max_{(start:end)}\ (Fx_2+ Fy_2+ Fz_2)^{0,5}$	Maximize
FEF	%	The ratio of effective to total force that was applied to the handrim during one push	$Mean_{(start:end)i}((Tz/r)/((Fx^2 + Fy^2+ Fz^2)^{0,5}))\cdot 100\%$	Maximize
Push distance	m	The distance covered with each push	$Mean_{(start:end)}V\cdot\Delta t$	Maximize
Peak force	N	3d peak force applied to the handrim during one push	$Max_{(start:end)}\ (Fx^2+ Fy^2+ Fz^2)^{0,5}$	Minimize

[a] Only applicable for the second block of the practice session in the feedback group. [b] Smoothness is calculated by dividing average force (N) by peak force(N). Abbreviations: t, time(s); start(i), start of the current push (sample); end(i), end of the current push (sample); Tz, torque around wheel axle (Nm); Ø, angle (rad); Fx, Fy and Fz, force components (N); r, wheel radius (m); V, velocity (m/s).

for the analysis. Both measurement wheels were mounted to the 0.61 m wheels (diameter of the handrim was 0.53 m) with inflatable tires. The measurement frequency of both wheels was set at 200 Hz. The data collected during the last minute of each 4-min block was used for analysis. The output from the measurement wheels was analyzed using custom-written Matlab algorithms [25].

Statistical analysis

Statistical analysis concerning the data from the practice sessions and the characteristics of the participants was performed using IBM SPSS Statistics version 21.0 (SPSS Inc., Chicago, IL, USA). All data showed normal distribution at baseline, therefore parametric tests were applied. The age and body mass of the participants were compared between the natural learning and the feedback group, using independent t-test, to check for presence of the initial differences.

For the 3 blocks of the pre-test, the 7 practice sessions (2 blocks each) and the 3 blocks of the post-test, the intra-individual variability for each propulsion variable was quantified as the coefficient of variation, calculated over the last minute of each individual block (CV, the ratio of the standard deviation to the mean, $CV=\sigma/\mu \times 100$ (%)) and averaged across the 7 propulsion variables. Finally the CV was averaged across subjects within one group.

In order to determine if the participants indeed increased their intra-individual variability during the practice sessions, a repeated measure ANOVA with session (7 practice sessions) and group (feedback or natural learning) was performed for block 1 and block 2 separately. The group effect was used to determine the difference in variability (CV) between the feedback and natural learning group.

To examine the difference between the two groups over the duration of the experiment, pre- and post-test values of mechanical efficiency, propulsion technique and intra-individual variability were compared using MLwiN version 2.31 (Center for Multilevel Modeling, University of Bristol, Bristol, UK). The data from the 3 pre-test blocks (4 min each, last minute used for the analysis) and from the 3 post-test blocks were compared between the groups. Pre- and post-test were represented in the model as time in minutes. Dummy coding was used to distinguish between the groups (0-feedback; 1-natural learning). Considering the possible influence of the power output on the mechanical efficiency and propulsion technique, it was checked whether there was a difference in the power output between the pre- and the post-test between the groups (time x group effect) and within the groups (time effect). In order to prevent bias, in all cases where relative power output differed between two conditions, it was chosen to correct for it by adding power output to the model.

Significance for the repeated-measures ANOVA was set at $p < 0.05$ and by use of the Bonferroni correction the significance for the post hoc t-tests watch adjusted for the number of comparisons.

RESULTS

All participants completed the protocol. There were no differences between the groups at baseline with regard to the demographics.

The relative power output during pre- and post-test was significantly lower ($p<0.001$) for the feedback group (0.242 ± 0.021 W/kg) compared to the natural learning group (0.248 ± 0.017 W/kg). Power output within the feedback group at pre-test (0.253 ± 0.015 W/kg) was significantly ($p<0.001$) higher compared to the post-test (0.232 ± 0.021 W/kg). No differences between the pre- and the post-test were seen within the natural learning group.

Feedback-induced variability

Visual feedback-based practice succeeded in increasing the intra-individual variability during the practice sessions (Fig. 5 for individual curves and Fig. 6A for the mean of the seven variables). During all the practice sessions (Table 2), the feedback group showed more variability than the natural learning group. This effect was not only visible in the first block where the feedback group received an instruction to perform most variable possible ($p<0.001$), but also in the second block in which they had to optimize the value of the given propulsion variable ($p<0.001$).

Although the variability in the feedback group showed an increase over the practice sessions, the interaction effect between groups was not significant over time when looking at the pre- and post-test (group x time interaction, $p=0.110$) (Table 3).

Mechanical efficiency

The change in mechanical efficiency across the whole study duration is presented in Fig. 6B. As presented in Table 3, the feedback group did not improve the mechanical efficiency over the practice period ($p=0.134$). In contrast, the natural learning group improved mechanical efficiency significantly when comparing the pre-and post-test ($p<0.001$). Moreover, the interaction effect of group x time also reached significance ($p=0.012$), indicating that the natural learning group improved the mechanical efficiency in contrast to the feedback group.

Propulsion technique

No significant differences were found between the groups regarding the change in propulsion technique over time. Both groups significantly decreased the frequency and increased the push distance and contact angle. Although the natural learning group significantly improved smoothness, FEF and braking moment, this effect was not significantly different in the feedback group. The differences in propulsion technique between the pre- and post-test are presented in Table 3.

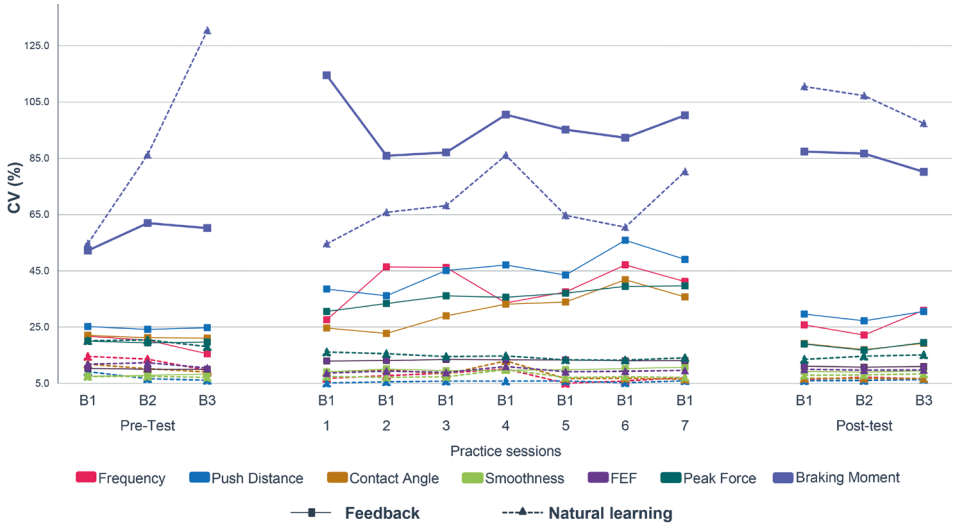

Figure 5. Course of variability (CV) for each propulsion variable. B1, B2 and B3 represent respectively Block 1, Block 2 or Block 3.

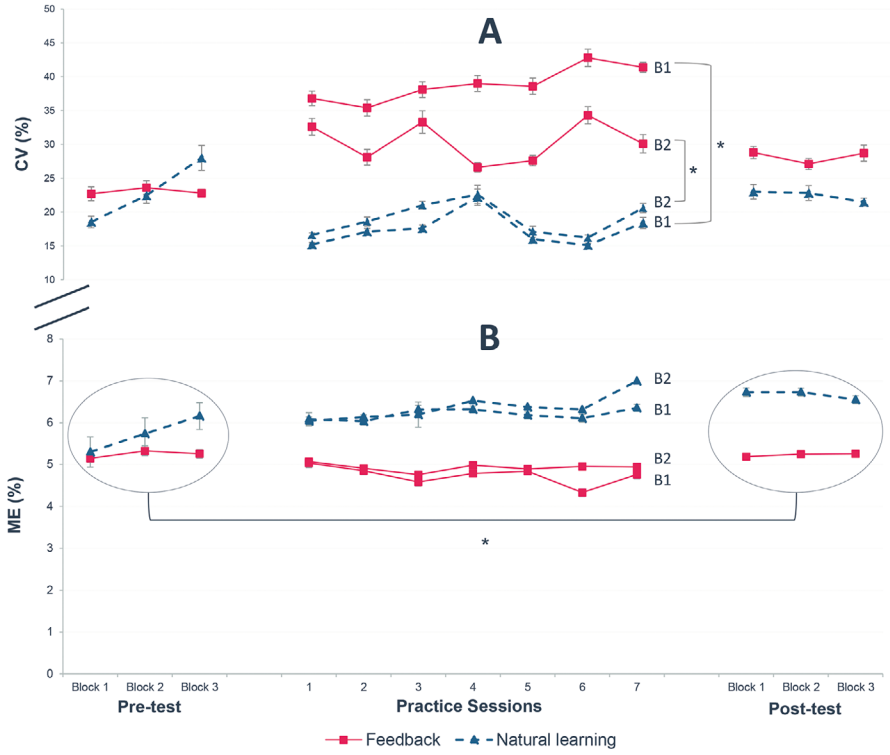

Figure 6. Course of variability (CV) and mechanical efficiency (ME) across the experiment in both groups. (A) Course of variability (mean CV of all seven propulsion variables and standard error) in the feedback and the natural learning group. Participants in the feedback group (n=17) showed higher variability during both blocks of the practice sessions when compared to the natural learning group (n=15). (B) Mechanical efficiency (mean and standard error) was lower in the feedback group (n=17) between pre- and post-test when compared to the natural learning group (n=15). * indicates a significant difference $p<0.05$. B1 and B2 represent respectively Block 1 and Block 2 of the practice sessions.

Table 2. Variability (CV) and mechanical efficiency (ME) in the feedback and the natural learning group in the practice sessions.

	Mean ± SD				CV		
	Feedback		Natural learning		Repeated measures ANOVA, group effect		
	CV	ME	CV	ME		P value	F (df, df)
Practice 1							
Block 1	36.8 ± 22.8	5.03 ± 0.9	15.2 ± 3.0	6.08 ± 1.2	Blocks 1[a]	<0.001	56.304 (1, 26)
Block 2	32.6 ± 24.5	5.07 ± 1.1	16.6 ± 3.4	6.04 ± 0.7			
Practice 2							
Block 1	35.4 ± 13.2	4.85 ± 0.9	17.1 ± 5.5	6.03 ± 1.1	Blocks 2[a]	<0.001	36.935 (1, 26)
Block 2	28.1 ± 12.7	4.91 ± 0.7	18.6 ± 7.6	6.13 ± 0.6			
Practice 3							
Block 1	38.1 ± 12.8	4.58 ± 0.8	17.6 ± 5.4	6.32 ± 0.7			
Block 2	33.3 ± 18.3	4.76 ± 0.8	21.0 ± 6.2	6.19 ± 0.7			
Practice 4							
Block 1	39.0 ± 12.6	4.79 ± 0.6	22.2 ± 12.7	6.32 ± 0.6			
Block 2	26.5 ± 7.5	4.98 ± 0.7	22.6 ± 13.6	6.53 ± 0.7			
Practice 5							
Block 1	38.6 ± 13.2	4.84 ± 0.5	16.0 ± 6.7	6.18 ± 0.7			
Block 2	27.6 ± 8.5	4.89 ± 0.6	17.1 ± 9.0	6.38 ± 0.7			
Practice 6							
Block 1	42.8 ± 13.9	4.33 ± 0.8	15.1 ± 3.3	6.11 ± 0.5			
Block 2	34.3 ± 13.9	4.96 ± 0.6	16.1 ± 4.5	6.31 ± 0.3			
Practice 7							
Block 1	41.4 ± 8.0	4.76 ± 0.9	18.4 ± 9.3	6.36 ± 0.4			
Block 2	30.1 ± 14.8	4.94 ± 0.7	20.6 ± 7.8	7.00 ± 1.2			

[a] Comparison of CV between the groups, separately for all blocks 1 and blocks 2 of all practice sessions; CV of all 7 propulsion variables was averaged across each group.

Table 3. Results of multilevel analysis concerning the difference in variability (CV), mechanical efficiency (ME) and propulsion technique variables (Mean ± SD) between the pre- and the post-test between the feedback (n=17) and the natural learning group (n=15).

	Feedback			Natural learning			
	Mean ± SD		P value	Mean ± SD		P value	P value
	Pre[a]	Post[a]	Time	Pre[a]	Post[a]	Time	Interaction Time x Group
CV[b]	23.0 ± 10.0	28.2 ± 10.8	0.032	22.8 ± 15.1	22.4 ± 10.6	0.495	0.110
ME	5.25 ± 0.85	5.23 ± 0.59	0.134	5.71 ± 1.34	6.67 ± 0.72	< 0.001	0.012
Propulsion variable (unit)							
Frequency (pushes/min)	62.1 ± 18.7	41.5 ± 13.7	< 0.001	71.3 ± 18.8	52.5 ± 13.8	< 0.001	0.778
Push Distance (m)	1.16 ± 0.28	1.81 ± 0.67	< 0.001	1.04 ± 0.33	1.42 ± 0.38	< 0.001	0.134
Contact Angle (degrees)	66.3 ± 15.4	88.0 ± 16.8	< 0.001	60.0 ± 13.2	77.5 ± 13.4	< 0.001	0.424
Smoothness	0.61 ± 0.04	0.58 ± 0.06	0.138	0.62 ± 0.03	0.60 ± 0.04	0.009	0.823
FEF (%)	69.5 ± 10.1	71.7 ± 9.8	0.694	68.6 ± 10.4	73.6 ± 10.0	0.013	0.246
Peak Force (N)	89.7 ± 30.1	91.9 ± 27.8	0.708	80.1 ± 22.1	76.4 ± 14.2	0.301	0.359
Braking Moment (Nm)	-0.79 ± 0.55	-0.69 ± 0.96	0.134	-0.56 ± 0.81	-0.19 ± 0.20	0.012	0.096

[a] the average value of 3 blocks. [b] CV of all 7 propulsion variables was averaged across each group

DISCUSSION

The aim of the present study was to assess if feedback-induced variability on wheelchair propulsion variables will enhance the motor learning process more than natural learning practice. Motor learning was operationalized as an improvement in mechanical efficiency and propulsion technique variables.

The findings of the present study showed that in the feedback group, intra-individual variability could be successfully increased by means of visual feedback on the propulsion technique variables. However, the increase in feedback-induced variability did not lead to the improvement in the mechanical efficiency. In contrast, the natural learning group did increase the mechanical efficiency. The improvement of mechanical efficiency in the natural learning group that practiced without any external instruction or feedback is in line with other natural learning training studies performed with able-bodied individuals [10-13] and patient populations [28-30].

In contrast to mechanical efficiency, both the natural learning and the feedback group, changed their propulsion technique by for instance decreasing push frequency, increasing push distance and increasing the contact angle, implying a similar improvement in motor learning on these propulsion technique variables. The change in propulsion technique in both groups was in agreement with changes that were previously observed during motor learning studies in wheelchair propulsion [10-13, 31].

Previous research found that changes in propulsion technique due to motor learning, were related to a change in mechanical efficiency [12]. It must, however, be emphasized that in the present study, change in propulsion technique in the feedback group was not linked to the improvement in the mechanical efficiency in contrast to the natural learning group. Even though both groups improved the propulsion technique to a similar extent, only in the natural learning group this change was accompanied by an improvement in mechanical efficiency.

These results suggest that improvement in propulsion technique does not automatically imply an increase in mechanical efficiency. Considering that lower mechanical efficiency in the feedback group was concomitant with the increased variability, it may be that variability was the factor that confounds the relationship between the mechanical efficiency and propulsion technique in the wheelchair propulsion.

The feedback-induced variability practice led to an increase in the intra-individual variability. The pronounced difference in the variability between the groups was visible at all practice sessions and in both blocks. However it presumably interrupted the energy optimization of the motor system. We will discuss several factors that may have contributed to this outcome.

To our knowledge, no other wheelchair propulsion study used real-time visual feedback to target the increase in intra-individual variability. Various studies that targeted an increase in the variability at the task goal changed for instance the target location in a striking task [32] or used various body configurations of the learner [33]. In those experiments, increased variability was actually forced on a learner by the task constraints. In the present study, participants were provided with an opportunity to be variable, which allowed them to independently select the amount of variability that was comfortable for them. Moreover, participants in the present study were instructed to show highest possible variability within the practiced variables that are thought to be task-relevant. Nevertheless, one may argue that variability in current study was not task-relevant as seen from the motor control point of view. Wu et al [16] found that increased task-relevant variability predicts faster learning capability. It may be that participants in current study practiced the total variability, which may have been too unspecific and perhaps did not direct the learner's exploring capabilities to the most relevant motor solutions. Targeting task-relevant variability by for instance instructing the participants to simultaneously increase variability and optimize the absolute value of the variable may have yielded different results. This possibility needs to be assessed in future studies.

Distinction between total and task-relevant variability shows that variability should not be treated as a single construct. Type of variability should be recognized and considered in the interpretation of the research results. With respect to this, the intrinsic and intervention-induced variability needs to be distinguished [34]. Intrinsic variability is "inherent to the motor system while performing a task" and is naturally exhibited by the participant. Intervention-induced variability on the other hand is introduced in the form of instruction or feedback. It may be that intrinsic variability (variability observed during a natural learning process like in Vegter et al. [13]) and intervention-induced variability (variability introduced by the means of feedback such as in the present study) are distinctly different and, therefore, influence the change in energy efficiency differently. As suggested by Ranganathan and Newell [34], the difference in magnitude between intrinsic and feedback-induced variability might have been responsible for their divergent influence on energy efficiency of the motor system. The intrinsic intra-individual variability measured by Vegter et al. [13] oscillated around 15%, while in our study mean variability in the feedback group was 39% in the first and 30% in the second practice block. This suggests that increasing motor exploration beyond some level may not benefit the motor learning process. It may be that only variability within some range enhances performance. Participants in the present study were naïve to the task of wheelchair propulsion and, therefore, their motor performance may not have been stable yet. It may be that provoking increased variability, especially in the early stages of skill acquisition when performance is not stable, creates dysfunctional movement patterns and is detrimental to learning [34,35].The dysfunctional movement patterns and non-stable motor behavior may have inhibited the optimization of mechanical efficiency in the feedback group.

Another possible explanation for the lack of improvement of mechanical efficiency in the feedback group might be the chosen intervention type. The use of visual feedback can be seen as an extra cognitive task that contributed to higher metabolic energy expenditure during the feedback sessions. However the feedback was not present during the pre- or post-test, which is when the change in mechanical efficiency was evaluated.

Although we did not find a positive influence of variability on the mechanical efficiency, it may be that variability influences other relevant aspects of wheelchair propulsion such as shoulder pain. Rice et al [36] found that the analysis of intra-individual variability allowed making a distinction between pain and no-pain groups, suggesting a link between reduced variability and increased upper-extremity injury risk. The authors recommended investigating whether wheelchair users can be trained to propel the wheelchair in a more variable way in order to decrease the injury risk [36, 37]. The current study showed that an increase in variability in able-bodied participants can be achieved by targeting propulsion variables during feedback-based practice. Possible effect of the feedback-induced variability on the injury risk in wheelchair users is yet to be determined.

The feedback group, next to receiving the visual feedback on their propulsion technique, has also received a brief verbal instruction to show highest possible variability within the practiced variable (1st practice block) and optimize the absolute value of the variable (2nd practice block). The natural learning groups did not receive any verbal instruction. It was purposely chosen not to provide any verbal instruction to the natural learning group. The natural learning protocols in wheelchair propulsion are well researched and show that letting the participants to choose their way of propulsion yields positive effects in propulsion technique and mechanical efficiency [10-13, 31]. In all these protocols, no verbal instruction was provided to the participants. Introducing extra instruction in the natural group in present study would modify the learning process and make the interpretation of the results difficult since observed effect could be an effect of either learning process or the instruction or a combination of both. Therefore, providing verbal instruction to the natural learning group would result in a learning process which could not be described anymore as natural. It has to be acknowledged that the results obtained in the feedback group are the consequence of the added visual feedback on the given variable in combination with a brief standardized verbal instruction.

Finally, a relative homogeneous group of able-bodied participants performed the experiment in a standardized wheelchair without adjustments for the participant's anthropometry. Therefore, the generalization of the results obtained in this study to patient populations should be done with caution. At the moment we would not advocate to use the tested protocol with patient groups. Future experiments should first further explore the feasibility of increasing the functional component of variability to promote motor learning.

Our study introduced a new experimental approach that, to our knowledge, has not been used before in wheelchair propulsion research: the use of visual feedback to evoke

variability. Moreover, present study reveals a possibly complex relationship between propulsion technique and mechanical efficiency that may depend on the intra-individual variability. Yet, it must be noted that the effect of the visual-feedback variability on the mechanical efficiency and propulsion technique is specific to the particular experimental design chosen in this study and should not be generalized to other sorts of feedback-induced variability.

CONCLUSION

The feedback group was successful in performing the task with higher intra-individual variability and improved the propulsion technique between pre- and post-test to the same extent as the natural learning group. In contrast, mechanical efficiency remained unchanged in the feedback group but improved between pre- and post-test in the natural learning group.

These results may possibly imply that feedback-induced variability was not beneficial for the motor learning process, but rather hindered the improvement in mechanical efficiency. Moreover since both groups improved propulsion technique but in the feedback group this improvement was not accompanied by the improvement within mechanical efficiency, it can be concluded the mechanical efficiency and propulsion technique are not directly related. It may be that changes in mechanical efficiency and propulsion technique during motor learning process are mediated by other factors such as the amount of the intra-individual variability. This novel finding provides new insights concerning the motor learning process in wheelchair propulsion and it should be considered in the research concerning the relationship between variability and motor learning. Future research should try to replicate the results obtained in the present study on a group of manual wheelchair users (in early rehabilitation), in order to allow to use the results in the development of the clinical interventions.

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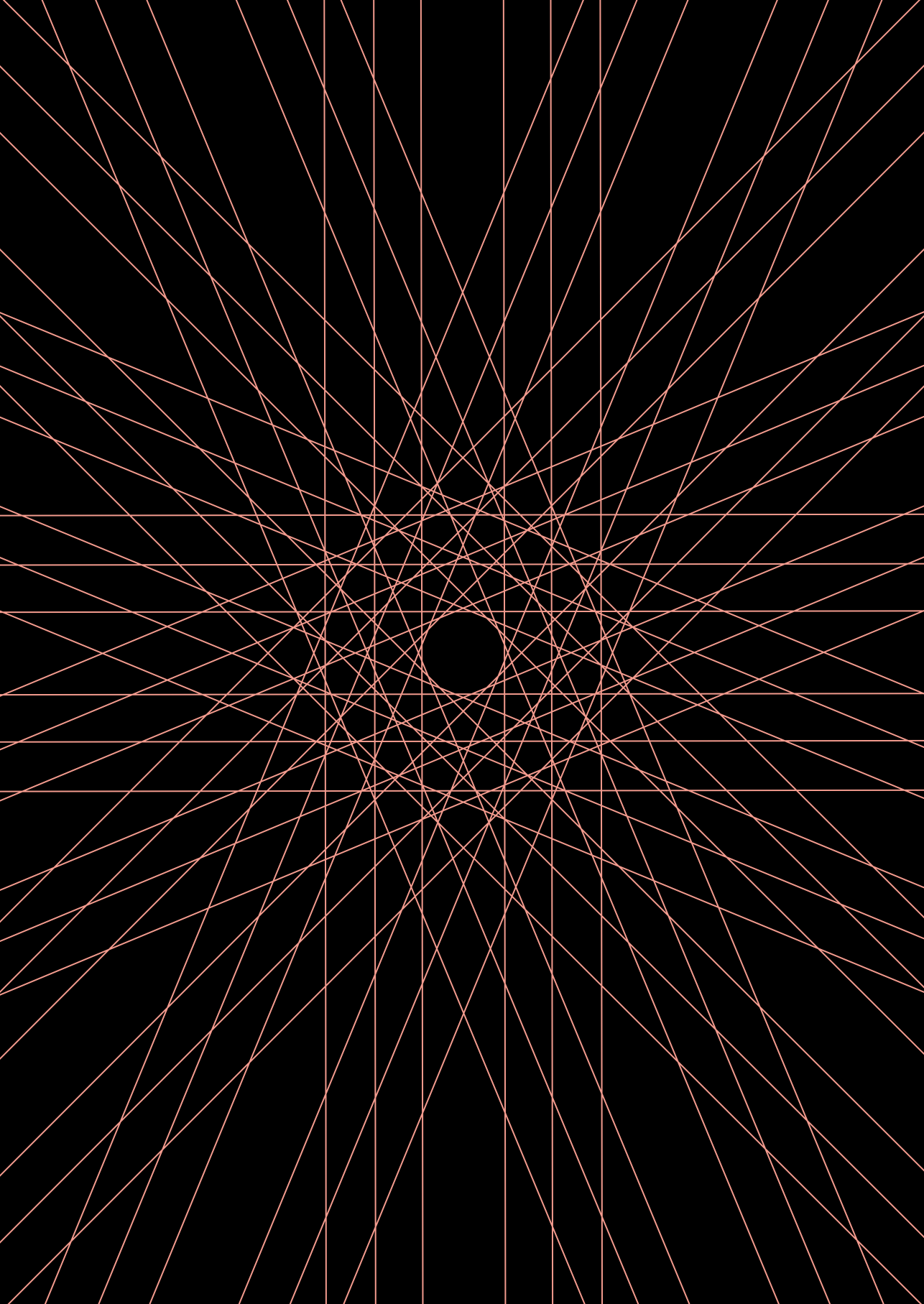
SUPPORTING INFORMATION

Supporting information is available on the website of the publisher.

S1 Dataset. Complete Data Set used for data analysis.



3

EFFECTS OF VARIABLE PRACTICE ON THE MOTOR LEARNING OUTCOMES IN MANUAL WHEELCHAIR PROPULSION

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ABSTRACT

Background: Handrim wheelchair propulsion is a cyclic skill that needs to be learned during rehabilitation. It has been suggested that more variability in propulsion technique benefits the motor learning process of wheelchair propulsion.

Goal: To determine the influence of variable practice on the motor learning outcomes of wheelchair propulsion in able-bodied participants. Variable practice is introduced in the form of wheelchair basketball practice and wheelchair-skill practice. Motor learning was operationalized as improvements in mechanical efficiency and propulsion technique.

Methods: 11 Participants in the variable practice group and 12 participants in the control group performed an identical pre-test and a post-test. Pre- and post-test were performed in a wheelchair on a motor-driven treadmill (1.11 m/s) at a relative power output of 0.23 W/kg. Energy consumption and the propulsion technique variables with their respective coefficient of variation were calculated. Between the pre- and the post-test the variable practice group received 7 practice sessions. During the practice sessions participants performed one-hour of variable practice, consisting of five wheelchair-skill tasks and a 30 min wheelchair basketball game. The control group did not receive any practice between the pre- and the post-test.

Results: Comparison of the pre- and the post-test showed that the variable practice group significantly improved the mechanical efficiency (4.5 ± 0.6%→ 5.7 ± 0.7%) in contrast to the control group (4.5 ± 0.6%→ 4.4 ± 0.5%) (group x time interaction effect $p<0.001$).With regard to propulsion technique, both groups significantly reduced the push frequency and increased the contact angle of the hand with the handrim (within group, time effect). No significant group x time interaction effects were found for propulsion technique. With regard to propulsion variability, the variable practice group increased variability when compared to the control group (interaction effect $p<0.001$).

Conclusions: Compared to a control, variable practice, resulted in an increase in mechanical efficiency and increased variability. Interestingly, the large relative improvement in mechanical efficiency was concomitant with only moderate improvements in the propulsion technique, which were similar in the control group, suggesting that other factors besides propulsion technique contributed to the lower energy expenditure.

BACKGROUND

Wheelchair propulsion offers mobility and independence to individuals who lost the ability to walk. In wheelchair propulsion, the ambulatory function of the legs is taken over by the arms. This type of ambulation is novel to most individuals with a permanent lower-body impairment and, therefore, has to be learned during the early stages of rehabilitation. The need for effective practice protocols that enhance the motor learning process of wheelchair propulsion is widely recognized. At the same time evidence-based guidelines are missing. The present study will evaluate a practice protocol that aims to facilitate the motor learning process of wheelchair propulsion, using variability as a key feature.

Research suggests that increased variability helps to improve motor learning by creating a flexible and adaptable biological system [1-4]. Movement variability is defined as fluctuations across repetitions during performance of a task. A higher variability is expected to increase the motor exploration, which in turn helps to find the most relevant motor solutions for a given task. Also in wheelchair propulsion, higher motor variability observed during a natural learning process (changes over time resulting from practice without feedback or instruction) appeared to be associated with better learning outcomes in terms of mechanical efficiency and propulsion technique [4,5].

So far, motor learning in wheelchair propulsion was mostly investigated in a constrained, non-variable, laboratory environment [5,6]. These highly internally valid experiments provided valuable information about the motor learning process in terms of mechanical efficiency (the ratio of external power output and energy expenditure) and propulsion technique, which are thought to represent the motor learning process in wheelchair propulsion [4,6,7]. The present study bases its hypotheses on the findings of these lab-based studies, but also partly moves away from a highly controlled experimental environment and towards a setting that resembles the environment of early clinical rehabilitation and daily life more closely.

Performance of daily tasks in a wheelchair, such as doing groceries, is highly variable and requires different skills e.g. turning, acceleration, maneuvering and interaction with obstacles. This sort of variability is not present when propelling a wheelchair on a treadmill at a steady velocity in a laboratory. A study that attempted to increase variability on a treadmill, using visual feedback on the propulsion technique variables, found improvements in propulsion technique but no improvement in mechanical efficiency [8]. Authors suggested that the addition of an extra constraint, which was visual feedback, may have compromised the optimization of the energy efficiency of wheelchair propulsion.

This finding inspired us to propose a practice protocol, which would increase variability in a different, more internal and 'natural' way, without an addition of feedback or instruction. While the feedback-induced variability required participants to 'learn to be variable', the current study aimed at facilitating 'learning by being variable'. The participants in the present study were asked to perform tasks that require and stimulate variability, but

contrary to the feedback-induced variability study [8], they were not explicitly asked to be variable. The tasks chosen for the current protocol were five isolated wheelchair skill tasks (such as a slalom or a sprint) and wheelchair basketball. Those tasks are inherently variable and do not require feedback or instruction, giving freedom to the learners to individually explore their motor solutions during uninstructed practice.

The goal of the current study was to determine the influence of variable practice on the motor learning outcomes. We assessed whether participants, who received variable practice (variable practice group), learned more than participants who did not receive any practice (control group). A no-practice control group was chosen to exclude the possibility where the repeated tests themselves could produce performance changes. We hypothesized that the variable practice group would improve both mechanical efficiency and propulsion technique during the push phase more than the control group. Mechanical efficiency is calculated as the ratio of power output and energy expenditure during steady-state submaximal cyclic exercise. Values of mechanical efficiency in hand-rim wheelchair propulsion hardly ever exceed 10% in experienced wheelchair users [9,10]. A decrease in energy expenditure over time for a given task with a constant power output (i.e. an increase in mechanical efficiency) has been used to quantify the motor learning process [11,12] and is suggested to be a global indicator for motor proficiency [13]. Improved propulsion technique is defined as a technique in which the contact angle of the hand with the handrim increases and push frequency decreases [4,6,7]. These changes are accompanied by a reduction of braking torque, meaning that wheelchair users grasp and release the handrim more fluently, and in turn save energy. Increasing variability in manual wheelchair propulsion can be achieved by varying the above mentioned propulsion technique variables in timing and magnitude by e.g. using shorter and longer pushes interchangeably or varying the frequency of pushes. We expect that variable practice will allow enhanced motor exploration which may lead to larger improvements in propulsion technique and mechanical efficiency compared to the control group. Variable practice is introduced in the form of wheelchair basketball practice and wheelchair-skill practice, which are thought to encourage motor exploration. Able-bodied participants were chosen because they are a homogenous group (similar age, lack of wheelchair experience and no comorbidities), which minimizes the inter-individual variation and allows to better isolate the effect of variable practice on the outcomes of motor learning process.

METHODS

Participants

Eleven individuals in the variable practice group and twelve individuals in the control group participated voluntarily in the current study. The characteristics of both groups can be found in Table 1. Following detailed verbal and written information about the character of the study, all participants signed an informed consent before the onset of the study. The protocol of the study was approved by the Local Ethics Committee (Nr. ECB/2014.12.18_2), of the Center for Human Movement Sciences, University Medical Center Groningen,

University of Groningen, The Netherlands. Inclusion criteria were being able-bodied, having no upper-extremity injuries and having no previous experience with manual wheelchair propulsion. Individuals were excluded when they suffered from any medical conditions that could influence the parameters measured in the study, including musculoskeletal disorders, primarily those involving the shoulder girdle or upper extremities.

Table 1. The characteristics (Mean ± SD) of the variable practice (N=11) and the control group (N=12).

Measure	Variable practice group (N=11)	Control group (N=12)	P value
Gender (males/females)	3/8	6/6	0.400[a]
Age (years)	20.2 ± 2.0	20.7 ± 1.4	0.507[b]
Body mass (kg)	73.2 ± 10.3	72.5 ± 9.4	0.869[b]
Body height (m)	1.78 ± 0.1	1.81 ± 0.1	0.456[b]

[a] 2-sided p-value of a Fisher's exact test. [b] 2-sided p-value of an Independent Samples t-test

Protocol

The experimental protocol for the variable practice and the control group is presented in Fig.1. Both groups completed the pre-test and the post-test consisting of 12 minute (3 x 4min, with bouts of 2-min rest between the exercise blocks) wheelchair propulsion on a motor-driven treadmill under standardized conditions (Fig. 2). Time between the pre- and the post-test was the same in both groups (8 weeks). Between the pre- and the post-test the control group did not receive any intervention and the variable practice group participated in seven practice sessions. The practice sessions took place once a week. Participants who missed one session during the seven weeks (N=8) received a seventh session in week 8. Each practice session lasted one hour and included the performance of five standardized wheelchair skills tests and a 30 min uninstructed wheelchair basketball game. The actual practice time per session equaled approximately 35 min for each participant (5 min of the skill practice + 30 min of wheelchair basketball).

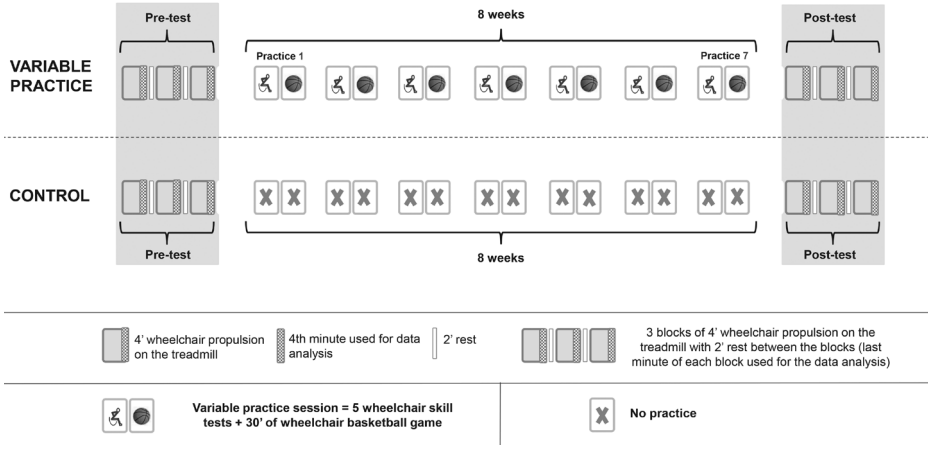

Figure 1. The experimental protocol for the variable practice and the control group. Both groups received identical pre- and post-test. Between the pre- and the post-test, the variable practice group received 7 practice sessions, while the control group did not receive any practice.

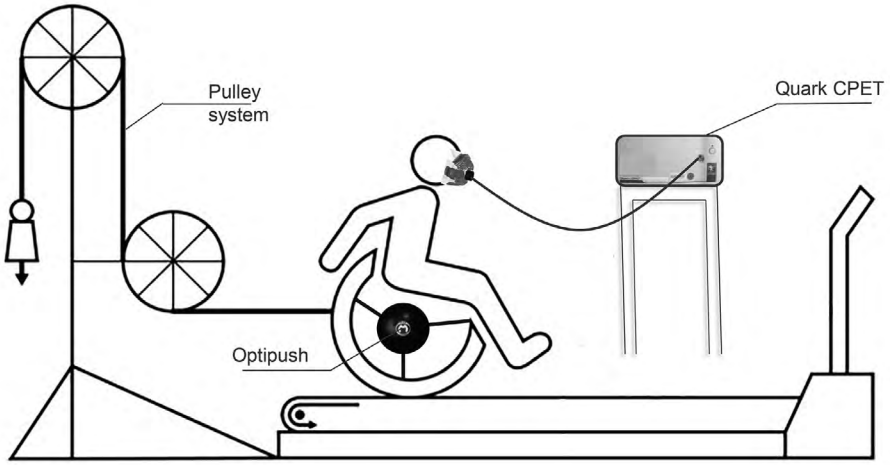

Figure 2. The experimental setup for the pre- and post-test. Pre- and the post-test were identical in both groups. Power output was set using the pulley system (0.23 W/kg). Treadmill speed was 1.11 m/s. The Optipush wheel measured 3D forces and torques applied to the handrim by the participant. A Quark CPET was used to determine the oxygen uptake and respiratory exchange ratio, which are necessary to calculate the mechanical efficiency. Modified figure from Vegter et al [4].

Pre- and post-test protocol

Pre- and post-test in both groups were performed in the same experimental handrim Küschall K4 wheelchair (Küschall AG, Witterswil, Switzerland, 24", no camber, seat height: 0.5 m (measured from the floor to the front of the seat), seat width: 0.47 m) placed on a 2.4 m long by 1.2 m wide level motor-driven treadmill (Forcelink b.v, Culemborg, The Netherlands). Tire pressure of the rear wheels was set at 600 kPa. Treadmill velocity was set at 1.11 m/s and power output at 0.23 W/kg body mass. The extra resistance needed to maintain the power output was calculated for each participant individually, based on the data acquired from a drag test prior to experimentation. The drag test, developed by the technical workshop of the Faculty of Human Movement Sciences at the VU University in Amsterdam, measures the rolling resistance, which together with the velocity determines the power output [14,15]. The extra resistance was added using a pulley system [16] (Fig. 2). The experimental setup is presented in Fig. 2.

Variable practice session protocol

Wheelchair skills practice

The wheelchair skill practice and wheelchair basketball game took place in a gymnasium of The University Medical Center Groningen, Centre for Rehabilitation, location Beatrixoord (Haren, The Netherlands). Eleven handrim wheelchairs were used during seven practice sessions. The five wheelchair skill tasks were performed in a wheelchair that was assigned individually to each participant for all the practice sessions, in order to make sure that possible improvement in performance between sessions was a result of the change in propulsion technique and not due to a different wheelchair. The tire pressure of the wheelchairs was standardized checked before each practice session.

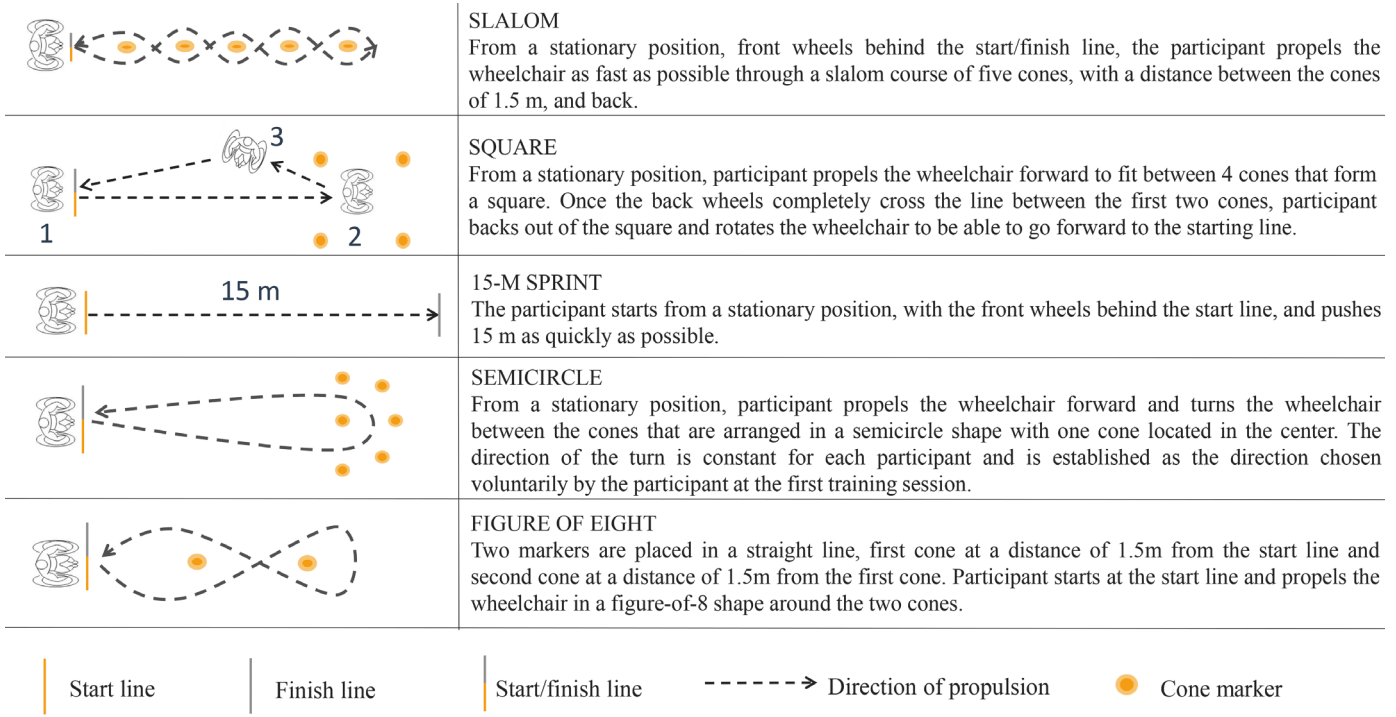

Figure 3. The wheelchair skill practice. Five wheelchair skill tasks were performed in the variable practice group one time by each participant at each practice session.

Most important selection criterion for the skill tasks was that they had to stimulate variability and therefore involve the changes of e.g. direction, acceleration, speed. Moreover the tasks involving backward and forward handrim propulsion (represented in the present study by: slalom, figure of 8, square, semicircle), maneuvering (figure of 8 shape, slalom, square, semicircle) and sprint (15-m sprint) were used in previous research to assess the degree of wheelchair skill proficiency necessary for every day functioning [17-20]. Exact description and illustration of the tasks can be found in Fig. 3. Time for all tasks was manually recorded with a stopwatch with a precision of 0.01 s. Time was recorded from the moment the participant began to drive until the front wheels of the wheelchair passed the finish line. It took approximately 30 min to test 11 participants with the complete test battery. The sequence of the skill tasks was fixed for each participant (and counterbalanced across participants using a Latin square) to make sure that the results over time were not influenced by fatigue.

The changes within the time scores on the wheelchair skill tasks were not the main study outcome measures, but were included in the results because it gives an indication about the improvement in the maneuverability across the practice sessions in the variable practice group.

Wheelchair basketball game

The 30-min wheelchair basketball game was performed in a different wheelchair (out of 11 available basketball wheelchairs) at every practice session in order to account for the generalization of the learned skills to different types of wheelchairs. Participants were instructed to adhere to the basic rules of wheelchair basketball as established by the International Wheelchair Basketball Federation [21]. Other than that no instructions were given.

Data analysis

The mechanical efficiency and the propulsion technique were determined during the pre- and the post-test in both groups.

Mechanical Efficiency

Oxygen uptake (VO2) and respiratory exchange ratio (RER) during steady-state wheelchair propulsion were continuously determined breath-by-breath using Quark Cardio-Pulmonary Exercise Testing (CPET) (COSMED, Rome, Italy). Heart rate was measured continuously throughout the experiment using CPET. The CPET was calibrated before each measurement occasion using 3 l syringe, room air and a calibration gas mixture.

Gross mechanical efficiency was calculated over the last minute of each 4-min block. The equation used to calculate mechanical efficiency was: $ME = PO \times E^{-1} \times 100\%$, where PO is power output and E is the gross energy expenditure, calculated according to:

PO (W) =T (torque (Nm)) x Av (Angular velocity (rad/s))

E (W) = (4940 x RER + 16040) x VO_2 (l/min) / 60, where RER and VO_2 are the average values over the last minute of each exercise block [22].

Propulsion Technique

The 3-dimensional forces and torques applied on the handrim of the right wheel were continuously measured during the pre- and the post-test using the software of the instrumented Optipush wheel (MAX Mobility, LLC, Antioch, TN, USA) or Smartwheel (Three Rivers Holdings, Mesa, AZ, USA). The sample frequency of the measurement wheel was set at 200 Hz. Data was sampled at 200 Hz and filtered with a fourth-order recursive Butterworth digital low-pass filter with a 20 Hz cutoff frequency [23]. The data collected during the last minute of each 4-min block were used for analysis. The output registered by the measurement wheel was calculated into specific propulsion technique variables using custom-written Matlab algorithms [4] (Table 2). The propulsion variables: frequency, braking torque and contact angle, were chosen based on their previously found association with mechanical efficiency [4]. Positive work per push and maximal torque per push were chosen as they describe the height and width of the torque signal, the properties of which the variability is likely to change as a result of variable practice. Coefficient of variation (the ratio of the standard deviation to the mean, CV=σ/μ x 100 (%)) of the five propulsion technique, separately and as an average of five propulsion variables, was used to determine the amount of variability.

Table 2. The propulsion technique variables. The variables were used to compare the change in propulsion technique between the pre- and the post-test. All variables, except push frequency, were calculated as an average value of all pushes performed during the last minute of each practice block. Modified table from Leving et al [8]; Equations from Vegter et al [4].

Propulsion variable	Unit	Description	Equation
Push frequency	push/minute	The number of pushes performed during one minute	$N_{pushes}/\Delta t$
Braking torque	Nm	The braking torque applied to the handrim with each push. The sum of braking torque exerted on the handrim during coupling and decoupling of the hand	$\Sigma_{end}(i)_{:start}(i+1)\,(Tz \cdot \Delta\emptyset)$
Contact Angle	degrees (°)	The angle measured along the handrim, where subject's hand maintained contact with the handrim during each push	$\emptyset_{end}(i)\text{-}\emptyset_{start}(i)$
Max Torque	Nm	The maximum torque generated around the wheel axle within a push	$Max_{start(i):end(i)}(Tz)$
Positive Work	J	The torque around the wheel axle intergrated over the contact angle of the push	$\Sigma_{start}(i)_{:end}(i)\,(Tz \cdot \Delta\emptyset)$

Abbreviations: t, time(s); start(i), start of the current push (sample); end(i), end of the current push (sample); Tz, torque around wheel axle (Nm); Ø, angle (rad);

Statistical analysis

Statistical analysis concerning the characteristics of the participants was performed using IBM SPSS Statistics version 21.0 (SPSS Inc., Chicago, IL, USA). All data showed normal distribution at baseline, therefore parametric tests were applied. Baseline values of age,

body mass and height of the participants, as well as values of all outcome measures at the pre-test, were compared between the variable practice and the control group, using independent t-test, to check for presence of the initial differences. Difference in the number of men and women between the groups was compared using Fisher's exact test.

To examine the effect of variable practice on the outcomes of motor learning process, pre- and post-test values of mechanical efficiency, energy expenditure, heart rate and propulsion technique were compared between the variable practice and the control group using MLwiN version 2.31 (Center for Multilevel Modeling, University of Bristol, Bristol, UK). The data from the 3 pre-test blocks (4 min each, last minute used for the analysis) and from the 3 post-test blocks were compared. Pre- and post-test were represented in the model as time in minutes. Dummy coding was used to distinguish between the groups (0-variable practice; 1-control). Considering the possible influence of the power output on the mechanical efficiency and propulsion technique (and therefore on the variability), it was checked whether there was a difference in the power output between the pre- and the post-test between the groups (time x group effect) and within the groups (time effect). In order to prevent bias, in all cases where relative power output differed between two conditions, it was chosen to correct for it by adding power output to the model. The following regression equation was used:

Outcome measure = β_0Constant + β_1Time effect + β_2Group effect + β_3Time*Group interaction effect + (β_4 Relative Power Output).

To determine whether variable practice influences variability during steady-state propulsion on a treadmill, coefficient of variation for the (average of) five propulsion technique variables was compared between the pre- and post-test and between the groups using the same multilevel analysis as described above. The time x group effect was the outcome of interest for all analyses.

For the variable practice group, the time scores of each of five wheelchair skill tasks were compared across seven practice sessions using repeated measure ANOVA (IBM SPSS Statistics version 21.0, SPSS Inc., Chicago, IL, USA) with time (7 practice sessions) as within-subject factor. The significance level for all above-mentioned statistical procedures was set at $p < 0.05$. When a significant main effect of time was found during the ANOVA, post-hoc pairwise comparisons were performed between the seven consecutive practice sessions, for each wheelchair skill task, in order to determine the exact location of the differences. This resulted in 6 comparisons per skill task. A Bonferroni correction was applied to correct for the number of comparisons. Significance of individual dependent t-tests was therefore set at a *P* value of less than 0.05/6 = 0.008.

RESULTS

All participants in the variable practice (N=11) and the control group (N=12) completed the pre- and the post-test. Moreover all participants in the variable practice group completed 7 practice sessions. The relative power output between the pre-test and the post-test differed significantly within each group (time effect) and between groups (time x group effect) (Table 3). As a result, the relative power output was added to all multilevel regression models as a correction factor.

The characteristics (age, body mass and height) of the participants were not different between the groups at baseline (Table 1). The values of all outcome measures including mechanical efficiency, propulsion technique and propulsion variability were not different between the groups at the pre-test ($p>0.05$). The only exception was contact angle which was significantly higher in the variable practice group compared to the control group ($p=0.04$).

Mechanical efficiency and heart rate

The change in mechanical efficiency of both groups between the pre- and post-test is shown in Fig. 4. As presented in Table 3, the variable practice group increased the mechanical efficiency with an absolute 1.2% (relative 27%) over the practice period ($p<0.001$). Mechanical efficiency in the control group remained unchanged ($p=0.587$). Moreover, the interaction effect (time x group) reached significance ($p<0.001$), indicating that the variable practice group improved the mechanical efficiency in contrast to the control group.

Table 3. Change in mechanical efficiency, energy expenditure, heart rate, propulsion technique and variability (CV) between the pre- and the post-test for the variable practice (N=11) and the control group (N=12). Mean and SD of the original data. P values are based on multilevel regression model outcomes (main effect of time and interaction effect time x group).

	Variable practice N=11 Mean[a] ± SD			Control N=12 Mean[a] ± SD			
Outcome Measure	**Pre-Test**	**Post-Test**	**p value Time**	**Pre-Test**	**Post-Test**	**p value Time**	**p value Time x Group**
Mechanical Efficiency (%)	4.5 ± 0.6	5.7 ± 0.7	<0.001	4.5 ± 0.6	4.4 ± 0.5	0.587	<0.001
Energy Expenditure (W)	368.2 ± 59.8	303.7 ± 42.6	<0.001	372.4 ± 61.0	346.7 ± 41.1	0.047	0.070
Heart rate (beats per minute)	125.9 ± 27.4	103.1 ± 19.0	<0.001	108.2 ± 21.4	100.6 ± 16.6	0.441	0.027
Propulsion Technique							
Frequency (pushes/min)	65.4 ± 12.3	57.8 ± 8.6	0,011	72.3 ± 17.2	60.0 ± 16.7	0.008	0.296
Contact Angle (degrees)	67.0 ± 8.6	77.6 ± 9.1	<0.001	57.7 ± 11.9	70.3 ± 12.8	0.001	0.322
Braking Torque (Nm)	-1.1 ± 0.8	-0.5 ± 0.4	<0.001	-1.0 ± 0.7	-0.7 ± 0.5	0.088	0.216
Positive Work (J)	9.0 ± 1.8	9.7 ± 1.8	0,369	8.3 ± 2.0	9.0 ± 2.6	0.105	0.397
Max Torque (Nm)	12.5 ± 2.2	11.6 ± 1.9	0,084	13.2 ± 2.0	12.3 ± 2.1	0.305	0.729
Variability (%)							
CV Mean[b]	21.4 ± 4.2	32.7 ± 6.1	<0.001	20.5 ± 4.6	18.5 ± 3.2	0.484	<0.001
CV Frequency	7.5 ± 3.0	6.7 ± 4.2	0,536	9.5 ± 5.1	6.8 ± 2.3	0.113	0.335
CV Contact Angle	10.7 ± 3.0	34.4 ± 5.6	<0.001	12.8 ± 3.6	9.3 ± 2.4	0.013	<0.001
CV Braking Torque	48.7 ± 18.9	70.5 ± 25.3	0,091	40.8 ± 9.9	43.6 ± 15.6	0.228	0.200
CV Positive Work	22.0 ± 4.0	38.4 ± 7.2	<0.001	23.2 ± 5.7	16.6 ± 4.2	0.002	<0.001
CV Max Torque	19.2 ± 3.7	15.4 ± 2.8	<0.001	18.5 ± 3.6	15.7 ± 3.4	0.053	0.242
Relative Power Output (W/kg)	0.22 ± 0.01	0.23 ± 0.02	0.005	0.23 ± 0.01	0.21 ± 0.02	<0.001	<0.001

[a] Mean of 3 blocks of pre- or post-test. [b] Mean CV of Frequency, Contact Angle, Braking Torque, Positive Work and Max Torque

Heart rate decreased significantly between the pre- and post-test in the variable practice group ($p<0.001$) (Table 3) and remained unchanged in the control group ($p=0.441$). Moreover, the interaction effect (time x group) reached significance ($p<0.027$), confirming that the heart rate in the variable practice group decreased more than in the control group.

Propulsion technique

The differences in propulsion technique between the pre- and post-test are presented in Table 3 and Fig. 5. Both groups significantly reduced the push frequency and increased the contact angle of the hand with the handrim. Additionally, the variable practice group reduced the braking torque at (de)coupling. No significant changes were found in both groups for the positive work per push and max torque per push. The time x group interaction effect was not significant for all propulsion variables implying that there were no differences in the change of propulsion technique over time between groups.

Variability

Mean variability increased significantly between the pre and post-test in the variable practice group and did not change in the control group (Table 3). The interaction effect was significant which means that the variable practice group became more variable compared to the control group. Variability of contact angle and positive work changed in opposite direction in the two groups, i.e. they increased in the variable practice group and decreased in the control group. The time x group interaction effect for these two variables was significant. Variability of max torque decreased in both groups, although in the control group this change was not significant. There were no significant changes in the variability of frequency and braking torque in both groups. The course of variability during the pre- and the posttest is presented in Fig. 6.

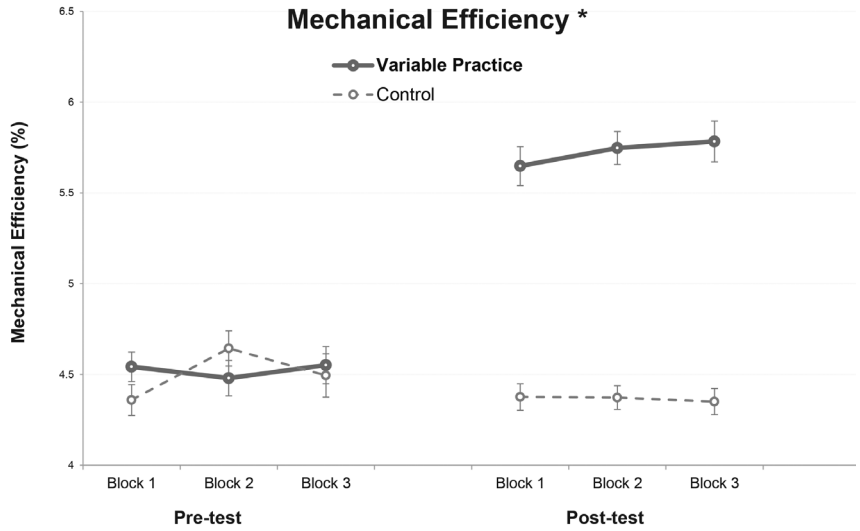

Figure 4. Change in mechanical efficiency between the pre- and post-test in the variable practice (N=11) and the control group (N=12). Mean and standard error of original data are provided per practice block. (*) Significant ($p<0.05$) effect of time x group determined by the multilevel regression modeling.

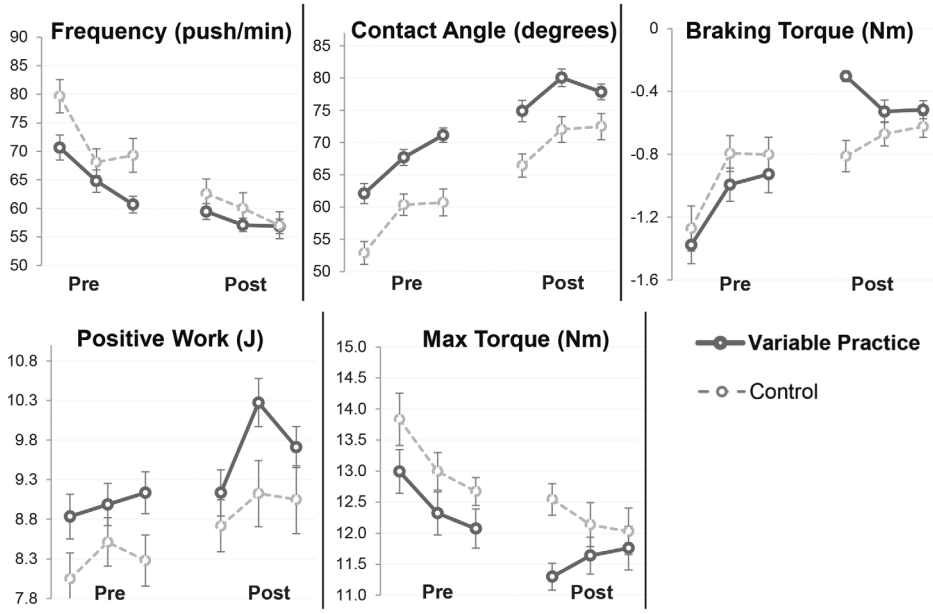

Figure 5. Change in propulsion technique between the pre- and post-test in the variable practice (N=11) and the control group (N=12). Mean and standard error of original data are provided per practice block. The time x group interaction effect was not significant for all propulsion variables.

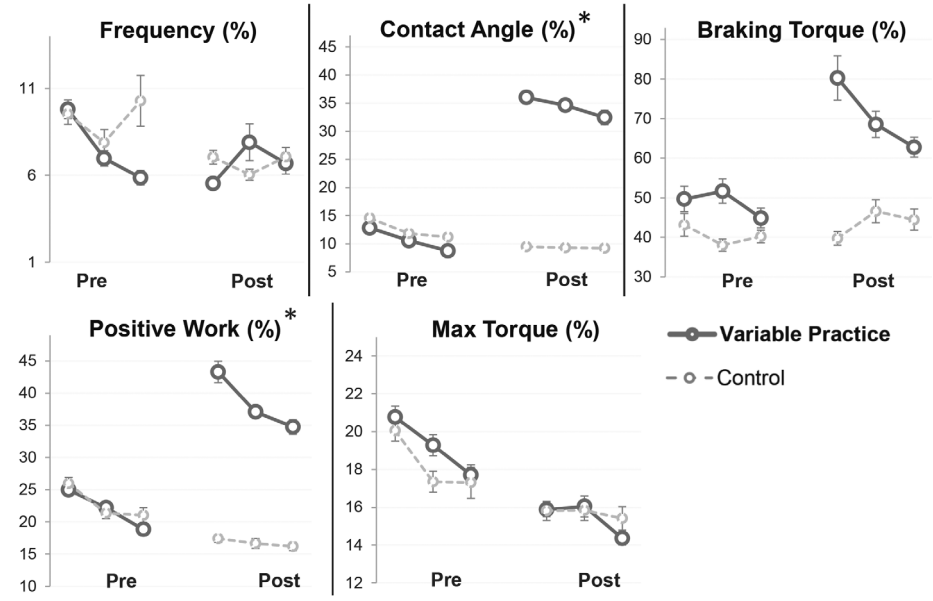

Figure 6. Change in variability (CV) between the pre- and post-test (%) in the variable practice (N=11) and the control group (N=12). Mean and standard error of original data are provided per practice block. (*) Significant ($p<0.05$) effect of time x group determined by the multilevel regression modeling.

Wheelchair skill practice

Participants in the variable practice group improved their performance significantly on all wheelchair skill tasks across the seven practice sessions. Fig. 7 shows the exact location of the differences as determined by the post-hoc analysis.

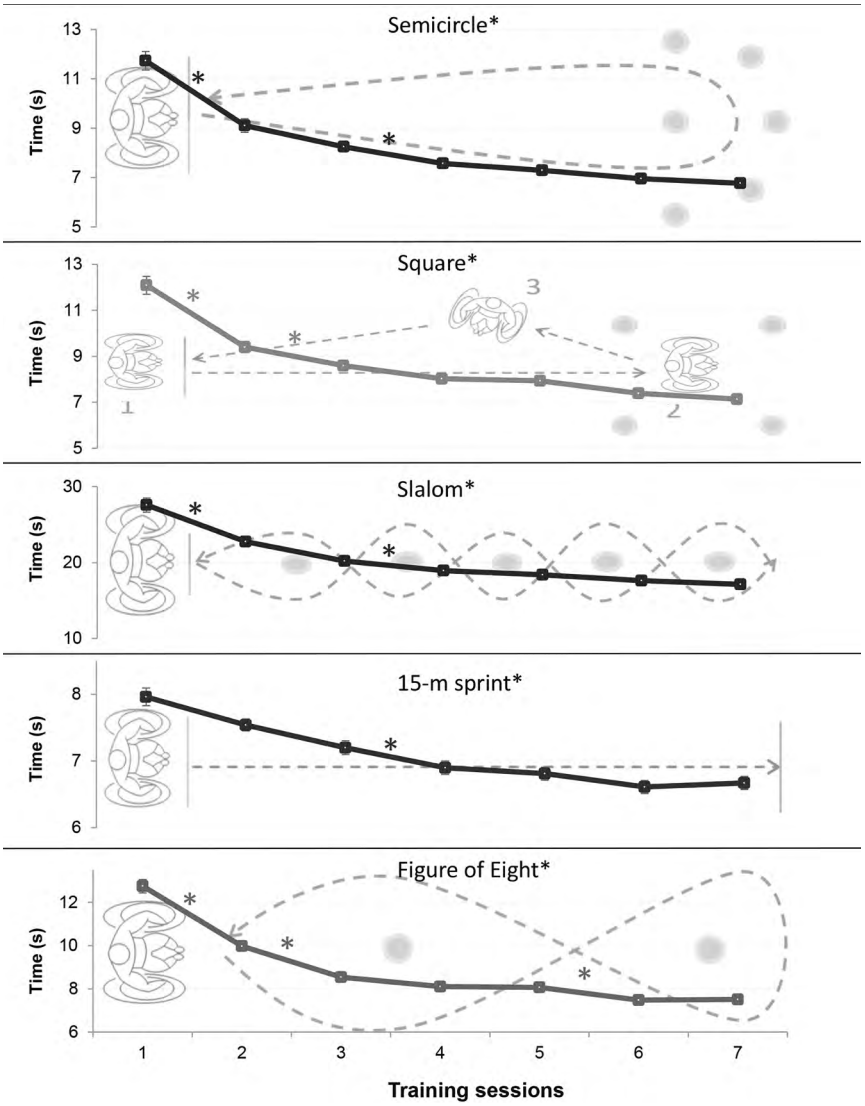

Figure 7. Results of repeated measure ANOVA showed that participants in the variable practice group (N=11) improved their performance between the first and last session on all wheelchair skill tasks ($p<0.05$). Mean and standard error per practice session are provided. (*) Significant ($p<0.008$) differences between the consecutive practice sessions, determined with post-hoc tests.

DISCUSSION

The goal of the current study was to determine the influence of uninstructed variable practice on the motor learning outcomes of wheelchair propulsion. Results showed that participants in the variable practice group improved their mechanical efficiency more and became more variable than the control group. Improvements in the propulsion technique between the groups over time were comparable.

Mechanical Efficiency

The purpose of this study was to understand whether and how variable learning impacts on novel motor skill. By providing fewer constraints (participants did not receive any feedback or instruction) we aimed to allow motor exploration and therefore facilitate learning.

In Table 4 the change in mechanical efficiency observed in the present study is compared with studies concerning steady-state wheelchair propulsion on the treadmill or wheelchair ergometer. For studies where we had access to data, we performed a direct statistical comparison with the current findings of the variable practice group. All these studies were, just as the current study, performed with able-bodied participants. Mechanical efficiency in the variable practice group in the current study increased over approximately 269 min (5 min of the skill practice+ 30 min of wheelchair basketball = 269 min of intermittent exercise across 10 weeks) of uninstructed practice relatively by 27% (4.5 % → 5.7%). This is quite a large increase compared to a control group in which mechanical efficiency remained unchanged (4.5 % → 4.4 %), as well as to the other studies. Participants in a feedback-induced variability study (80min, low-intensity, 3 weeks) decreased their mechanical efficiency between the pre- and post-test (5.25% → 5.23%) [8]. Pre- and post-test protocol in that study was similar to the present study. Natural learning protocols of various durations found an increase in mechanical efficiency. The natural learning group in the experiment of Leving et al. (80 min, low-intensity, 3 weeks) increased the mechanical efficiency by 17% between pre- and posttest (5.71% → 6.67%) [8]. Another study, which also offered 80min of low-intensity wheelchair training (within one day or 3-weeks), found 0% (5.5% → 5.5%) of relative improvement in slower learners and 20% improvement in faster learners (4.9% → 5.9%) [5]. A study that offered two training intensities across 630 min (3x per week across 7 weeks) found a relative improvement ranging from 17 to 24% [24]. The largest relative improvement in mechanical efficiency of 30% (5.37% → 6.99%) was found following a 7-week low intensity wheelchair practice program (3x per week, 70 min = total of 1470 min) [6].

The duration of exercise in the present study, 269 minutes, is longer than the duration of 80-min studies which found an increase of 0-20% in mechanical efficiency but it is also considerably shorter than the 630 min study, which found 17 to 24% improvement, or 1470 min study, which found 30% of relative improvement. As shown in Table 4, where the results of the variable practice group where statistically compared with previous literature, the relative increase in mechanical efficiency in the variable practice group is comparable to the improvements found by the historical studies, which used higher exercise doses [6,24]. Nonetheless, it should be acknowledged that the increase in

mechanical efficiency in the present study might not just be the effect of increased skill and underlying coordination, but also of improved physical capacity as response to exercise.

Table 4. The results of the present and other studies concerning the change in mechanical efficiency resulting from wheelchair practice in able-bodied individuals.

Study	Group	N	Treadmill/ Ergometer	Total duration (min)	Velocity m/s	Power output	Mechanical Efficiency (%) [a]	P value; Current vs previous studies [b]
Present study	Variable practice	11	Testing on treadmill, practice in a gym	± 269	1.11	0.23 W/kg	4.5 →5.7 (27)	-
Present study	Control	12	Testing on treadmill, no practice	24	1.11	0.22 W/kg	4.5 → 4.4 (-2)	-
Vegter et al., 2014 [5]	Fast improvers	26	Treadmill	80	1.11	0.20 W/kg	4.9 →5.9 (20)	x
	Slow improvers	13	Treadmill				5.5 →5.5 (0)	x
De Groot et al., 2008 [6]	x	14	Testing on ergometer, Practice on treadmill	1470	1.39	20% POpeak	4.32 → 5.65 (31)	0.413
	x					40% POpeak	6.41 → 8.33 (30)	0.662
De Groot et al., 2002 [7]	x	10	Ergometer	72	1.11	0.15 W/kg	5.54 → 5.87 (6)	x
	x					0.25 W/kg	7.45 →8.11 (9)	x
Leving et al., 2015 [8]	Feedback	17	Treadmill	80	1.11	0.24 W/kg	5.25 → 5.23 (-0.4)	<0.001
	Natural learning	15	Treadmill		1.11	0.25 W/kg	5.71 → 6.67 (17)	0.167
de Groot et al., 2013 [24]	Training at 30%HRR	9	Testing on ergometer, Practice on treadmill	630	1.39	20% POpeak	5.36 → 6.27 (17)	0.197
						40% POpeak	7.25 → 9.0 (24)	0.684
	Training at 70%HRR	13	Testing on ergometer, Practice on treadmill	630	1.39	20% POpeak	6.25 → 7.36 (18)	0.371
						40% POpeak	8.33 → 9.85 (18)	0.220

Abbreviations: AB, able-bodied; HRR, heart rate reserve; POpeak, estimated peak power output. [a] Value at the pre-test → value at the post-test (relative change over time). [b] Relative change in mechanical efficiency (%) was compared pairwise between the present and historical studies using independent samples t-test. 'x' indicates that data from a given study were not available.

Next to the improvement in mechanical efficiency in the present study, also a decrease in the heart rate suggests that propulsion became less strenuous for the participants. Heart rate at the post-test was on average almost 23 beats per minute slower in the variable practice group than at the pre-test. The time x group interaction effect was also significant indicating that the decrease in heart in variable practice group was larger than in the control group. As mentioned above, it should be considered whether the reduction in heart rate could solely be attributed to changes in motor control, or whether cardio-respiratory changes have also taken place because of practice. Especially that practice

sessions took place in an entertaining and social setting which could have increased participant's motivation, involvement in practice and in turn, the physiological adaptation.

However, evidence-based recommendation of the American College of Sports Medicine states (ACSM) that 150 min of moderate exercise, or 75 min of vigorous exercise per week are necessary to improve cardiorespiratory fitness [25]. Considering the moderate intensity and intermittent character of wheelchair basketball [26-28], in order to implement the ACSM guidelines and maintain the cardiorespiratory and muscular fitness, a training frequency of 3–5 sessions per week with a duration of 20–60 min each would be required [26]. Participants in the variable practice group did not meet this exercise frequency requirement, suggesting that possible improvements in the cardio-respiratory parameters might not have been of a large influence on the mechanical efficiency. Moreover, considering the intermittent character, moderate intensity and duration of the present practice it is rather unlikely that muscle hypertrophy took place [29,30].

A more logical assumption that could account for the improvement in mechanical efficiency in the present study is the improvement in neuromuscular coordination. Neural facilitation is thought to manifest itself already in the early stages of training [29-31]. Neuromuscular adaptation results from changes in coordination and task-specific learning that occur during learning of novel skills [29]. It can, therefore, be that if certain practice facilitates motor learning, it may also influence the rate of neuromuscular adaptation [32,33]. The present study shows that variable practice facilitates motor learning, which perhaps may have in turn influenced neuromuscular adaptation. This may have resulted in better motor coordination and a more synchronized movement, which led to a lower energy cost of wheelchair propulsion at the post-test.

Propulsion Technique

Participants in both groups improved the propulsion technique between the pre- and post-test to a similar extent. In Table 5 the change in propulsion technique observed in the present study is compared with able-bodied participant studies concerning steady-state wheelchair propulsion on the treadmill or wheelchair ergometer. The baseline values of all propulsion technique variables in both groups were similar to those found in other studies [4,6-8]. The direction of improvement of frequency, contact angle, braking torque and positive work is in line with natural learning studies [4,6-8]. The relative improvement is smaller in the variable practice group compared to the natural learning studies for push frequency (12% vs 22-33% respectively) and positive work (8% vs. 24-78%) and similar for contact angle (16% vs. 12-41%) and braking torque (59% vs. 48-66%). The relative improvement is smaller in the present study compared to the feedback-induced variability experiment for contact angle (16% vs 33% respectively) and push frequency (12% vs. 33%) and larger for braking torque (59% vs 13%) [8].

The direction of change in max torque in both groups in the present study was opposite to the 80-min experiment of Vegter et al [5]. Max torque decreased (although not significantly) in the present study and increased significantly in the experiment of Vegter

et al [5]. Considering that baseline values of max torque were very similar, the difference at post-test may be caused by the lower push frequency in the study of Vegter (52 (Vegter et al.) vs. 58 (variable practice group) and 60 (control group) pushes/min), since the value of contact angle at the post-test was also very similar between the studies.

Improvement in the propulsion technique in the present study was rather moderate when compared to the relatively large improvement in the mechanical efficiency. A natural learning study suggested that improvement in mechanical efficiency is related to the improvement in the propulsion technique [4]. The relatively large improvement in the mechanical efficiency in the present study cannot completely be accounted for by the improvement in propulsion technique as captured on the level of force production on the handrim, since it was quite small compared to other studies. This suggests that, next to the currently investigated propulsion technique variables, other factors contributed to the lower energy expenditure. The upper body has redundant degrees of freedom to perform the propulsion task. The applied force comes from a combination of forces generated by the trunk, shoulder, elbow and wrist muscles. It was shown that on the short term participants transfer force production away from the elbow towards the shoulder [34]. Future studies might look at the effect of motor learning not only on measurement wheel based propulsion technique measures, but also incorporate the upper body kinematics to better understand propulsion technique changes.

Table 5. The results of the present and other studies concerning the change in propulsion technique variables resulting from wheelchair practice in able-bodied individuals.

Study	Group	Frequency (push/min)[a]	Contact Angle (degrees)[a]	Braking Torque (Nm)[a]	Max Torque (Nm)[a]	Positive Work (J)[a]
Present study	Variable practice	65.4 → 57.8 (12)	67 → 77.6 (16)	-1.1 → -0.5 (59)	12.5 --> 11.6 (7)	9.0 → 9.7 (8)
Present study	Control	72.3 → 60.0 (17)	57.7 → 70.3 (21)	-1.0 → -0.7 (30)	13.2 → 12.3 (7)	8.3 → 9.0 (8)
Vegter et al., 2014 [5]	Fast improvers	68 → 49 (28)	61 → 76.2 (25)	x	12.6 --> 13.0 (-3)	8.3 → 10.8 (31)
	Slow improvers	67 → 52 (22)	62.5 → 69.7 (12)	x	12.0--> 12.8 (-7)	8.1 → 10.0(24)
De Groot et al., 2008 [6]	x	x	57.6 → 81.2 (41)	x	x	12.7 → 22.6 (78)
	x	x	66.2 → 88.5 (34)	x	x	23.8 → 36.2 (52)
De Groot et al., 2002 [7]	X	61.0 → 41.7 (32)	x	x	x	13.9 → 21.6 (56)
	x	62.8 → 46.4 (26)	x	-5.6 → -2.9 (48)	x	22.6 → 32.7 (45)
Leving et al., 2015 [8]	Feedback	62.1 → 41.5 (33)	66.3 → 88 (33)	-0.8 → -0.7 (13)	x	x
	Natural learning	71.3 → 52.5 (26)	60 → 77.5 (29)	-0.6 → -0.2 (66)	x	x

[a] Value at the pre-test → value at the post-test (relative change over time)

Another possibly not captured change is the participant's control over the wheelchair. The wheelchair skill tasks all showed clear improvements in performance times suggesting an improved maneuverability and control. Possibly this translated to less speed fluctuations and left-right steering correction on the treadmill, subsequently leading to less energy losses and thus a higher mechanical efficiency. The left-right steering and subsequently medio-lateral position on the treadmill has, to our knowledge, not been investigated yet in wheelchair propulsion. It could potentially be evaluated in future studies as an outcome measure of the motor learning process. The left-right steering could be seen as an equivalent of medio-lateral displacement during gait, a measure used to describe dynamic balance and ability to manifest obstacles [35-38]. Investigating it could be accomplished with the use of motion capture systems.

Variability

Both, present study protocol and natural learning protocols [4,6-8,24] led to improvement in mechanical efficiency and propulsion technique. The main difference between them is the course of variability, which increased in the present study and either did not change or decreased in the natural learning protocols [5,8], including the current control group. It was a surprising finding since wheelchair propulsion on a treadmill does not particularly require variability. It is not certain whether the level of variability reached in the current study is a desirable feature. From the motor exploration point of view, once a solution for a task has been found, high variability becomes superfluous. However variability may have a different role in developing a novel skill (increasing motor exploration) and different role in a formed, skilled behavior (facilitating flexibility in dealing with perturbations). Change in variability in the present study is certainly worth mentioning since the direction of change is opposite to the one during natural learning [5,8]. However, whether increasing and maintaining variability should be a training goal for any motor skill, including wheelchair propulsion, is a subject for future research.

Increase in variability in the present study was concomitant with the improvement in mechanical efficiency. This suggests that the conclusion made by Leving et al. [8] that higher variability requires more energy and therefore may disturb the energy efficiency optimization may be true for feedback-induced variability but is not in this study. The present study showed that an increase in variability can be achieved by offering variable uninstructed practice and that this increase seems to benefit the mechanical efficiency.

Wheelchair skill practice

Participants in the present study showed improvement on all five wheelchair skill tasks. Inspection of Fig.7 allows to see that most rapid improvement can be seen between the first and third practice session. After the fourth session, performance improvement are smaller. This seems to suggest a large short-term improvement, which is followed by some smaller long-term improvement. Most important selection criterion for the wheelchair skill tasks was that they stimulated variability during practice. This goal was achieved since participants increased the variability at the post-test. However, the improvement over the practice sessions is important in itself since good performance

on wheelchair skills allows the wheelchair users to improve their life-space mobility and participation [39-43]. Moreover, it was shown that the tasks similar to the ones used here, involving backward and forward propulsion, maneuvering and sprint, can be used to assess the degree of wheelchair skill proficiency necessary for every day functioning, also during and after rehabilitation [17-20].

Advantages and limitations

The advantage of the present study is its ecological validity and good feasibility. Facilities and equipment used during the practice sessions are present in many rehabilitation centers. Additionally, the used protocol allows training relatively large groups of participants during one hour practice sessions with minimal staff supervision. This decreases the financial, time and transportation constraints, which are commonly mentioned as barriers to physical activity in individuals with spinal cord injury [44-50].

It should be noted that while in other wheelchair practice studies, the training was performed in the same or similar conditions as the testing conditions, the practice sessions in the present study were performed in a very different setting. The fact that participants were not used to propelling on the treadmill may have influenced their energy efficiency, which may have potentially been even higher. The present study showed that propulsion technique, efficiency and variability trained in an ecologically valid setting transferred to the steady-state treadmill propulsion setting.

We think that choosing a no practice group in combination with the statistical comparison with previous literature on the influence of less variable practice on the outcomes of motor learning provides sufficient evidence in favor of variable practice in wheelchair propulsion and points to possible directions in future research.The inclusion of able-bodied subjects in this study may be seen as limitation. Selecting able-bodied participants with similar age and lack of wheelchair experience eliminates potential confounders, which are often present in the wheelchair-dependent population: e.g. lack of sitting balance, presence of pain or secondary medical complications. The inclusion of able-bodied participants ensures a homogenous group, which allows to more accurately isolate the effect of variable practice on the outcomes of motor learning process. Translation of results from this study, for implementation in clinical rehabilitation, should be done with caution. It may be that actual wheelchair users have an inhibited trunk or upper extremity function or sitting balance, which in turn could not only decrease the overall range of motion but also influence the motor variability.

The experimental wheelchair for the pre- and the post-tests, as well as the basketball wheelchairs used during the practice sessions in the variable practice group did not allow any correction for individual height or width. This could be seen as a limitation of this study. However, importantly all dimensions within the subjects were constant over the pre- and the post-test.

The exact dose of variability for each participant during the practice sessions is unknown. This is a limitation of the current study, since some participants may have been more active or more variable than others. However, when looking at the intra-individual change between the pre and the post-test in the variable practice group, we could see that all participants improved their mechanical efficiency. This would suggest that the level of activity and variability during the practice sessions was comparable between them since we could not see differences in the outcome measures. Furthermore, a researcher was always present during the practice sessions and there were no striking differences in the activity or propulsion strategy between the participants. Future studies on motor learning could benefit from task-specific activity monitors and more detailed information on wheelchair speed (preferably power output) and physical strain (i.e. heart rate) during the practice sessions.

Future research

A recent study showed that positive changes in mechanical efficiency and propulsion technique during very early stages of motor learning process are not necessarily accompanied by a decrease in shoulder load, which gives an important indication about the injury risk [34]. Other studies point out that there may be a relationship between variability and shoulder pain [51,52]. Future studies should evaluate whether the increase in variability, next to enhancing the motor learning process, decreases the shoulder load during manual wheelchair propulsion.

The present study provides support for the suggestion by Ranganathan and Newell [53] that various kinds of variability may influence the outcomes of motor learning process differently. Variability introduced in the present study, contrary to the visual feedback-induced variability [8], allowed for improvements in mechanical efficiency. Future research should attempt to explore the differences between various kinds of variability and their influence on the motor learning process. Moreover translation of the motor learning principles to clinical rehabilitation is important, since all novel wheelchair users go through a process of motor learning where most rapid changes happen at the beginning. Better monitoring of this process and development of evidence-based protocols are expected to positively influence the outcomes of rehabilitation.

CONCLUSIONS

The present study showed that encouraging intrinsic variability, by introducing variable practice, resulted in an increase in mechanical efficiency and increased variability compared to a control group. Large relative improvement in mechanical efficiency was concomitant with moderate improvement in the propulsion technique suggesting that factors other than propulsion technique as measured by the instrumented wheel contributed to the lower energy expenditure. It may be that variable practice stimulated variation of propulsion technique and facilitated the exploitation of the dynamics of the task and improved coordination and/or maneuverability. This may

have contributed to more efficient and thus less straining propulsion. Future research should determine whether changes in variability and the motor learning process found in the present study influence the load on the shoulder and thus injury risk resulting from wheelchair propulsion.

LIST OF ABBREVIATIONS

VO2 – Oxygen uptake

RER – Respiratory Exchange Ratio

CPET - Cardio-Pulmonary Exercise Testing

ME – Mechanical Efficiency

PO – Power Output

E – Energy expenditure

T- Torque

Av – Angular velocity

ACSM - American College of Sports Medicine

DECLARATIONS

Ethics approval and consent to participate

Following detailed verbal and written information about the character of the study, all participants signed an informed consent before the onset of the study. The protocol of the study was approved by the Local Ethics Committee (Nr. ECB/2014.12.18_2), of the Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, The Netherlands.

Availability of data and material

All data generated or analyzed during this study are included in this published article and its supplementary information files.

Competing interests

The authors declare that they have no competing interest.

Funding

There are no founding sources to declare.

Authors' contributions

MTL and RJKV were involved in the following activities: research design, execution of the experiment, data analysis, data interpretation and writing the manuscript. SG and LHVW contributed to the following activities: conception and organization of the study, analysis and interpretation of the data and revision of the manuscript. All authors read and approved the manuscript.

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ADDITIONAL FILES

Additional files are available on the website of the publisher.

Additional file 1. The specifications of wheelchair skill task: slalom.

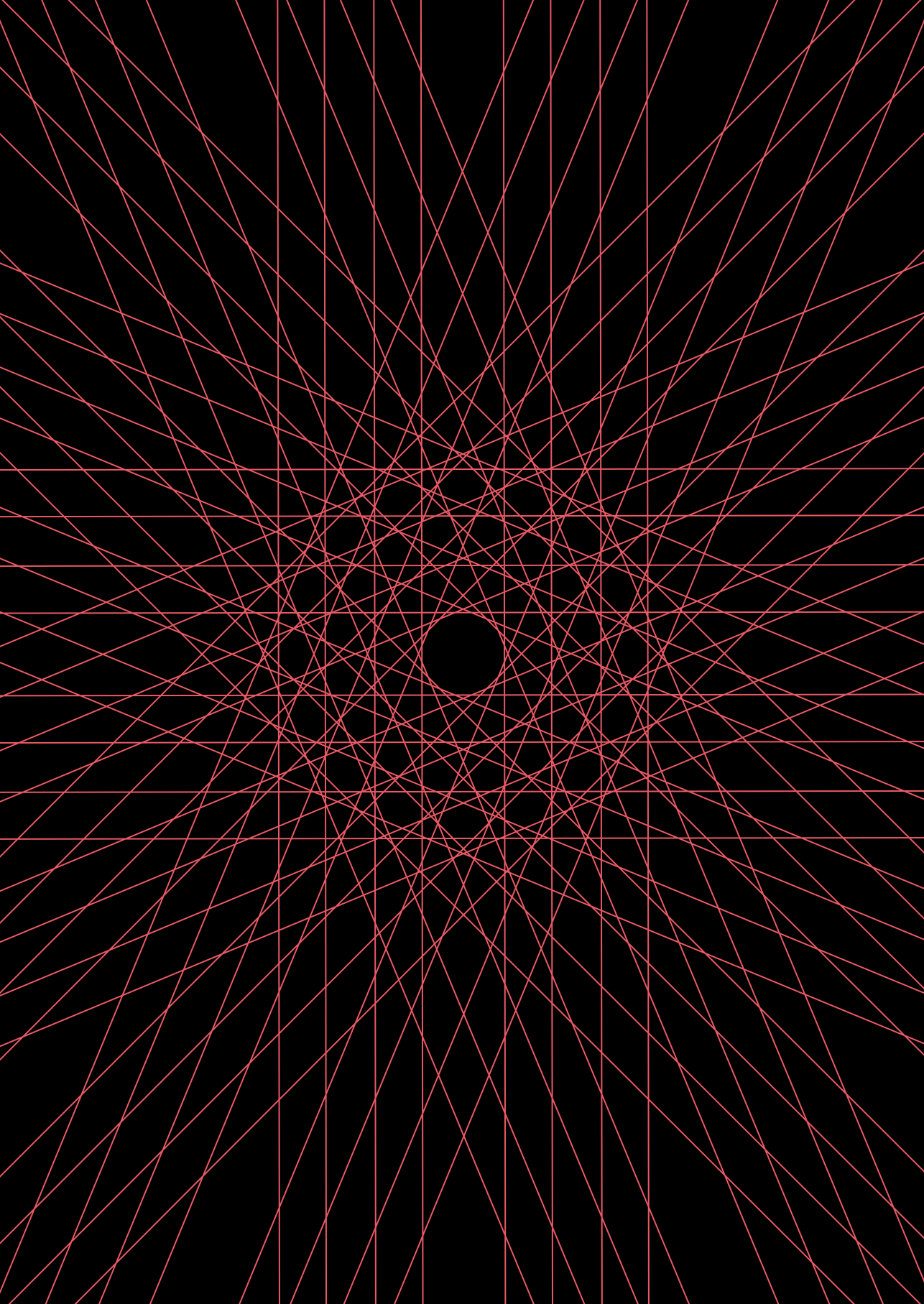
Additional file 2. The specifications of wheelchair skill task: semicircle.

Additional file 3. The specifications of wheelchair skill task: figure of eight.

Additional file 4. The specifications of wheelchair skill task: square.

Additional file 5. The specifications of wheelchair skill task: 15-m sprint.

Additional file 6. Complete data set.



4

CHANGES IN PROPULSION TECHNIQUE AND SHOULDER COMPLEX LOADING FOLLOWING LOW-INTENSITY WHEELCHAIR PRACTICE IN NOVICES

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ABSTRACT

Background: Up to 80% of wheelchair users are affected by shoulder pain. The Clinical Practice Guidelines for preservation of upper limb function following spinal cord injury suggest that using a proper wheelchair propulsion technique could minimize the shoulder injury risk. Yet, the exact relationship between the wheelchair propulsion technique and shoulder load is not well understood.

Objective: This study aimed to examine the changes in shoulder loading accompanying the typical changes in propulsion technique following 80 min of low-intensity wheelchair practice distributed over 3 weeks.

Methods: Seven able-bodied participants performed the pre- and the post-test and 56 min of visual feedback-based low-intensity wheelchair propulsion practice. Kinematics and kinetics of propulsion technique were recorded during the pre- and the post-test. A musculoskeletal model was used to calculate muscle force and glenohumeral reaction force.

Results: Participants decreased push frequency (51→36 pushes/min, p=0.04) and increased contact angle (68→94°, p=0.02) between the pre- and the post-test. The excursion of the upper arm increased, approaching significance (297→342 mm, p=0.06). Range of motion of the hand, trunk and shoulder remained unchanged. The mean glenohumeral reaction force per cycle decreased by 13%, approaching significance (268→232 N, p=0.06).

Conclusions: Despite homogenous changes in propulsion technique, the kinematic solution to the task varied among the participants. Participants exhibited two glenohumeral reaction force distribution patterns: 1) Two individuals developed high force at the onset of the push, leading to increased peak and mean glenohumeral forces 2) Five individuals distributed the force more evenly over the cycle, lowering both peak and mean glenohumeral forces.

INTRODUCTION

People who lose lower-limb function need to rely on their arms to maintain mobility and learn to propel a wheelchair in the early stages of rehabilitation. The anatomy of the upper-extremities, specifically the relatively small muscle mass and high glenohumeral joint mobility, makes the shoulder complex vulnerable to overuse injuries. Because of the low physical capacity of persons at the beginning of rehabilitation and the highly straining character of wheelchair propulsion, shoulder pain frequently develops at this stage [1]. Among the individuals who developed shoulder complaints during early rehabilitation, only 20% will show any improvement over time [2].

The Clinical Practice Guidelines for preservation of upper limb function following spinal cord injury describe various ways to minimize the shoulder injury risk, such as: proper wheelchair configuration or assistance during transfers but also using a proper wheelchair propulsion technique [3]. Shoulder load and propulsion technique are thought to be linked as wheelchair propulsion is a highly repetitive task, where the same motion is performed approx. 2700 times per day [1,4]. This is especially evident in novice wheelchair users as their propulsion is characterized by a very high frequency, high peak forces and small contact angle of the hand on the handrim [5-7]. In contrast, the advice of The Clinical Practice Guidelines is to minimize the peak forces and push frequency during propulsion and maximize the contact angle of the hand with the handrim.

We know from a number of studies that as natural motor learning progresses wheelchair users naturally improve their technique i.e. lower the push frequency and increase the contact angle [5,6,8-11]. Even though the Clinical Practice Guideline states that this should be a more optimal technique, experimental evidence supporting this advice is missing. It is unclear how the changes in propulsion technique taking place during practice relate to the mean and peak loads on the shoulder. That is because the propulsion technique as defined in this study, includes spatio-temporal variables which are calculated based on the kinetic data measured on the level of the forces applied to the handrim by the user. To gain understanding of what the association between the propulsion technique and the local strain on the shoulder complex is, a combination of modeling, kinematics and kinetics needs to be implemented.

To do that, we will use data from a previously published study, which found typical improvements in propulsion technique following low-intensity wheelchair practice, specifically a large increase in contact angle and decrease in push frequency [6]. The goal of the current study will be to investigate the association between the typical changes in propulsion technique and the shoulder load. The effect of intervention will be omitted as it was already described [6]. The focus will be laid on the description of the co-emergence of the typical improvements in propulsion technique observed during a learning process and changes in the local load on the shoulder. So far, this has only been investigated in the very initial stages of practice. Vegter et al. [5] found a reduced push frequency and larger contact angle following a 12 min practice period. Interestingly, the improvements in the propulsion technique were concomitant with higher shoulder load expressed as an

increase in relative muscle forces, especially within the rotator cuff muscles and higher peak and mean glenohumeral reaction forces [5]. The effects of practice on the local strain on the shoulder exceeding a 12-min period are unknown.

The goal of this study is to describe the changes in shoulder load and kinematic characteristics of movement taking place after the 80-min low-intensity wheelchair practice. To be able to exclude the effect of experience and secondary conditions on the outcomes, a group of able-bodied participants with no wheelchair experience was selected for this study. We hypothesize that a decrease in push frequency and increase in contact angle will contribute to a decrease in mean glenohumeral reaction force and individual muscle forces. Identifying properties of the propulsion technique that are beneficial for the shoulders could be used in the future to propose evidence-based interventions to target early prevention of shoulder pain in manual wheelchair users.

MATERIALS AND METHODS

Participants and ethics statement

A convenience sample consisting of seven able-bodied men (Age median= 23 years, interquartile range (IQR) =5 years; Body mass median= 76 kg, IQR=19 kg) participated in the study. This is a subsample of 17 participants who were included in the previous study [6]. Inclusion of only 7 participants from the original sample is a consequence of the technical difficulties during the very complex data collection process. All participants provided written informed consent following detailed information about the character of the study. The protocol of the study was approved by the Local Ethics Committee, of the Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, The Netherlands. Individuals were eligible for inclusion if they had no previous experience with wheelchair propulsion and no severe musculoskeletal complaints, especially within the upper extremities and the trunk.

Study design

All participants received 80-min of handrim wheelchair practice at a submaximal intensity distributed across 3 weeks (Fig 1). The 80-min experiment consisted of a pre- and post-test (3x4 min exercise blocks each with 2 min break between the blocks) and 7 practice sessions (2x4 min exercise blocks each with 2 min break between the blocks) between the pre- and the post-test. During the pre- and the post-test participants received no feedback or instruction. During the 7 practice sessions participants received real-time visual feedback on their propulsion technique. At each session, a different propulsion technique variable was presented. Each variable was presented only once, meaning that there were 7 unique propulsion technique variables: push frequency, braking moment, contact angle, peak force, push distance, smoothness and fraction effective force (Table 1). Participants were instructed to be as variable as possible (applying stroke to stroke variation in a given propulsion technique variable e.g. alternating short and long pushes or applying variable peak forces) in the first 4 min block of practice and to optimize

the variable in the prescribed direction in the second 4 min block. The name and the description of the practiced variable were not provided to encourage motor exploration. Therefore the name of the variable on the screen was covered. The last minute from the pre- and last minute from the post-test were compared to determine the change in propulsion technique and shoulder load following low-intensity practice. The last minute from the pre-test was chosen because changes in the propulsion technique and shoulder load for the first 12 minutes of practice in able-bodied individuals have been documented in a previous study [5].

Experimental setup

The 80 min experiment was performed by each participant in the same experimental handrim wheelchair with 24 inch wheels, 5° camber, seat height of 0.54 m and seat width of 0.45 m (Double Performance BV, Gouda,The Netherlands) placed on a level motor-driven treadmill (length x width=2.4 m x 1.2 m; Forcelink b.v, Culemborg The Netherlands) (Fig 2). Tire pressure of the rear wheels was set at 600 kPa during all practice and test sessions. Treadmill velocity of 1.11 m/s and power output of 0.24 W/kg body mass were maintained throughout the experiment. Required power output was imposed using a pulley system. The mass of the pulley was determined individually for each participant based on the results of the wheelchair drag test which took place prior to the experiment [12,13].

Propulsion technique and kinematics of wheelchair propulsion

Kinetics and kinematics of wheelchair propulsion were recorded continuously during the pre- and the post-test. The data of the last minute of the pre-test was compared with the data of the last minute of the post-test to examine the changes in shoulder loading following the low-intensity wheelchair propulsion practice.

Propulsion technique

Software of the instrumented 24″ Optipush wheel (MAX Mobility, LLC, Antioch, TN, USA), which measures 3D forces and torques applied to the handrim, was used to gather data from the right wheel and to provide the real-time visual feedback. The measurement frequency of Optipush wheel was set at 200 Hz. The output from the measurement wheels was analyzed using custom-written Matlab algorithms [9] (Table 1).

Kinematics

Kinematic data were collected using an optoelectronic camera system (Optotrak, Northern Digital, Waterloo, Canada) at 100Hz with technical cluster markers attached to the right side of the participant's body and to the rigid frame of the wheelchair (Fig 3). The location of anatomical landmarks was determined in relation to their technical clusters. Based on this calibration procedure, the positions of the anatomical landmarks were reconstructed for each participant (Fig 3) and used to create the joint coordinate systems of the shoulder, elbow and wrist [14]. The location of the rotation center of the glenohumeral joint was calculated using the regression method proposed by Meskers et al. [15].

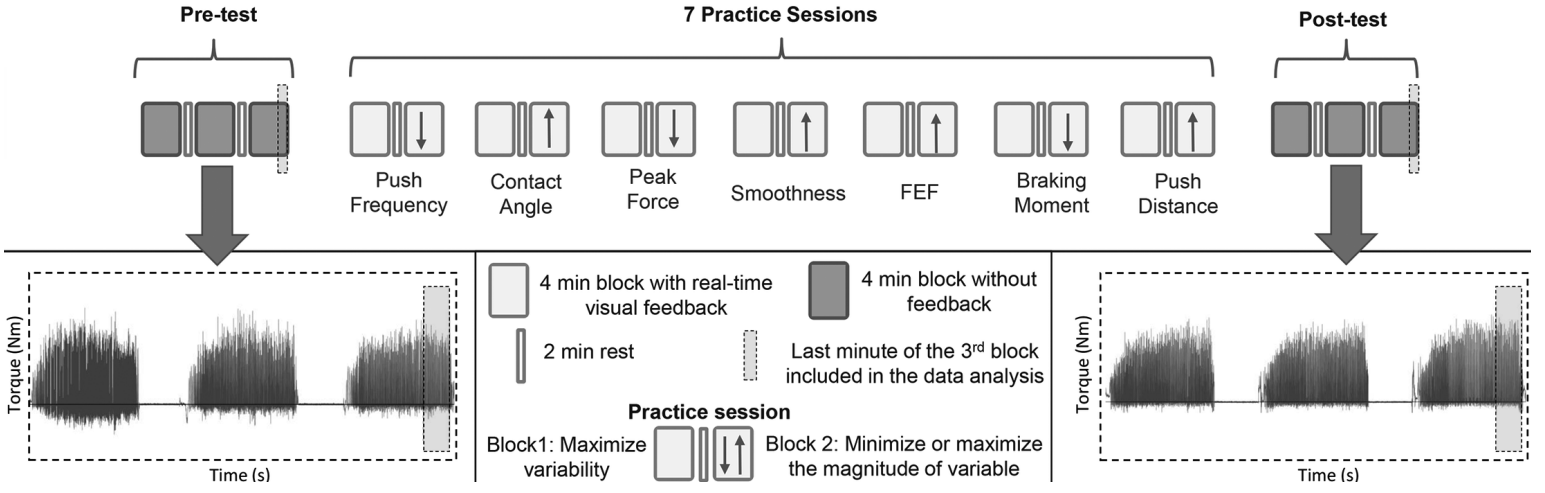

Figure 1. All participants (N=7) performed the pre- and the post-test and seven practice sessions in between. The pre-test and the post-test consisted of 3 blocks (4 min each) of propulsion during which participants received no feedback and the practice sessions consisted of 2 blocks (4 min each) during which real-time visual feedback on a specific propulsion technique variable was given.

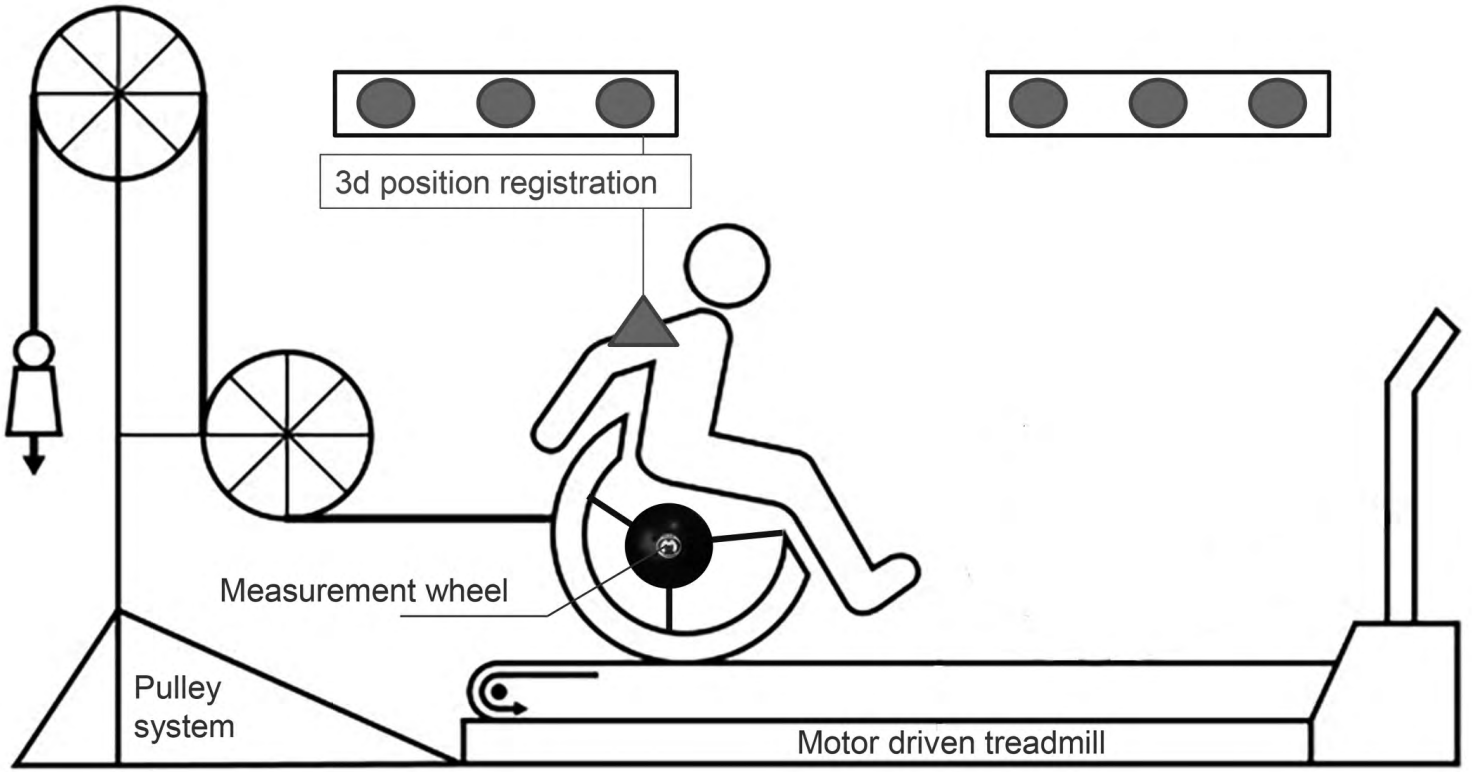

Figure 2. Experimental setup. Participants propelled a wheelchair on a motor-driven treadmill during all testing and practice sessions at a constant velocity of 1.11 m/s and relative power output of 0.24 W/kg. Power output was imposed using a pulley system. Kinetics and kinematics of propulsion were recorded during the pre- and the post-test. Modified figure from Vegter et al [5].

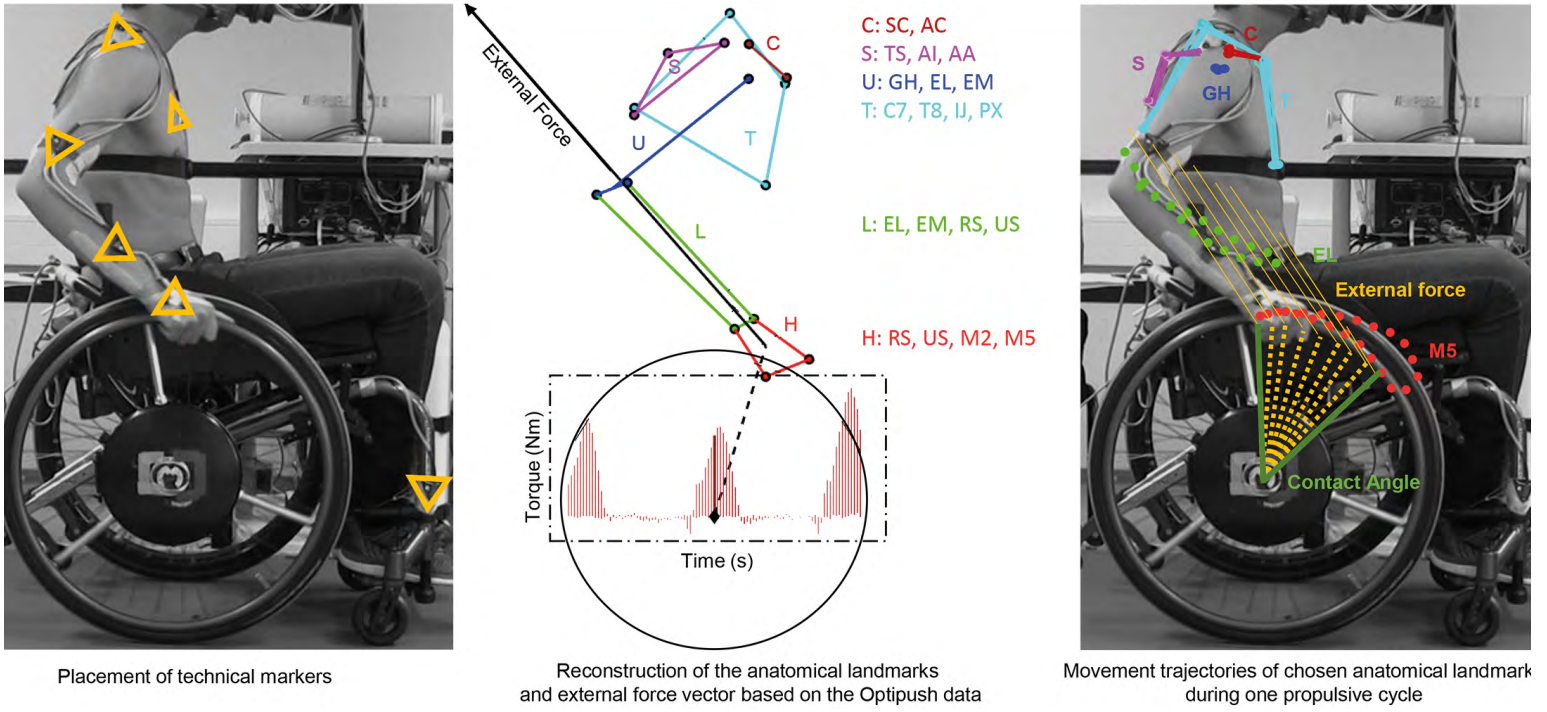

Figure 3. Typical placement of the technical markers (left panel), reconstruction of the anatomical landmarks (middle) and movement trajectories of the scapula, trunk, clavicle, EM and M5 anatomical landmarks combined with the external force vector exerted during one exemplary propulsive cycle (right panel).

Abbreviations: M5, Fifth metacarpal; EM, Medial epicondyle of humerus; GH, Glenohumeral joint; IJ, Suprasternal notch; C, Clavicle; S, Scapula; U, Upper arm; T, Trunk; L, Lower arm; H, Hand; SC, sternoclavicular joint; AC, acromioclavicular joint; TS, trigonum spinae scapulae; AI, Angulus Inferior Scapulae; EL, Lateralepicondyle of humerus; C7, Processus spinosus of 7th cervical vertebra, T8, Processus spinosus of 8th thoracic vertebra; PX, Processus xiphoideus; RS, Radial styloid; US, Ulnar styloid; M2, Second metacarpal

Table 1. Propulsion technique variables.

Propulsion variable (unit)	Description	Equation
Push frequency (push/min)	The number of pushes performed during one minute	$N_{pushes}/\Delta t$
Braking moment (Nm)	The braking moment applied to the handrim with each push. The sum of braking moment exerted on the handrim during coupling and decoupling of the hand	$\Sigma_{end}(i)_{:start}(i+1)\ (Tz \cdot \Delta\emptyset)$
Contact Angle (°)	The angle measured along the handrim, where subject's hand maintained contact with the handrim during each push	$\emptyset_{end}(i)_\emptyset_{start}(i)$
Smoothness	The ratio of mean to peak force per push	$Mean_{(start:end)}\ (Fx^2+ Fy^2+ Fz^2)^{0,5}/Max_{(start:end)}\ (Fx_2+ Fy_2+ Fz_2)^{0,5}$
FEF (%)	The ratio of effective to total force that was applied to the handrim during one push	$Mean_{(start:end)}((Tz/r)/((Fx^2+ Fy^2+Fz^2)^{0,5}))\cdot 100\%$
Push distance (m)	The distance covered with each push	$Mean_{(start:end)}V\cdot\Delta t$
Peak force (N)	3d peak force applied to the handrim during one push	$Max_{(start:end)}\ (Fx^2+ Fy^2+ Fz^2)^{0,5}$
Positive work per push (J)	The power integrated over the Contact angle of the push.	$\sum start : end(Tz * \Delta\emptyset)$
GH start position (mm)	Horizontal position of the glenohumeral joint (GHx) at the start of the push with respect to the wheel-axle (WAx)	$GHx_{start}(i) - WAx_{start}(i)$
AL displacement (mm)	The position difference between AL at the start and end of the push phase. AL represents M5, EM, GH, IJ	$AL_{end}(i) - AL_{start}(i)$

First seven variables were used in a form of visual feedback during the practice sessions. Frequency, contact angle, peak force, positive work per push and displacement of anatomical landmarks were used as outcome variables to compare the change in shoulder load between the pre- and the post-test. All variables except cadence were calculated as an average value of all pushes performed during the last minute of the last practice block. Equations from Vegter et al.[9]; table from Leving et al.[6]

Abbreviations: t, time(s); start(i), start of the current push (sample); end(i), end of the current push (sample); Tz, torque around wheel axle (Nm); Ø, angle (rad); Fx, Fy and Fz, force components (N); r, wheel radius (m); V, velocity (m/s); AL, Anatomical Landmark; M5, Fifth metacarpal; EM, Medial epicondyle of humerus; GH, Glenohumeral joint; IJ, Suprasternal notch

Delft Shoulder and Elbow Model

To evaluate the load on the shoulder complex during wheelchair propulsion, inverse dynamics can be used as input for a musculoskeletal model to estimate joint reaction forces and individual muscle force. The model used in this study was the Delft Shoulder and Elbow Model (DSEM). The DSEM is a finite-element 3D inverse-dynamics model consisting of 22 muscles (31 muscle parts), divided into 155 muscle elements [16]. It includes all bones and joints of the shoulder and has 17 degrees of freedom of which six for the thorax are the moving base. Bones are modelled as rigid bodies, muscles as active trusses and ligaments as passive trusses. Information concerning muscle architecture parameters was obtained from cadaver studies and was therefore not individualized for each participant [17,18]. This model was used previously to estimate the shoulder load during handrim wheelchair propulsion [5,19-21]. Kinematic input for the model consisted of the orientations of the humerus, scapula, thorax, forearm and hand and

the position of the jugular notch (incisura jugularis). Kinetic input consisted of the 3D external forces applied by the hand of the user to the handrim. Based on the recorded motions and external loads, the muscle and joint contact forces are calculated as model outputs through an inverse-dynamics analysis (Table 2). DSEM allows two optimization methods: static and dynamic optimization [22]. In this study, dynamic optimization was used since it takes the dynamics of segments and muscles in account. An energy-related cost function, with the objective to minimize the summed energy consumption, was used to estimate the individual muscle forces: $\sum_{i=1}^{n} \dot{E}mi = \sum_{i=1}^{n} \dot{E}fi + \dot{E}ai$ [23]. In this function the muscle energy consumption (E_m), is based on the two major energy-consuming processes in the muscle: detachment of cross bridges (E_f) and re-uptake of calcium (E_a). The relative muscle forces were calculated to be able to compare the contributions between muscles taking their physiological cross-sectional area into account. Relative muscle forces were calculated as a percentage of the maximum force based on a force per physiological cross-sectional area of 100 N/cm^2 [17]. Five consecutive pushes of the final minute of the pre- and the post-test were inserted in the model. The selected pushes were assumed to be representative of the pushes within the given minute. Therefore, they were chosen based on their mean power output per push, which could not differ more than 10% from the mean power output calculated for all pushes within the last minute of propulsion. The outcome measures are calculated either per push or per cycle. Propulsive cycle is defined in accordance with previous literature and consists of the push and the recovery phase [24]. The push begins with the initial hand contact and ends with the release of the hand from the handrim. The recovery phase is the period between the two consecutive pushes.

Table 2. DSEM outcome variables.

Variable (unit)	Description
GH mean Net Moment/Push (Nm)	The mean external net moment of the reaction force around the glenohumeral joint
GH peak Net Moment/Push (Nm)	The peak external net moment of the reaction force around the glenohumeral joint
HU mean Net Moment/Push (Nm)	The mean external net moment of the reaction force around the Humeroulnar joint
HU peak Net Moment/Push (Nm)	The peak external net moment of the reaction force around the Humeroulnar joint
Muscle Power total mean/Push (W)[a]	The mean sum of all muscle powers during the push
Muscle Power total peak/Push (W)	The peak sum of all muscle powers during the push
Muscle Power total mean/Cycle (W)	The mean muscle power performed per cycle
GH Reaction force mean/Push (N)	The mean glenohumeral reaction force per push
GH Reaction force peak/Push (N)	The peak glenohumeral reaction force per push
GH Reaction force mean/Cycle (N)	The mean glenohumeral reaction force per cycle

Table from Vegter et al.[5]. [a] Muscle power is calculated per a contractile element by multiplying the estimated force of each element with its shortening velocity.

Statistical analysis

Based on the number of participants N=7, non-parametric testing was chosen. Unless reported otherwise a median and interquartile (IQR) range are reported to describe the outcomes. To evaluate the change in kinetics, kinematics and shoulder load between the last block of the pre-test and the last block of the post-test the Wilcoxon Signed

Rank test was used. Significance level of $p<0.05$ was used. The variables compared with the Wilcoxon Signed Rank test were: propulsion technique variables (frequency, contact angle, peak force and net work per push), 3D displacement of anatomical landmarks, mean and peak net moments per push around the glenohumeral and humeroulnar joints and mean and peak muscle powers and glenohumeral joint reaction forces. The effect size of the Wilcoxon Signed Rank test was calculated using the following formula $r = \frac{Z}{\sqrt{N}}$, where Z is the test statistic and N, the total number of observations [25]. Effect sizes >0.1 are considered small, >0.3 moderate and >0.5 are considered large [26].

RESULTS

All participants (N=7) completed all practice and test sessions. The relative power output did not change significantly between the pre- and the post-test (0.249 W/kg → 0.234 W/kg, p=0.18). Results of all statistical analyses are presented in Table 3.

Table 3. Outcomes (Median (IQR)) for all participants (N=7) for the last minute of the third practice block of the pre- and the post-test and outcomes of statistical analyses (Wilcoxon Signed Rank Test: $p<0.05$) including the effect size.

	Median (Interquartile Range)				
	PRE	POST	p	Relative	Effect
Kinetics			value	change	size
Relative Power Output (W/kg)	0.249 (0.01)	0.234 (0.03)	0.18	6 %	-0.36
Frequency (push/min)	51 (27)	36 (22)	0.04	29 %	-0.54
Contact Angle (°)	68 (14)	94 (24)	0.02	38 %	-0.63
Positive work per push (J)	12 (4)	14 (5)	0.06	17 %	-0.50
Peak Force (N)	73 (19)	82 (20)	0.40	12 %	-0.23
Kinematics					
M5 displacement (mm)[a]	347 (134)	350 (80)	0.24	1 %	-0.32
EM displacement (mm)[a]	297 (64)	342 (56)	0.06	15 %	-0.50
GH displacement (mm)[a]	37 (24)	27 (66)	0.40	27 %	-0.23
IJ displacement (mm)[a]	27 (20)	31 (30)	1.00	15 %	0
GH start position (mm)	-62 (51)	-46 (100)	0.74	26 %	-0.09
Net moments per push					
GH mean Net Moment (Nm)	14 (5)	16 (4)	0.40	14 %	-0.23
GH peak Net Moment (Nm)	31 (13)	33 (6)	0.61	6 %	-0.14
HU mean Net Moment (Nm)	4 (4)	1 (5)	0.13	75 %	-0.41
HU peak Net Moment (Nm)	16 (8)	15 (2)	0.61	6 %	-0.14
Model results					
Muscle power total mean per push (W)	62 (15)	56 (44)	0.87	10 %	-0.05
Muscle power total peak per push (W)	138 (140)	107 (158)	0.74	22 %	-0.09
Muscle power total mean per cycle (W)	37 (6)	28 (9)	0.18	24 %	-0.36
GH Reaction force mean per push (N)	392 (208)	448 (175)	1.00	14 %	0
GH Reaction force peak per push (N)	889 (353)	920 (323)	0.87	3 %	-0.05
GH Reaction force mean per cycle (N)	268 (105)	232 (49)	0.06	13 %	-0.50

[a] 3D displacement of anatomical landmarks during push phase
Abbreviations: M5, Fifth metacarpal; EM, Medial epicondyle of humerus; GH, Glenohumeral joint; IJ, Suprasternal notch; HU, Humeroulnar joint

Effect of practice on propulsion technique and kinematics of propulsion

The change in kinetic and kinematic aspects of movement during one typical push for the pre- and the post-test for each participant is illustrated in Fig 4.

Propulsion technique

Push frequency decreased significantly between the pre- and the post-test (51 push/min → 36 push/min, p=0.04), while the contact angle increased (68.9° → 94.5°, p=0.02). Positive work approached significance (p=0.06) and peak force per push (0.40) did not change significantly between the pre- and the post-test. The effect size was large for frequency and contact angle and moderate for positive work per push and peak force.

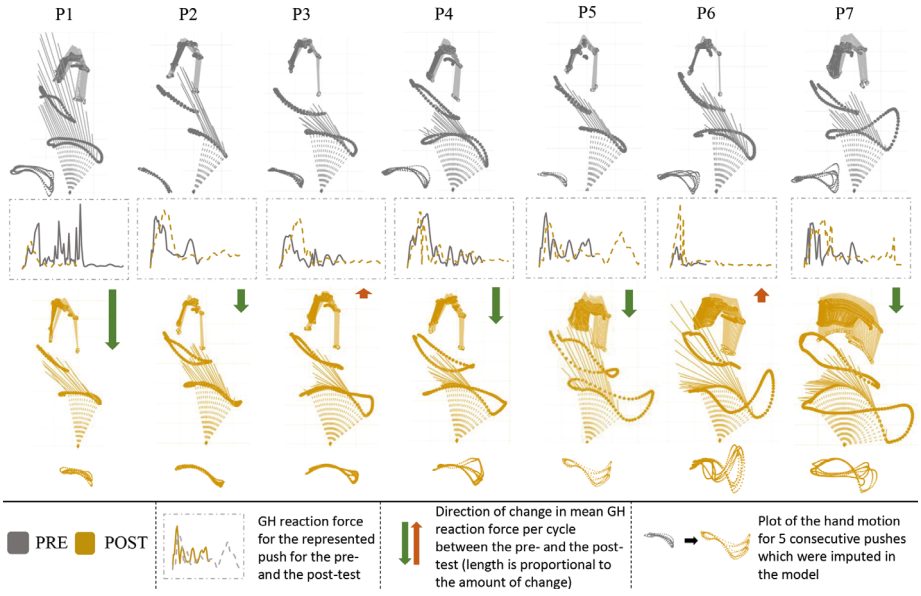

Figure 4. Typical example of one propulsive cycle for each participant (P1-P7) for the pre- (top) and the post-test (bottom section). The kinematic and kinetic input (reaction force vector) for the model in relation to the trajectories of the shoulder, elbow and hand over the push and recovery phase (cycle) for the pre- (grey) and the post-test (yellow) (row 1 and 3). Glenohumeral reaction force for the presented push for the pre- and the post-test (row 2). The illustrations of participants were sorted in ascending order based on the hand excursion at the post-test

Kinematics

To describe the change in kinematic aspects of movement, the displacement of anatomical landmarks was used. On the level of the group the displacement of the fifth metacarpal (M5), medial epicondyle of humerus (EM), glenohumeral joint (GH), suprasternal notch (IJ) did not change significantly between the pre- and the post-test. The excursion of the upper arm increased in 6 out of 7 participants (humeral medial epicondyle displacement, 297 mm → 342 mm, p=0.06), approaching significance, while excursion of the hand, trunk and shoulder did not change between the pre- and the post-test.

Effect of practice on shoulder complex loading

The mean and peak net moments of the external force around the glenohumeral and humeroulnar joints did not change significantly between the pre- and the post-test (Table 3). The mean glenohumeral reaction force per cycle decreased between the pre- and the post-test in 5 out of 7 participants, approaching significance in the whole group

(269 N→233 N, p=0.06). Effect size of the decrease in the mean GH reaction force per cycle was large, r=0.5. Mean and peak glenohumeral reaction force per push did not change significantly and exhibited low effect sizes. Mean muscle power per cycle decreased in 6 out of 7 participants but the group means were not significantly different (37 W→ 28 W, p=0.18). Effect size of change in mean muscle power per cycle was moderate r=0.36. Change in peak and mean muscle power per push was not significant and had a low effect size.

Effect of practice on individual muscle force

The contribution of individual muscles relative to their theoretical maximal force (Fig 5), as opposed to the absolute muscle force, takes the differences in size between the muscles into account. The higher the relative muscle force, the bigger the chance of injury as higher numbers mean that a muscle approaches its maximum force generating capacity. The highest mean relative forces during the push phase at the pre- and the post-test were found in triceps (24.1 % → 18.6 %), followed by one of the rotator cuff muscles: supraspinatus (18.6 % → 17.1 %). Also biceps (13.0 % → 14.9 %) and pectoralis major (11.3 % → 12.3 %) developed quite high relative muscle forces. The same muscles also needed to endure the highest peak relative forces in the push phase. Yet, none of the changes in relative muscle force between the pre- and the post-test were significant.

Triceps delivered the highest mean negative power contribution (-9.8 W → -6.9 W) and biceps delivered the highest mean positive contribution (7.1 W → 4.2 W) during the push phase at both testing occasions (Fig 6). Although the mean power during the push did not change significantly over time, there is a decreasing trend visible for all muscles except the supraspinatus, subscapularis and deltoideus in the push phase and supraspinatus in the recovery phase.

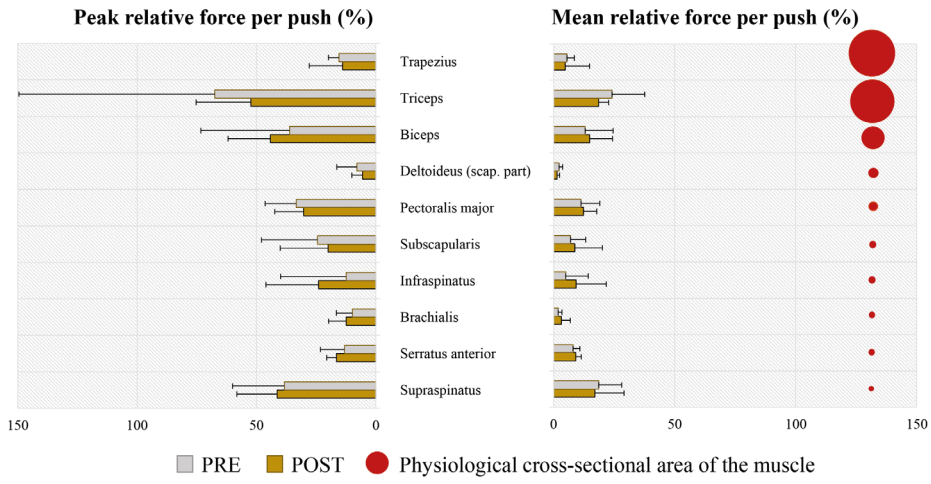

Figure 5. Relative peak and mean forces (N=7) of individual muscles during the push phase for the pre- and the post-test. The proportional differences in the physiological cross-sectional area between the muscles are shown (right). Bars represent the median and the error bars represent the IQR. Only the muscles that had mean muscle forces during the push phase larger than 25 N are illustrated. The muscles are arranged in a descending order of physiological cross-sectional area.

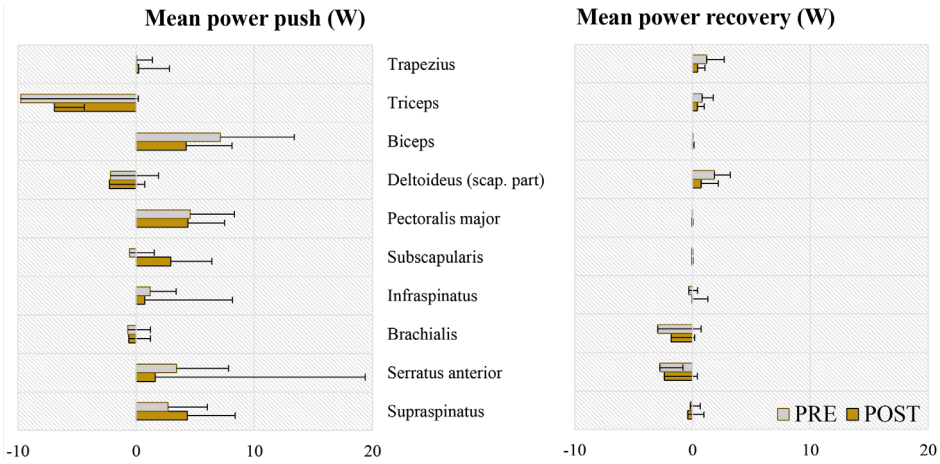

Figure 6. DSEM estimates of individual muscle powers (N=7; median and IQR) during the push (left) and recovery (right) phase for the pre- and the post-test. Only the muscles that had mean muscle forces during the push phase larger than 25 N are illustrated. The muscles are arranged in a descending order based on their physiological cross-sectional area

DISCUSSION

The goal of this study was to examine the changes in upper-limb dynamics and shoulder complex loading accompanying the typical changes in propulsion technique following 80 min of low-intensity handrim wheelchair propulsion practice. This study is unique, as it looked at changes in shoulder loading over three weeks in a group of inexperienced able-bodied individuals. Finding comparable studies is therefore challenging. In order to allow the reader a proper interpretation of the results, we put our findings in light of both able-bodied and actual wheelchair user literature, taking into consider the differences between study protocols and participants.

Propulsion technique

The changes in the propulsion technique, based on the forces and moments applied to the handrim, found in the current study are very similar in direction and magnitude to the changes reported by other low-intensity practice studies in able-bodied individuals [7,10,11,27]. For instance the change in push frequency in the current study from 51 to 36 pushes/min matches the direction and magnitude of change in the study of de Groot (61→42 push/min) [27] or in the study of Vegter (68 → 49 push/min) [10]. Both studies included able-bodied individuals who received a similar dose of practice as the current study. When considering the values of push frequency and contact angle at the post-test, they closely resemble the values of those parameters in experienced wheelchair users, e.g. contact angle of 94° in the current study vs 98° in the study with 59 experienced wheelchair users with paraplegia [24], or 97° in an experiment including 21 experienced wheelchair users [28], frequency of 36 pushes/min here vs 43 pushes/min in a study which included 10 adolescent experienced wheelchair users with various disabilities [29].

Kinematics

Despite the rather uniform changes in propulsion technique, participants developed various kinematic solutions in response to an identical task (Fig 4). The only change that was consistent across the participants was the increase in the excursion of the upper arm (Medial Epicondyle). Involvement of the trunk during propulsion varied strongly among the participants. The Suprasternal Notch displacement increased in 3 participants and did not change in the other 4. Change in the excursion of the hand also varied in magnitude and direction among the participants with 5 participants increasing and 2 decreasing it (Fig 4). There was no apparent pattern between the excursion of various landmarks and change in mean and peak GH forces. Meaning that participants who managed to lower the shoulder load between the pre- and the post-test developed rather varying kinematic solutions. Wheelchair propulsion is a redundant task, which means that there are more motor components involved in the production of action than are essentially required. In other words, the same forces can be applied to the handrim using various upper-arm and trunk configurations. This may explain why the users developed various kinematic patterns without compromising the equivalent outcome [30], the production of a mean velocity and power output over time.

Effect of practice on shoulder complex loading

In contrast to the rather variable kinematic output, it seems that participants exhibited two glenohumeral reaction force distribution patterns during the propulsive cycle. Two participants (P3 and P6 in Fig 4) applied high force in a rapid and relatively short-lasting push, which led to a high increase in the peak GH force during the push and, as a consequence, to an increase in mean GH force per cycle. All other participants managed to maintain the treadmill velocity by distributing the force more evenly over the propulsive cycle and in consequence decreasing the peak GH forces. This, combined with lowering the push frequency, led to a decrease in mean GH force during the propulsive cycle.

Next to the force distribution pattern, there may be another factor that caused an increase in shoulder loading in P3 and P6. A Recent study by Requejo et al. [31] concluded that a more anterior placement of the hand at release relates to a higher shoulder load. As visible in Fig 4, at the post-test, P3, P6 and P7 had the most anterior placement of the hand when decoupling from the handrim. From those three participants, P7 was the only one who lowered the shoulder load at the post-test. This could be related to the fact that P7 distributed the handrim forces evenly throughout the push, avoiding high peak forces when the hand was in the vulnerable anterior position. However we would like to emphasize that based on the findings of this and previous experiment [31], we cannot explain what the exact factors are that cause the anterior hand placement at release to be potentially more harming for the shoulder. We recommend to investigate this issue in the future.

The median peak GH forces of 920 N found at the post-test are comparable to those reported in other wheelchair propulsion studies with experienced wheelchair users [1,5,32] and able-bodied participants [5,33]. However it should be noted that P6 increased the peak GH force at the post-test to over 2300 N per push, achieving a value, almost

1300 N (~60%) higher than the second highest score recorded in the current study. This exceptionally high value is comparable to peak forces measured during ramp propulsion (2555 N) [32]. Peak force of P6 measured at the handrim was nearly 30% higher than the second highest peak force recorded at the post-test. High peak force was necessary to maintain the belt velocity as P6 developed the lowest push frequency recorded at the post-test of 21 pushes per minute. The peak forces in the majority of participants are lower than peak forces found during for example weight-relief lifting in a wheelchair (~1500 N) [34,35]. However it should be considered that wheelchair propulsion is a highly repetitive task, meaning that the cumulative tissue overload can be much higher than for weight-relief lifting.

Maintaining a certain velocity and power output during wheelchair propulsion can be achieved in a number of ways, keeping in mind that there is a relationship between the propulsion technique variables. As push frequency decreases during practice, the contact angle and work per push need to increase to maintain a constant velocity. The advice of current clinical practice guidelines [3] to use long strokes and low frequency during propulsion, is based on the assumption that larger contact angle would lead to a decrease in the peak glenohumeral reaction forces, as load is evenly distributed over a larger angle. However, there may be a threshold beyond which excessive lowering in frequency, despite the high contact angle, is not desired as it has to be compensated by an increase in peak forces, in order to maintain constant velocity, like in the example of P6. This statement is supported by the study of Rankin [36], 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. Similar statements were made for other propulsion technique variables such as peak force [36] or fraction effective force [37].

Although assumed critical, it is not clear whether the goal of wheelchair propulsion practice should be lowering the mean or the peak GH loads. The controversy is caused by the lack of consensus on what is more damaging to the tissue, less frequent high forces (with longer recovery periods) or persistent high frequency lower forces. According to the studies on animal models of muscle damage and studies documenting repetitive workplace injuries, even low-load movement sustained for an extended period, has a great potential to cause overuse damage to the muscle and ligament tissue [38]. The highest injury-inducing potential lies in the high-repetition and high-load tasks but the exact relationship between the dose of mechanical load and tissue response is unknown.

Effect of practice on individual muscle force

The highest mean relative forces and highest power production at the pre- and the post-test were generated by a pair of antagonist muscles: the triceps and the bices muscle. Those two muscles showed to generate power interchangeably during the majority of the push phase [39] and remain among the largest contributors to the power generation throughout the propulsive cycle independent of the simulated propulsion technique [36]. Large contribution of the triceps muscle is in accordance with the study of Vegter et al.

[5] who also found that triceps was the biggest power producer in the very initial stages of practice in wheelchair propulsion and with a study of Slowik et al. [40] who found the triceps muscle among the primary contributors to the propulsive cycle, independent of the hand pattern during the recovery phase. It is however striking that the magnitude of the peak relative force production of the triceps in the current study exceeded 50%, both at the pre- and the post-test, while in the study of Vegter et al., it oscillated around 15%. Another study reported triceps force production of 25% [1]. The second biggest contributor was the biceps muscle exerting approximately 40% of the attainable force at both testing occasions and largely contributing to the power production. Contribution of the biceps is higher in the current study than in previous literature. Veeger et al. [1] found peak relative force of biceps of just under 25% in experienced wheelchair users and Vegter et al. a contribution of approx. 15% [5]. The notably high contributions of biceps and triceps muscles in the present study may be related to the quite large differences in push frequency between the studies. Vegter et al [5] (>55 push/min) and Veeger et al [1] (96 pushes/min) reported a higher frequency compared to our study (36 pushes/min). Both experiments were performed at a very similar velocity and power output as the current study. As our participants lowered the push frequency to 36 pushes/min, more muscle power had to be exerted during the push to maintain the treadmill velocity. This explanation is supported by a previous study which used forward dynamics simulation and found that simulating minimizing push frequency and maximizing contact angle both result in large increases in power production of biceps and triceps muscles during the push phase [36].

The contributions of biceps and triceps are followed by large power and relative force production of pectoralis major and the following rotator cuff muscles: supraspinatus, infraspinatus and subscapularis. High contribution of those muscles during the push phase is in accordance with other studies with experienced wheelchair users [1,41] and able-bodied persons [5,33]. Supraspinatus produced relative force of almost 40% at the post-test which is comparable to the values found in experienced wheelchair users [1]. High load on all rotator cuff muscles, but especially supraspinatus is concerning. Supraspinatus muscle, because of its relatively small size, and anatomical location, running through the narrow subacromial space, is vulnerable to overload and impingement [42]. Finally, the contribution of the anterior part of the deltoideus was very low in the able-bodied participants in the current study. This is agreement with a previous study which used the same musculoskeletal model and a very comparable participant group [5] but contradicts other studies which reported it to be a main contributor [39,41].

Advantages and limitations

The primary advantage of this observational single group pre-post experiment is that the changes in shoulder load were investigated over a longer practice period, excluding the very initial stages that have been documented before [5]. Including able-bodied participants is a useful method to preliminary examine the kinetic and dynamic changes occurring during the learning process. Firstly, because the participant have no experience at the onset of the study. Secondly, because confounders that are present

in actual wheelchair users such as sitting balance, presence of pain or limited muscle function cannot influence the acquired results. However, to be able to fully understand the way propulsion technique relates to shoulder pain, actual wheelchair users should be investigated in future studies. Although 7 participants is not a very unusual number when compared with other modeling studies [1,5], we recommend to include more participants in the future. Power analysis calculation (G*Power, α=0.05; Power=0.80; [43]) indicated that 11 participants would be necessary to reach a significant decrease in the mean glenohumeral reaction force per cycle. In order to make sure that the test conditions were standardized for all participants, no individual fitting was provided within the user-wheelchair interface. Although this could initially have some influence on the propulsion technique, it should be considered that the wheelchair remained unchanged between the pre- and the post-test. All observed changes were therefore a result of practice. Although within-subject comparisons remain valid, across-subject comparisons may be confounded by the fixed dimensions of the experimental wheelchair in the context of individual anthropometric differences. Lastly, DSEM is a non-personalized musculoskeletal model. This means that for the well-trained individuals and athletes the relative loads could be lower as their muscles are habituated to handle higher loads.

Future directions

Future studies should include actual wheelchair users, preferably with various levels of experience and various lesion levels, in order to further explore the relationship between wheelchair propulsion technique and upper extremity concerns. Investigation should take place as early as possible in the learning process since recent evidence suggests that shoulder pain develops already in the early stages of rehabilitation [2]. Future research should attempt to determine how the quantified changes in shoulder load influence the actual damage to the soft tissue. Including a higher number of participants could allow forming clusters of individuals with similar propulsion characteristics, which could explain various trajectories of overuse injury development. Moreover, larger participant group could help to determine what the underlying biological patterns are that drive the optimization in cyclic wheelchair exercise.

CONCLUSIONS

Changes in the propulsion technique found in this pre-post single group study are in agreement with other low-intensity wheelchair practice studies and values at the post-test resemble the values in actual wheelchair users. Despite developing a uniform propulsion technique, the kinematic solution to the task varied in magnitude and direction between the participants. In contrast to the rather variable kinematic output, participants exhibited two glenohumeral reaction force distribution patterns during the propulsive cycle. Individuals, who developed high force at the onset of the push, increased both peak and mean glenohumeral forces. Participants, who distributed the force more evenly over the propulsive cycle, lowered both peak and mean glenohumeral force. This study provides preliminary insights on the possible relation between the changes in wheelchair

propulsion technique and shoulder load taking place after low-intensity practice. This knowledge should be extended in the future by investigating actual wheelchair users with various levels of experience.

ACKNOWLEDGEMENTS

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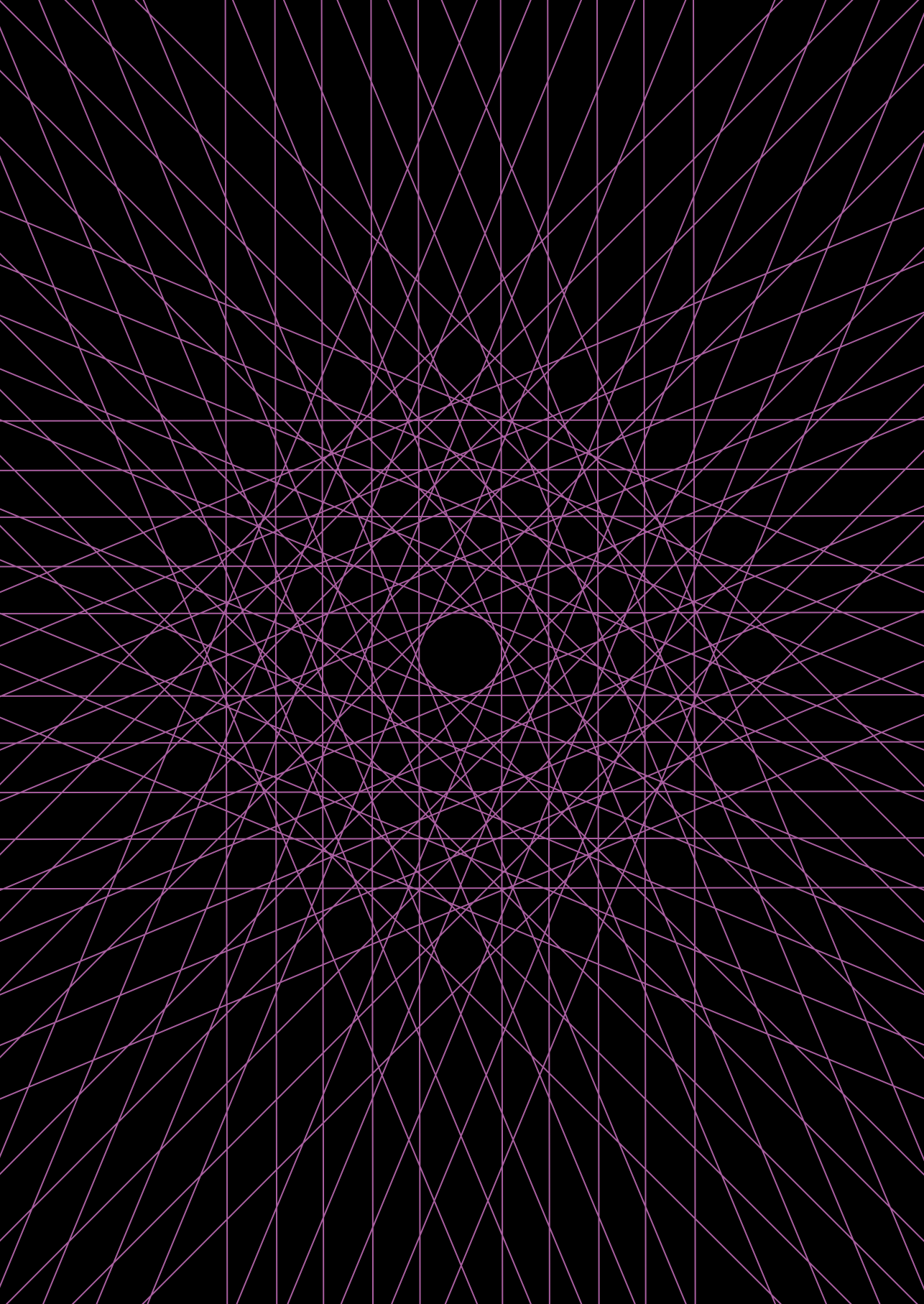
SUPPORTING INFORMATION

Supporting information is available on the website of the publisher.

S1 Data. Complete data set.



5

VALIDITY OF CONSUMER-GRADE ACTIVITY MONITOR TO IDENTIFY MANUAL WHEELCHAIR PROPULSION IN STANDARDIZED ACTIVITIES OF DAILY LIVING

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ABSTRACT

Background: Hypoactive lifestyle contributes to the development of secondary complications and lower quality of life in wheelchair users. There is a need for objective and user-friendly physical activity monitors for wheelchair-dependent individuals in order to increase physical activity through self-monitoring, goal setting, and feedback provision.

Objective: To determine the validity of Activ8 Activity Monitors to 1) distinguish two classes of activities: independent wheelchair propulsion from other non-propulsive wheelchair-related activities 2) distinguish five wheelchair-related classes of activities differing by the movement intensity level: sitting in a wheelchair (hands may be moving but wheelchair remains stationary), maneuvering, and normal, high speed or assisted wheelchair propulsion.

Methods: Sixteen able-bodied individuals performed sixteen various standardized 60s-activities of daily living. Each participant was equipped with a set of two Activ8 Professional Activity Monitors, one at the right forearm and one at the right wheel. Task classification by the Active8 Monitors was validated using video recordings. For the overall agreement, sensitivity and positive predictive value, outcomes above 90% are considered excellent, between 70 and 90% good, and below 70% unsatisfactory.

Results: Division in two classes resulted in overall agreement of 82.1%, sensitivity of 77.7% and positive predictive value of 78.2%. 84.5% of total duration of all tasks was classified identically by Activ8 and based on the video material. Division in five classes resulted in overall agreement of 56.6%, sensitivity of 52.8% and positive predictive value of 51.9%. 59.8% of total duration of all tasks was classified identically by Activ8 and based on the video material.

Conclusions: Activ8 system proved to be suitable for distinguishing between active wheelchair propulsion and other non-propulsive wheelchair-related activities. The ability of the current system and algorithms to distinguish five various wheelchair-related activities is unsatisfactory.

INTRODUCTION

Individuals with a spinal cord injury belong to the least physically active populations [1]. Hypoactive lifestyle leads to high prevalence of the metabolic syndrome [2], cardiovascular disease [3], and low fitness and contributes to the development of secondary complications of spinal cord injury [4]. This compromises the mobility and independence of wheelchair users and decreases their opportunities for experiences [5] and lowers their quality of life [6]. Daily wheelchair activity is assumed to be one way to counteract the negative effects of hypoactive behavior. Yet quantifying physical activity in wheelchair users is challenging. Both amount as well as intensity of propulsion need to be accurately determined. Knowing those factors is important because they have implications for the energy expenditure and in turn for body mass regulation and prevention of secondary complications.

There is a need for reliable, objective and user-friendly activity monitors for wheelchair-dependent individuals. Physical activity questionnaires are often inaccurate [7-9] and the availability of accelerometer-based consumer-grade devices is scarce, especially when compared to the availability of such systems for the general population [10,11]. Activity monitors used for research purposes involve as many as six body-bound units which makes them expensive and impractical for daily use in free living conditions [12]. In contrast, most monitors for the general population consist of one body-bound unit. Monitors available for the general population are not suitable for wheelchair user for two reasons: the algorithms used are built to recognize human stepping which is different from wheelchair propulsion; in order to recognize active propulsion, at least two units are necessary to record movement of hand and wheel independently. [13]. In this study we will test a new set of activity monitors, suitable for both research as well as end-consumer use. Ideally these will be able to accurately quantify wheeled activities and give feedback directly to the user, to the clinical practitioners and to researchers. Moreover they will provide information about the long-term doses of physical activity across days and weeks.

To make activity monitoring available to a broad group of users, an activity monitor should fulfil the following conditions: be affordable, comprise a minimal number of measurement units in order to improve users' comfort and ease of use, be able to distinguish among various forms of wheelchair propulsion and intensity levels [14]. To fulfil the first two conditions: affordable price and small number of units, we decided to include two Activ8 Professional activity monitors of which only one will be body-bound. This configuration was used previously with research-grade monitors (Actigraph GT3X, Actigraph LLC, Pensacola, USA) to assess the amount of independent wheelchair propulsion [13]. Since we would like to propose a system which will be available to end consumers, we found Actigraphs not suitable because of their price (> €1500 for two devices and necessary software); large size (4.6 x 3.3 x 1.5 cm) and the fact they provide no feedback to the user [10]. Instead, we chose Activ8 Professional Monitors because of their much lower price (€300 for two devices); open-access software capable of providing feedback and smaller size (3.0 x 3.2 x 1.0 cm).

The third condition was that the proposed system should recognize various kinds of propulsion and intensity levels. The primary concern in quantifying physical activity in a wheelchair is determining the amount of independent wheelchair propulsion, as opposed to other non-propulsive wheelchair-related activities such as being pushed in a wheelchair. However, within independent wheelchair propulsion, it would be interesting to distinguish low, moderate and high intensity levels corresponding to slow walking, normal speed walking and running in the general population. Those activities correspond to various energy expenditure levels and may therefore be implemented in more accurate prescription for body mass regulation and prevention of secondary complications.

The primary goal of this study was to investigate whether a set of two Activ8 Professional Activity Monitors (one attached to the dorsal side of the right wrist and one to the right wheel) can distinguish between independent wheelchair propulsion and other non-propulsive wheelchair-related activities. The first step of data analysis resulted therefore in a division into those two classes. The secondary goal was to determine whether the same set of monitors can distinguish more classes than just the two aforementioned ones. The second step resulted in a division of all tasks into five wheelchair-related activities differing by the movement intensity level: sitting in a wheelchair (hands may be moving but wheelchair remains stationary), maneuvering, normal speed propulsion, high speed propulsion and assisted wheelchair propulsion.

MATERIALS AND METHODS

Participants

Sixteen right-handed able-bodied individuals (8 male and 8 female) participated voluntarily in this study. The average mass of the participants was 73.8 ± 10.7 kg and the average height of the participants was 1.81 ± 0.07 m. Participants were recruited through the network of the researcher or the students who assisted during the performance of the experiment. Potential participants received an information letter regarding the character of the study. Before the onset of the study all participants provided written informed consent. The protocol of the study was approved by the Local Ethics Committee (Nr. ECB/2016.04.28_1), of the Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, The Netherlands. Inclusion criteria were having no severe upper-extremity injuries that could influence the parameters measured in this study.

Able-bodied participants were selected for this study for practical reasons as they were already involved in another wheelchair propulsion experiment. We found this group suitable to perform a validity study as the placement and implementation of the data from two accelerometers would not change for a different target group. However to be able to implement the monitor in various patient populations, a set of extra measurements may need to be performed to establish the threshold values for various classes in each group as movement intensity and resulting energy expenditure may

differ between able-bodied and wheelchair users, as well as between various groups of persons who typically use wheelchairs for mobility.

Table 1. Sixteen tasks used to validate the Activ8 Activity Monitor in a group of able-bodied participants (N=16). The tasks (lasting 60 sec each) were performed by all participants in the order of presentation. There was a break between the tasks to instruct the participant about the next task (approx. 1 minute). Tasks were standardized i.e. tasks set-up, as well as instruction given to the participants were the same for all subjects.

Task #	Location	Task description
		Treadmill propulsion at a velocity of:
1	Treadmill	0.28 m/s
2	Treadmill	0.56 m/s
3	Treadmill	1.11 m/s
4	Treadmill	1.67 m/s
5	Treadmill	1.11 m/s and a slope of 3%
		Self-paced propulsion on flat surface at:
6	Corridor	low speed
7	Corridor	normal speed
8	Corridor	high speed
9	Corridor	Being pushed on flat surface with participant's arms placed on their lap
10	Corridor	Being pushed on flat surface with participant's arms moving. Participants received a bag with various objects inside. Bag was placed on the participant's lap. Participant was instructed to take various objects, named by the researcher, one-by-one out of the bag and hand them to the researcher. Participant was instructed to use the right arm to hand the objects. Researcher was walking next to the participant on the right side.
11	Corridor	Simulated setting up a table (maneuvering). There were two tables placed 3 meters apart. Participant was asked to carry items (plastic cups and plates) one by one from one table to another.
12	Corridor	Simulated washing and drying the dishes. Participant had to wash and dry plastic dishes.
13	Corridor	Using a laptop. Laptop is placed on a table in front of the participant. Participant is asked to type for 60s.
14	Corridor	Slaloming at a self-selected velocity (slalom with cones at 0, 1.5, 3, 4.5 and 6 meters). Participant had to slalom in both directions.
15	Corridor	Simulated wheelchair basketball. 2 researchers are standing 6 meters apart. The participant is asked to first propel from researcher 1 to researcher 2 while dribbling the ball every two pushes. Then participant passes the ball 3 times to the researchers and then drives back to researcher 1 (dribbling every 2 pushes) and passes the ball 3 times again. There are two cones placed between researcher 1 and 2 that participant has to go around. The participant should pass each cone on a different side (so for example pass cone on the left side and cone 2 on the right side).
16	Corridor	Going up a slope, turning around and going down a slope in a hallway. The total length of the slope was ~23 meters and inclination was ~5%.

Design

To validate the Activ8 Professional Activity Monitors, a series of 16 various standardized 60s-activities of daily living (ADL) were performed by each participant (see Table 1 for a description of all tasks). Participants had previous wheelchair experience, particularly riding on a treadmill (~30 min), but did not receive any specific training on other tasks. The order of tasks was identical for all participants. Each participant performed the tasks in the same experimental handrim wheelchair with 24 inch wheels, 5° camber, seat height of 0.54 m and seat width of 0.45 m (Double Performance BV, Gouda, The Netherlands). Tire pressure of the rear wheels was set at 600 kPa during all test sessions.

The first five tasks were performed on a level motor-driven treadmill (2.4 m long by 1.2 m wide) (Forcelink b.v., Culemborg, The Netherlands). Subsequently the other 11 tasks were performed over-ground in a corridor with linoleum floors.

Activ8 Professional Activity Monitors

Each participant was equipped with a set of two Activ8 Professional Activity Monitors (2M Engineering Ltd., Valkenswaard, The Netherlands), that include a triaxial accelerometer. One monitor was attached to the dorsal distal side of the right forearm. The other monitor was attached to the spokes of the right rear wheel, as close as possible to the wheel axis (Fig 1). Both monitors were attached using double-sided and surgical tape to eliminate any movement independent of the movement of respectively the arm or the wheel.

All tasks were videotaped. The activity monitors and the video camera were started once at the beginning of the measurement and recorded continuously until the end of the measurement. Activities performed between the tasks of the protocol were not included in the analysis. The monitors with internal clock were synchronized by making sure that the clocks of the laptops they were started on were synchronized with the same internet time server. The start and stop time of each task was written down in the measurement protocol. This was used to make a time selection of each task for the Activ8 data. Moreover, at the beginning and end of each task, the researcher conducting the test said the words 'start' and 'stop' to provide a synchronisation and time selection for the video recordings.



Figure 1. One Activ8 was attached to the distal dorsal side of the forearm and one to the right wheel. Picture was taken before securing the monitors with surgical tape.

Activity classification

Each monitor sampled raw data at 12.5 Hz and stored the summed output on a 5s epoch base. The vector counts data in the output was used to perform the classification. An example of the output used for the analysis can be seen in Fig 2. Classification was performed using custom-written Matlab algorithms, which were in part validated for detecting independent wheelchair propulsion [13]. Matlab was used to automate the process of assigning a class to a given 5s epoch based on the vector counts. The number of counts per time interval has frequently been used in accelerometer research to express movement intensity [10,13]. The vector counts in three directions were not weighted, i.e., no movement direction was amplified. The thresholds to discriminate between the classes were determined based on previously performed pilot measurements with both wheelchair users and able-bodied subjects. Pilot measurements were performed

using a different type of activity monitor, Actigraph GT3X+. The Actigraph counts were recalculated into the Activ8 counts once their ratio was determined with a set of additional pilot measurements. The acquired data from Activ8 activity monitor and video recording were classified independently. The algorithms were predetermined and were not in any way adjusted based on the acquired video recordings.

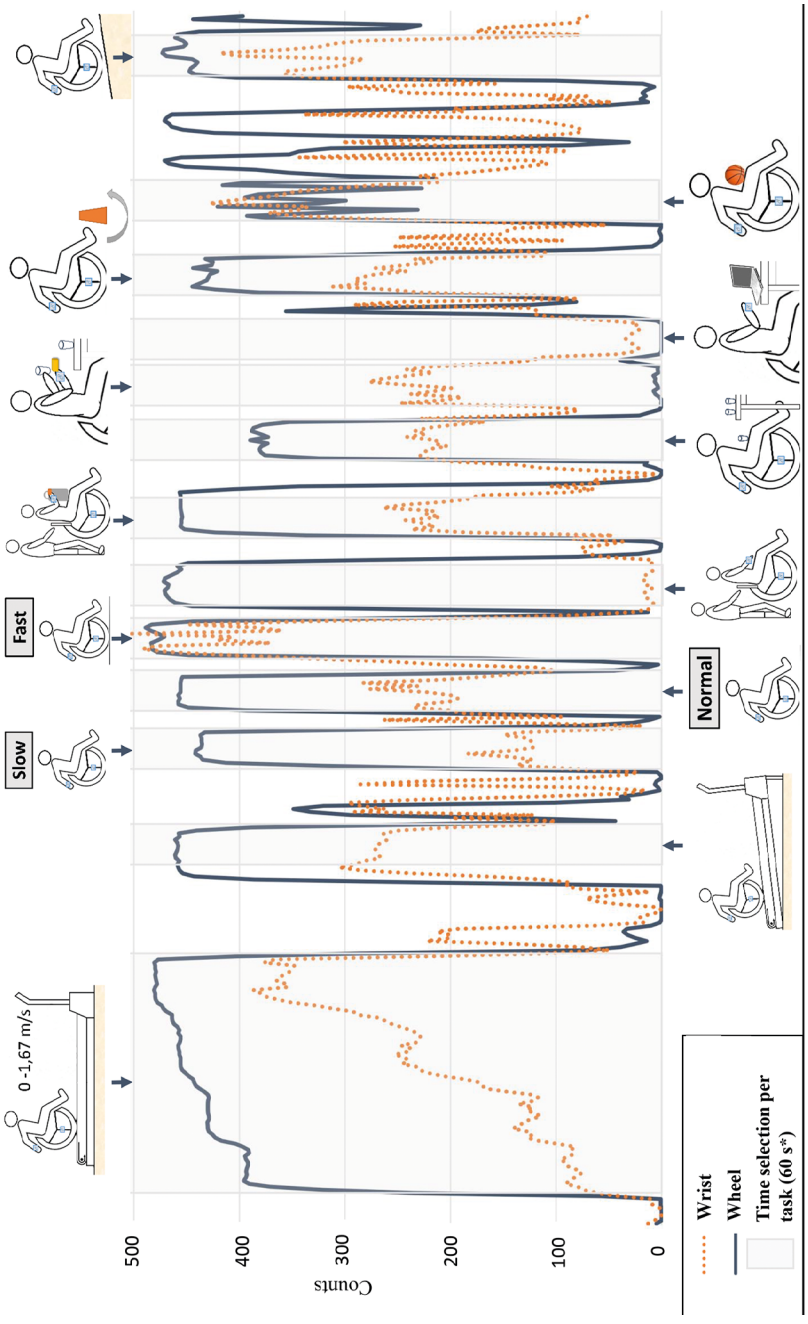

Figure 2. An example of the raw monitor output of one participant used for data analysis. Wrist and wheel monitors are synchronized. Time selection of all 16 tasks (grey areas) is presented. The intensity of movement is expressed in counts (y axis) for each 5 second interval (x axis). The main outcome measure is the time spent in a given class.
* Time selection for the first four tasks is longer. Treadmill was not stopped between the velocity 0 and 1.67 m/s.

The classification was performed in two steps (Table 2). The first step resulted in a division of all activities into two classes: 1. Independent wheelchair propulsion (participant independently propels the wheelchair with the use of his/her arms) 2. Other non-propulsive wheelchair-related activities (activities other than independent wheelchair propulsion such as being pushed in a wheelchair or performing ADLs). The second step was performed to determine whether it is possible to distinguish more classes than just the two aforementioned ones. The second step resulted in a division of all activities into five classes: 1. Sitting in a wheelchair (wheelchair remains stationary) 2. Maneuvering (low intensity independent propulsion) 3. Normal speed independent wheelchair propulsion 4. High speed independent wheelchair propulsion 5. Assisted wheelchair propulsion (being pushed in a wheelchair).

Table 2. Classification was based on the counts data from the two Activ8 monitors, one located on the dorsal side of the forearm and the other one on the right wheel. The table represents the division into five classes (Step 2). The shading represents the division in two classes (Step 1). White fields belong to class 1. Independent wheelchair propulsion; grey fields belong to class 2. Other activities.

		Wheel counts			
		<31	31-310	310-480	>480
Wrist counts	<98	Sitting in a wheelchair	Maneuvering	Assisted propulsion	Assisted propulsion
	>98	Sitting in a wheelchair	Maneuvering	Normal speed independent	High speed independent

Reference methods

Data from the two Activ8 monitors were compared with the video recordings. All activities were registered using a high resolution hand held camera (Canon Inc., Tokyo, Japan). The camera was simultaneously capturing the activity of both the right arm and right wheel. The video recordings were classified by two independent researchers into 5 classes (see step 2 in paragraph: Activity classification). The researchers performed pilot classification trials first to gain the necessary experience and discuss the results to make sure that the definition of each class was clear. Camera recordings and Activ8 data were compared with a resolution of 1s.

Data analysis

The outcome measure is the duration (time in seconds) of each class while performing the 16 tasks. The classification was compared between the video camera and Activ8 monitors. Validity was determined using the following properties:

- Relative time difference: Difference between the duration of a certain class identified by the video analysis and the same class identified by the Activ8 expressed as percentage (per task)

- Overall agreement: Ratio of correct classification by Activ8 and the total time that activities took place (per participant), calculated as: (Time correct classification by Activ8/total time classified for a given person)*100%

- Sensitivity: The percentage of time correctly classified by Active8 per class, calculated as: (Time a certain class was correctly identified by Activ8/time this class was identified by video)*100%

- Positive predictive value: Ratio between correct Activ8 classification and total classified time per class, calculated as: (Time a certain class was correctly identified by Activ8/Time that this class was identified in total (both correctly and incorrectly) by Activ8)*100%

In accordance with previous studies on activity monitoring for wheelchair users, a relative time difference below 10% is acceptable [13,15]. For the overall agreement, sensitivity and positive predictive value, outcomes above 90% are considered excellent, between 70 and 90% good, and below 70% unsatisfactory [13,15].

RESULTS

All 16 participants completed all the tests. Classification of all tasks is shown in Fig 3.

Relative time difference

Relative time difference per task between the output of the Activ8 and video analysis is presented in Table 3. After a classification in 2 classes, for 12 out of 16 activities, the relative time difference between Activ8 and video was below 10%. The highest time difference between Activ8 and video was registered for the following tasks: treadmill propulsion at 0.28 m/s, treadmill propulsion at 0.56 m/s, self-paced propulsion at low speed, being pushed with arms moving. Average relative time difference for all tasks after classification in 2 classes was 15.5%. After a classification in 5 classes, for 5 out of 16 activities, the difference was below 10%. On average the difference was 40%.

Overall agreement

The overall agreement between video and Activ8 data per participant for 2 classes was on average 82.1% (SD: 4.3; range 73.1 - 88.4%). In other words, 82% of the duration of all the tasks was correctly divided into 2 classes. For 5 classes on the other hand, the overall agreement was 56.6% (SD: 4.5; range 48.8 - 65.6%).

Sensitivity and positive predictive value

After a division in 2 classes, sensitivity of Activ8 was on average 77.7% and positive predictive value was 78.2% (Table 4), indicating a good sensitivity and positive predictive value. When 5 classes were created, average sensitivity of Activ8 was 52.8% and positive predictive value was 51.9%, which is considered unsatisfactory.

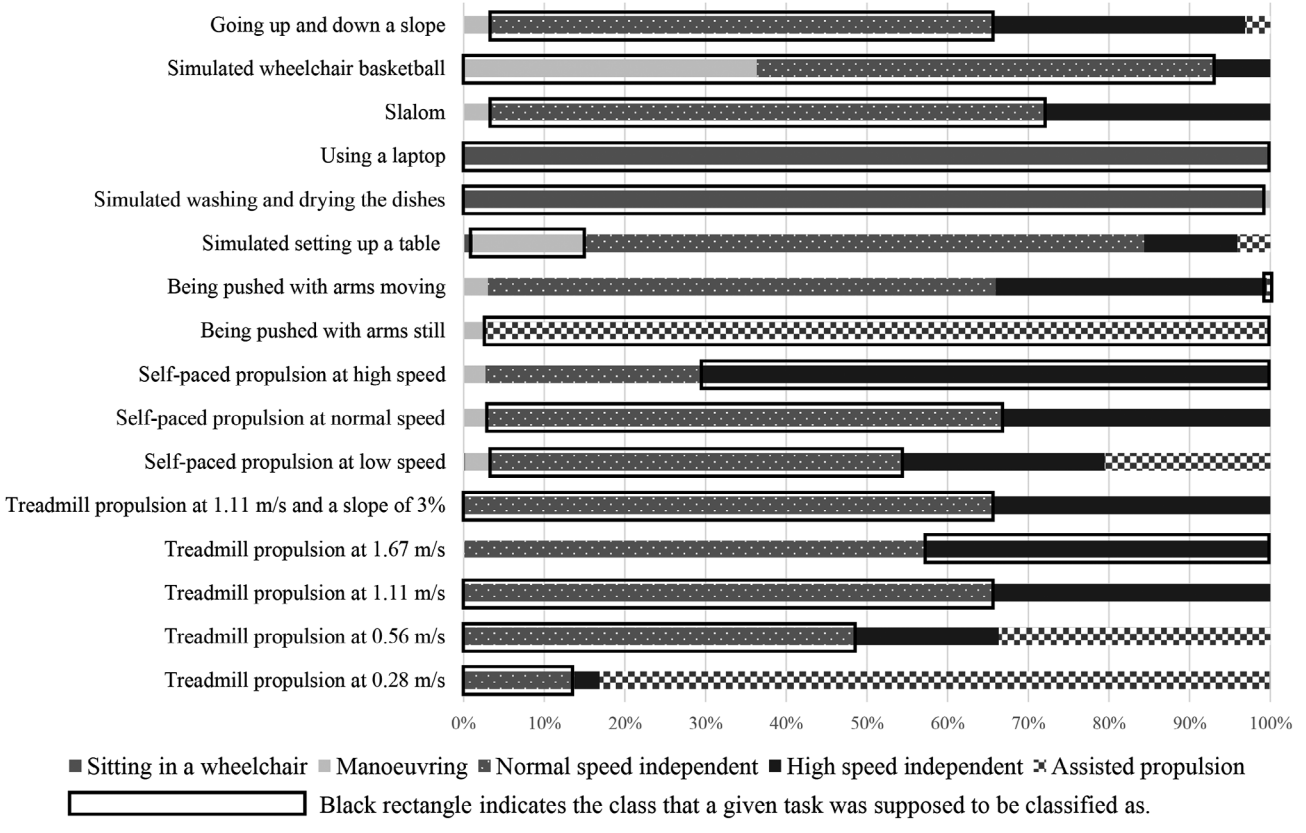

Figure 3. Classification of all tasks (N=16) performed by the activity monitor. Total duration of each task for all participants (100%) with indication of how much of total duration was spent in each out of five classes.

Table 3. Relative time difference per task between Activ8 and video recording after the division into two and five classes (N=16).

		Two classes			Five classes		
		Total duration (s)[a]		Relative difference (%)[b]	Total duration (s)[a]		Relative difference (%)
Task #	Task name	Video	Activ8		Video	Activ8	
	Treadmill propulsion at:						
1	0.28 m/s	960	162	83.1	960	132	86.3
2	0.56 m/s	960	637	33.6	960	467	51.4
3	1.11 m/s	960	960	0.0	960	631	34.3
4	1.67 m/s	960	960	0.0	960	410	57.3
5	1.11 m/s and a slope of 3%	960	960	0.0	960	631	34.3
	Self-paced propulsion at:						
6	low speed	960	763	20.5	960	490	49.0
7	normal speed	960	960	0.0	960	614	36.0
8	high speed	960	960	0.0	960	676	29.6
	Being pushed with:						
9	arms still	960	934	2.7	960	934	2.7
10	arms moving	960	4	99.6	960	4	99.6
11	Simulated setting up a table (maneuvering)	960	910	5.2	900	132	85.3
12	Simulated washing and drying the dishes	960	953	0.7	960	953	0.7
13	Using a laptop	960	959	0.1	960	959	0.1
14	Slalom	960	960	0.0	960	659	31.4
15	Simulated wheelchair basketball	960	960	0.0	960	893	7.0
16	Going up and down a slope	960	930	3.1	960	595	38.0
	Mean (SD)			**15.5 (31.2)**			**40.2 (30.7)**

[a] Total duration (s): total duration per task for all participants i.e. 16 participants*60 s per task = 960 s. [b] For clarification: According to the Activ8 monitor, participants were performing a certain activity for e.g. 162 s, while according to the video material (reference method) the duration of the activity was 960 s. From the two numbers the relative time difference is calculated, quantifying the difference in classification between the two methods. Abbreviations: SI, Sitting in a wheelchair; MA, Maneuvering; AP, Assisted propulsion; NSI, Normal speed independent; HSI, High speed independent

Table 4. Sensitivity and positive predictive value of Activ8 per class by division in two and five classes.

Two classes		Sensitivity*	Positive predictive value*
	Independent propulsion	87.5	87.8
	Other activities	68	68.5
	Mean	**77.7**	**78.2**
Five classes			
	Sitting in a wheelchair	84.2	99.3
	Maneuvering	18.4	23.7
	Normal speed independent	56.2	64.1
	High speed independent	56.6	29.1
	Assisted propulsion	48.9	43.2
	Mean	**52.8**	**51.9**

* mean values of all participants

DISCUSSION

Considering low values of relative time difference between Activ8 and video, high agreement, sensitivity and predictive value scores, it can be concluded that the Activ8 is a valid system to differentiate between independent wheelchair propulsion and other non-propulsive wheelchair-related activities. When it comes to the validity of classification into five classes, taking into the account the high relative time difference for most tasks and low agreement, sensitivity and positive predictive value scores, it can be concluded that using the current algorithms, the proposed system is not valid. We will discuss the results we found in the light of validity studies on consumer- and research-grade activity monitors for wheelchair users and the general population.

For the two class comparison, our results were similar to those obtained by researchers who also used two monitors (ActiGraph GT3X+) in a previous study [13]. In the following comparison, the first number reflects results from this study: average agreement of 82.1% vs. 85.2%, sensitivity scores 77.7% vs. 88.3% and positive predictive value 78.2% vs 83.3%. Our results also compare favorably with other validity studies on activity monitoring in wheelchair population. Accuracy of 92% in distinguishing between independent wheelchair propulsion and other activities was reported by authors of one study who used six body-fixed monitors [16]. Another study found 84% agreement between the video and activity monitor output consisting of 3 body-fixed monitors, when quantifying active behavior in wheelchair-dependent children [15]. Classification accuracy of 96% was found in recognizing resting, wheelchair propulsion, arm-ergometry and deskwork activities, using a multi-sensor activity monitor [17]. A set consisting of two Activ8 monitors can therefore be considered just as valid as other systems, consisting of a larger number of monitors (up to six) or multi-sensor units (combination of accelerometer and other sensors), to distinguish between active propulsion and other activities.

Four activities (out of 16) showed a high relative time difference between video and Activ8 when classifying into two classes. These activities were treadmill and over-ground propulsion at low speed and being pushed in the wheelchair while making arm movements. All these activities were also poorly classified in a previous study which used two monitors [13]. Low speed propulsion (below 0.56 m/s) was often classified in the current study as assisted propulsion because of the very low activity of the wrist. This is in agreement with the study in which slow propulsion was misclassified as housework in almost 40% of cases [18]. The low propulsion speed in itself seems problematic in wheeled mobility, as is also the case in able-bodied populations at low walking speeds [10].

Being pushed in the wheelchair with simultaneous arm movements was incorrectly classified as independent wheelchair propulsion in the current and previous study [13]. However it should be noted that the instruction given to the participants differed between both studies. Instruction given in the study of Kooijmans et al. [13] to make arm movements resulted in excessive arm waving, which as the authors concluded did not resemble any activity that takes place while being pushed in the wheelchair. After taking

this into consideration, we chose a different task. Participants were instructed to look for an item in a bag that was placed on their lap and hand it to the researcher. However, the incorrect classification of this task suggests that there is still large overlap in movement intensity with independent wheelchair propulsion. One of the solutions might be to use a weighted vector count, in which the axis of the accelerometer that resembles the propulsion direction most gets more weight. This could be studied in future research.

The classification in five classes gave unsatisfactory results, i.e. agreement, sensitivity and positive predictive value scores between 52-57%. Similarly, a study found accuracy between 55-61% when trying to identify 10 wheelchair-related activities with use of one body-bound monitor and just a slightly higher accuracy (62-63%) with two body-bound monitors [18]. The 10 activities included slow, fast and passive propulsion, like the current study, but not maneuvering and sitting in a wheelchair.

There were three activities that were almost always correctly classified (time difference between video and Activ8 <10%) by the classification in 5 classes: being pushed with arms still, simulated washing and drying the dishes and using a laptop. This shows that for the activities, where either the wheelchair or the arms are moving, but not both, it is easy to make a correct classification. When considering simulated wheelchair basketball (mixed task, where 3 classes where distinguished in the video analysis: normal speed wheelchair propulsion, maneuvering and sitting in a wheelchair), although the time difference between the video and Activ8 classification seems small, analysis per class revealed that sitting in a wheelchair and maneuvering were often mutually misclassified during this task.

Twelve out of sixteen tasks were often misclassified after the division in five classes. In addition to the tasks that were incorrectly classified by the division in two classes, the following tasks had high differences between video and Activ8: treadmill propulsion at 1.11 m/s, treadmill propulsion at 1.11 m/s and slope of 3%, treadmill propulsion at 1.67 m/s, self-paced propulsion at normal and high speed, simulated setting up a table, slalom, going up and down a slope. In all those activities except simulated setting up a table, normal and high speed propulsion often got mutually misclassified. Our algorithm classified velocities of more than approximately 1.53 m/s as high speed propulsion. However, it should be noted that both during treadmill and over-ground propulsion, accelerations may vary between the pushes. On the treadmill this could be caused by the left-right and front-back steering. During over-ground propulsion (which took place in a rectangular shape hallway to increase the ecological validity as propelling a wheelchair in daily conditions, often involves going around corners) the accelerations were smaller when taking corners. Additionally, it should be noted that over-ground propulsion was self-paced. It could therefore be that some participants were propelling too slow during the task of high speed propulsion and simply did not reach the threshold. Selecting a threshold between normal and high speed propulsion remains challenging. Perhaps this could be solved by making the threshold for high speed propulsion higher. This could, however, result in a situation where patients with less function, moving slower would have

all their propulsion classified as normal speed propulsion. To achieve correct classification, probably individual determination of the high speed threshold for each participant should take place, as inter-individual differences in propulsion technique and movement velocity may have large impact on the resulting classification. Individual determination of the threshold would compromise the user-friendliness. Another option would be to measure the velocity based on revolutions and known wheel diameter. For this purpose, number of revolutions should be added to the current output of the Activ8 monitor.

The activity setting-up a table was often misclassified. This task was designed to be classified as maneuvering, an activity where periods of propulsion are not longer than 5 seconds. The tables were placed at short distance from each other to make sure the participants did not propel fast and stopped every 3-4 seconds. Since this study included able-bodied participants, they were often able to perform this task very fast and often without having to stop for a long time. This resulted in setting-up a table often being misclassified as normal speed propulsion.

Lack of demonstrated ability to distinguish among the five classes is disappointing although similar challenges occur in physical activity monitoring used with able-bodied persons. We found that differentiating between maneuvering, normal speed propulsion and high speed propulsion is difficult. In both research- and consumer-grade devices for the general population, establishing the cut-off points for various intensity levels is challenging [14,19,20]. For research-grade devices, the cut-off points for moderate and vigorous intensity differ largely between studies, even when the same activity monitor was used [14]. Additionally, low-intensity activities such as household chores, low-speed walking, and light-occupational activity are considered hard to estimate correctly [10]. Validity of the consumer-grade activity monitors is even lower. When classifying moderate and vigorous activities, validity is moderate, and correlation with research-grade devices can be as low as r=0.52 for some consumer-grade activity monitors [11]. From this point of view, validity of classification of Active8 into five classes is comparable with the validity of the consumer-grade monitors available for the general population.

This study has advantages and limitations. Use of two monitors in this study, of which only one body-bound positively influences the price and users' comfort. Another advantage of the current study is a choice of ecologically valid tasks such as simulated wheelchair basketball or over-ground propulsion in a hallway. Finally this study has some limitations. For practical reasons, we chose to include a group of able-bodied participants who were already involved in another wheelchair propulsion study. Able-bodied persons may differ in some aspects such as range of motion or movements rates, from the actual wheelchair users. This may influence the classification, especially where a distinction is made between normal and high speed propulsion.

Future research should try to improve the accuracy of division in five classes, perhaps by adding velocity to improve the algorithms. In order to correctly identify assisted propulsion when arms remain in movement, weighted counts could be incorporated.

Experiments with various wheelchair-dependent populations are necessary to fine-tune the algorithms, determine the inter-individual differences and their influence on the classification. Additionally, the corresponding energy expenditure for various classes should be determined for various user groups such as patients with paraplegia and tetraplegia. Lastly, next to the amount of movement, the attention should be given to the quality of movements and parameters such as power output. This would be especially valuable when determining the dose-response relationship between various kinds of active propulsion and, for example, shoulder injury risk.

CONCLUSIONS

The proposed Activ8 system proved to be suitable for distinguishing amount of active wheelchair propulsion from other non-propulsive wheelchair-related activities. Activ8 is, therefore, suggested to be an appropriate device to describe the daily amount of independent wheelchair propulsion which constitutes for a substantial dose of physical activity in wheelchair-bound individuals. However, we concluded that the ability of the current system and algorithms to distinguish five various wheelchair-related activities is unsatisfactory. The five activities were: sitting in a wheelchair (wheelchair remains stationary), maneuvering, normal speed propulsion, high speed propulsion and assisted wheelchair propulsion.

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SUPPORTING INFORMATION

Supporting information is available on the website of the publisher.

S1 Data. Complete data set of 16 participants.

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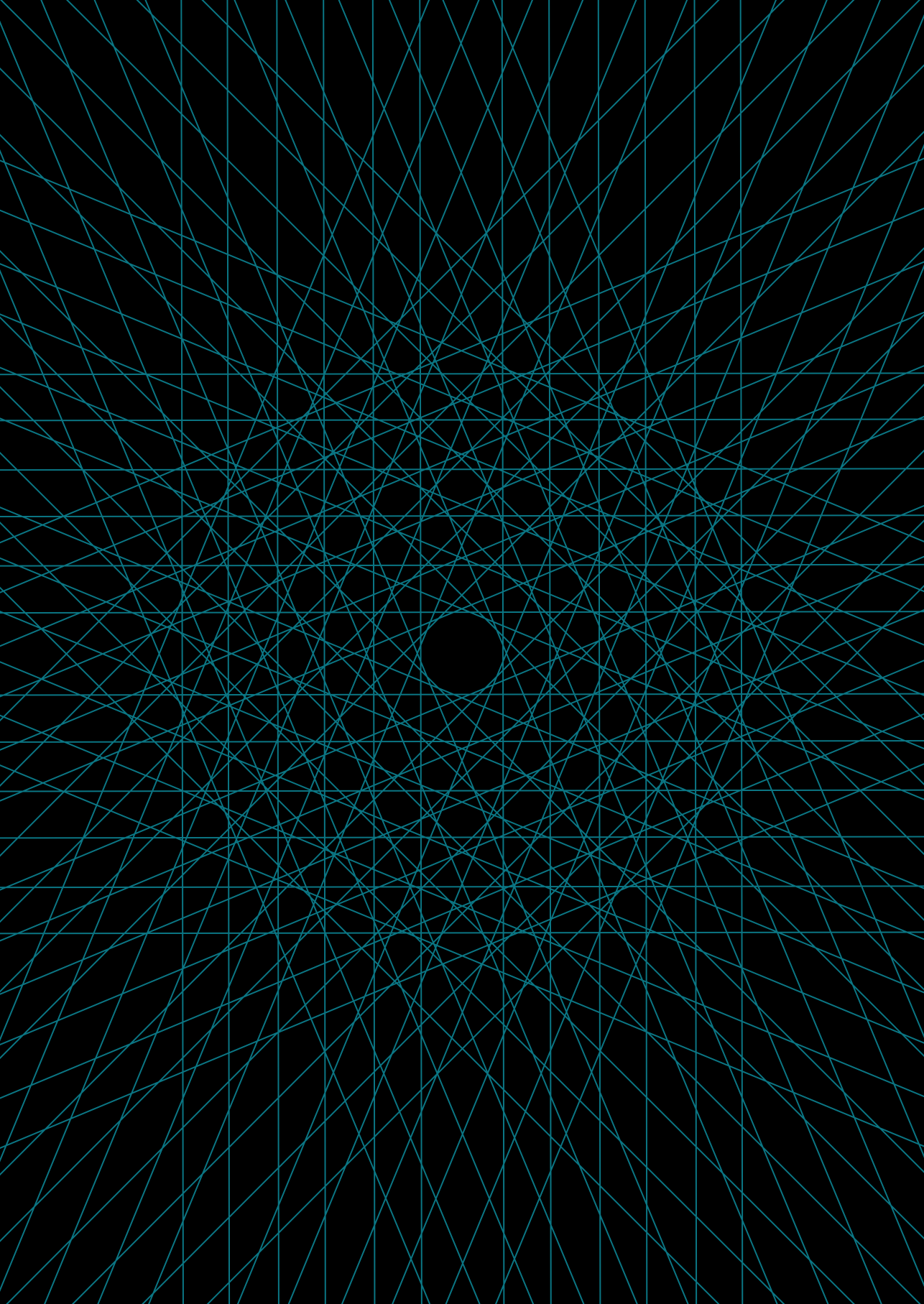

6

MOTOR LEARNING OUTCOMES OF HANDRIM WHEELCHAIR PROPULSION DURING ACTIVE SPINAL CORD INJURY REHABILITATION IN COMPARISON WITH EXPERIENCED WHEELCHAIR USERS

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ABSTRACT

Purpose: To investigate changes in wheelchair propulsion technique and gross mechanical efficiency (ME) across five weeks of active spinal cord injury (SCI) inpatient rehabilitation and to compare the outcomes at discharge with experienced wheelchair users with SCI.

Methods: Eight individuals with recent SCI performed six weekly submaximal exercise tests. The first and last measurement additionally contained a wheelchair circuit and peak graded exercise test. Fifteen experienced individuals with SCI performed all above-mentioned tests on one occasion.

Results: ME ($p=0.789$) and propulsion technique did not change during the first five weeks of active SCI rehabilitation. Peak power output increased ($p=0.028$) between the first and the last week. Performance time on the wheelchair circuit improved ($p=0.012$). No difference in propulsion technique, peak power output ($p=0.253$), and performance time ($p=0.463$) was found between the persons with a recent SCI and the experienced group. ME was higher after the correction for the difference in relative power output in the experienced group ($p<0.001$).

Conclusion: The group with a recent SCI did not improve ME and propulsion technique over the period of active rehabilitation, despite significant improvements on the wheelchair circuit and in work capacity. The only significant difference between the groups was found in ME.

INTRODUCTION

Proficiency in wheelchair propulsion is a key to independence among many individuals with a spinal cord injury (SCI). Low levels of wheelchair skill relates to social isolation and dependence on others [1,2]. In contrast, a high level of skill corresponds to higher independence, self-efficacy, participation and quality of life [2,3]. Even though the motor learning process of wheelchair propulsion is considered 'highly typical and important' [4], it is seldom studied during early rehabilitation. In this study we will describe the motor learning process of wheelchair propulsion across the period of active SCI rehabilitation and beyond, with appreciation of the complexity of the motor learning process and considering factors that mediate it.

The most frequently used outcome measures indicative for motor learning process of wheelchair propulsion are mechanical efficiency (ratio between energy expenditure and power output) and spatio-temporal aspects of propulsion technique measured by instrumented wheels [5-7]. Energy consumption and metabolic cost have been used as key indicators of motor learning of cyclic motion in work of Sparrow and Newell [8] and Almasbakk [9]. A previous study on the motor learning process in wheeled mobility showed that improvements in propulsion technique relate to an increase in mechanical efficiency [7]. Yet so far, in motor learning studies, those factors were described together primarily in experimental studies with able-bodied participants. Although mechanical efficiency has been shown to improve between the beginning of active rehabilitation (moment when the participant can sit in the wheelchair for three consecutive hours) and three months after [10], longitudinal changes in wheelchair propulsion technique during active SCI rehabilitation were not documented so far. Additionally, it is uncertain when the largest changes in efficiency took place as the mentioned study measured only at the beginning of active rehabilitation and 3 months after. Considering that wheelchair propulsion is often a novel skill learned during rehabilitation, and evidence from the able-bodied literature suggests that early motor learning process of this skill is rapid [7], it is crucial to intensify the frequency of the measurement occasions. Therefore, mechanical efficiency and propulsion technique in the current study will be measured longitudinally, once a week, across 5 weeks, starting at the beginning of active rehabilitation.

Changes in mechanical efficiency and propulsion technique across practice express the motor learning process in wheelchair propulsion. It is, however, necessary to mention that motor learning is a complex and multidimensional phenomenon, emerging from an interplay among various levels and constraints. To provide a comprehensive description of the motor learning process across rehabilitation, not only the mechanical efficiency and propulsion technique, but also factors influencing those outcomes need to be taken in account (Figure 1).

An increase in mechanical efficiency can take place due to i.e. improvements in propulsion technique and physiological adaptation. Using longer pushes at a low push frequency and creating little braking moment is thought to be more efficient [7]. On the

other hand, improvement in physical capacity during rehabilitation could also result in less energy being necessary to maintain a constant power output during propulsion i.e. an increase in mechanical efficiency. In order to properly identify the nature of changes in mechanical efficiency, physiological factors, cardio-respiratory function and muscle strength need to be considered.

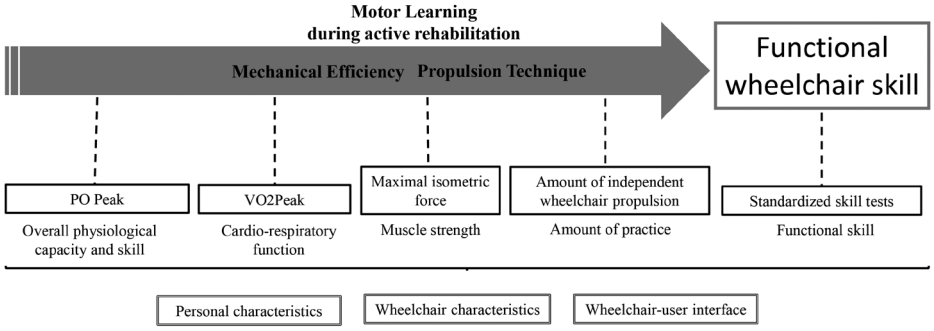

Figure 1. Motor learning in wheelchair propulsion leading to acquisition of the functional wheelchair skill can be quantified using the change in mechanical efficiency and propulsion technique. Although this study will not look at the association of mechanical efficiency and propulsion technique with other factors, we decided to include them to provide a complete picture of the multidimensional changes in physiology and skill during active SCI rehabilitation. Personal and wheelchair factors, as well as the wheelchair-user interface are not the focus of this study but it should be kept in mind that factors such as lesion level, kind of wheelchair or wheelchair fitting could potentially influence both the baseline level of motor skill as well as the pace of the motor learning process.

Motor learning of any skill is heavily dependent on the amount of practice. Amount of independent wheelchair propulsion was reported to increase during inpatient rehabilitation [11], but inter-individual differences in the amount of practice and their possible relation to motor learning have not yet been determined. Therefore the current study includes a reliable measure for quantifying the amount of independent wheelchair propulsion [12] across active SCI rehabilitation, which could potentially explain why some users show more skill than others. Moreover, in order to show how the above-mentioned outcome measures relate to a commonly performed clinical measure, which is simple, cheap and easy to administer, the score on the wheelchair skill circuit will also be included [13]. The wheelchair circuit provides information about the ability of the patient with SCI to perform functional wheeled-mobility skills.

Motor learning in wheelchair propulsion and many other motor skills takes place on various time scales [14]. Those scales range from the well-described within-session improvements in able-bodied novice wheelchair users [7] to improvements in propulsion technique or mechanical efficiency after weeks of practice [5,6,15,16]. Also improvements on a longer scale, across months or even years are expected. In this study next to the longitudinal description of the motor learning process across five weeks of active SCI rehabilitation, we would like to provide an indication concerning the level of wheelchair skill following the release from in-patient rehabilitation. In order to do that we will include

a group of experienced community-dwelling wheelchair users. This will also allow us to compare the functional status of the SCI patients at discharge from the rehabilitation center with experienced users.

The goal of this study is to investigate the longitudinal change in wheelchair propulsion technique and mechanical efficiency across five weeks of active in-patient SCI rehabilitation and to compare the outcomes at discharge from clinical rehabilitation with a group of experienced wheelchair users with SCI. Wheelchair propulsion technique and mechanical efficiency in both groups, will be presented in a context of related factors: physiological adaptation (Peak power output (POpeak), Peak oxygen consumption (VO2peak), bimanual isometric wheelchair-specific force), amount of practice (only in the longitudinal analysis) and level of functional wheelchair skills. We hypothesize that the group with a recent SCI will show improvement on all measured parameters across the duration of active SCI rehabilitation. Moreover, we expect the experienced wheelchair users to have a better propulsion technique, higher mechanical efficiency, achieve better results during the peak test and show better skill and higher strength than the group with a recent SCI. Quantifying wheelchair performance across and beyond the active SCI rehabilitation can help to point out the factors that may need more attention during active rehabilitation.

METHODS

Participants and ethics statement

Eight individuals with a recent SCI and 16 experienced wheelchair users with SCI participated voluntarily in this study (Table 1). All participants signed an informed consent before the onset of the experiment after receiving detailed written and verbal information about the character of the study and the nature and frequency of the measurements. The protocol of the study was approved by the Medical Ethical Committee, University Medical Center Groningen, The Netherlands (METC 2016/147; ABR: NL57063.042.16).

The group with a recent SCI was recruited from the clinical patient pool who were actively following inpatient rehabilitation at the Center for Rehabilitation, University Medical Center Groningen at the time of the study. Experienced participants were recruited from the out-patient population of the same center.

Criteria for inclusion were: having a recent SCI (for the longitudinal group); time since SCI > 2 year (for the experienced participants); expected manual wheelchair dependency; age between 18–65 years. Exclusion criteria were: having any cardiovascular contra-indications for testing according to the American College of Sports Medicine guidelines, or a resting diastolic blood pressure above 90 mm Hg or a resting systolic blood pressure above 180 mm Hg; insufficient knowledge of the Dutch language to understand the test instructions; progressive disease e.g. cancer or multiple sclerosis; psychiatric problem; pregnancy.

Study design

Both groups underwent a medical screening before the first measurement, to make sure they could safely participate in physical exercise testing. Screening was performed by a rehabilitation physician specialized in the post-SCI care. Participants in the group with a recent SCI performed six weekly measurements (Figure 2). First measurement took place at the start of active rehabilitation which was defined as a moment when participants could sit in a wheelchair for 3 consecutive hours. This is in accordance with previous studies [13] and ensured that participants were able to complete the first and last measurement moments which could take up to 3 hours. Experienced participants performed one measurement. The last measurement in the group with a recent SCI was also the discharge measurement and it was used to compare the wheelchair skill between the recent SCI and experienced group. Six out of eight participants in the group with a recent SCI performed the T6 measurement within 2 days from discharge. The remaining two, within 1 and 2 weeks.

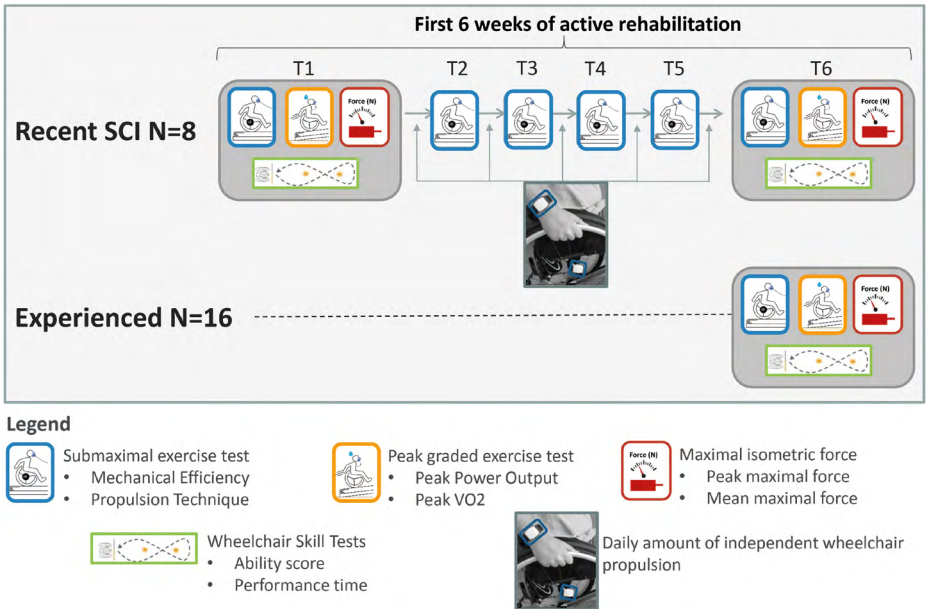

Figure 2. Study design. The first and the last measurement in the group with a recent SCI (N=8) and the measurement in the experienced group (N=16) contained the full test battery. The second to fifth measurement in the recent group were meant to monitor the motor learning process and consisted only of a submaximal test to determine ME and propulsion technique.

Experimental protocol

Screening

The screening aimed to determine whether any cardiovascular or musculoskeletal contraindications are present. The screening consisted of: lung and heart auscultation, measurement of the blood pressure, measurement of the resting ECG and screening for the cardiovascular contra-indications for testing according to the American College of Sports Medicine guidelines [17]. Additionally the lesion characteristics (level and

completeness according to American Spinal Injury Association International Standards for Neurological and Functional Classification of Spinal Cord Injury, [18] were established.

Drag test

Participants performed all tests in their own wheelchair which was either provided by the rehabilitation center (recent SCI) or in their personal daily wheelchair (experienced group). All changes to the wheelchair configuration, happening across the duration of the experiment in the group with a recent SCI, were recorded before each measurement occasion. Additionally the rolling resistance of the wheelchair and user was determined before each measurement during a drag test on the motor-driven treadmill [19,20].

Motor learning outcomes during submaximal exercise test

Propulsion technique and mechanical efficiency were determined during standard submaximal exercise testing on a motor-driven treadmill (2 identical blocks of 3 minutes, with 2 min rest in between, Figure 3) [10]. The last minute of each submaximal exercise block was analyzed. The mean value of two blocks per measurement occasion was used as input for the statistical test. The velocity for the testing was chosen for each participant and equaled either 0.55, 0.83 or 1.11 m/s (depending on the physical capability of the participant). Same applied to the inclination of the treadmill which equaled either 0 or 0.3°. Testing conditions (treadmill velocity and inclination) chosen for each participant at the first measurement occasion were not altered throughout the duration of the experiment (protocol fixed over time for a participant).

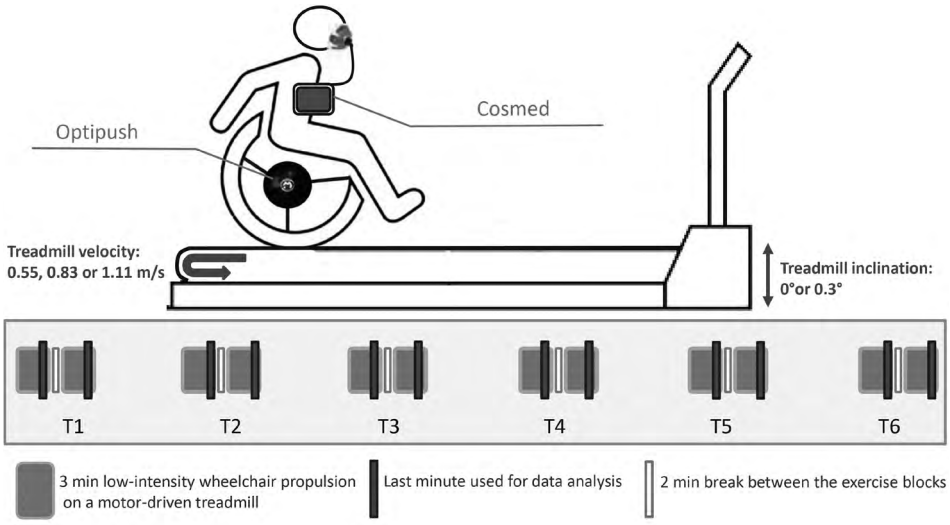

Figure 3. The submaximal exercise test was performed at each measurement occasion in the group with a recent SCI. Treadmill velocity and inclination were chosen for each participant based on their capabilities and were kept unchanged throughout the experiment. The right wheel was exchanged for an instrumented wheel with the same diameter, which continuously recorded the wheelchair propulsion technique. Oxygen consumption was determined breath-by-breath.

Propulsion Technique

During each submaximal test, the right wheel of the participant's wheelchair was exchanged for an instrumented Optipush wheel (MAX Mobility, LLC, Antioch, TN, USA) with the same diameter as participant's own wheels. The left wheel was exchanged for a dummy wheel with the same mass as the measurement wheel. The 3-dimensional forces and torques applied to the right handrim were continuously measured throughout the duration of each submaximal exercise test. The output registered by the measurement wheels was calculated into specific propulsion technique variables using custom-written Matlab algorithms [7] (Table 1).

Table 1. Propulsion technique variables. All variables except cadence were calculated as an average value of all pushes performed during the last minute of each practice block. Equations from Vegter et al [7].

Propulsion variable	Unit	Description	Equation
Push frequency	push/minute	The number of pushes performed during one minute	$N_{pushes}/\Delta t$
Contact angle	degrees (°)	The angle measured along the handrim, where participant's hand maintained contact with the handrim during each push	$Ø_{end\ (i)}–Ø_{start\ (i)}$
Positive work	J	The torque around the wheel axle integrated over the contact angle of the push	$\Sigma_{start\ (i)\ :end\ (i)}\ (Tz \cdot \Delta Ø)$
Braking torque	Nm	The braking torque applied to the handrim with each push. The sum of braking torque exerted on the handrim during coupling and decoupling of the hand	$\Sigma_{end\ (i)\ :start\ (i+1)}\ (Tz \cdot \Delta Ø)$
Peak force	N	3d peak force applied to the handrim during one push	$Max_{(start:end)}\ (Fx^2+ Fy^2+ Fz^2)^{0,5}$
Fraction effective force (FEF)	%	The ratio of effective to total force that was applied to the handrim during one push	$Mean_{(start:end)}(((Tz/r)/((Fx^2+ Fy^2+ Fz^2)0,5))\cdot 100\%$

Abbreviations: t, time(s); start(i), start of the current push (sample); end(i), end of the current push (sample); Tz, torque around wheel axle (Nm); Ø, angle (rad); Fx, Fy and Fz, force components (N); r, wheel radius (m); V, velocity (m/s).

Mechanical Efficiency

Oxygen uptake (VO2) and respiratory exchange ratio (RER) during steady-state wheelchair propulsion were continuously determined breath-by-breath using Quark CPET (experienced group) or Quark K4β2 (group with a recent SCI) (Cosmed, Rome, Italy). Quark CPET or Quark K4β2 were also used to record the heart rate.

Mechanical efficiency was calculated over the last minute of each 3-min block. The equation used to calculate mechanical efficiency was: ME =PO x E^{-1} x100%, where PO is power output and E is the energy expenditure, calculated according to the formula proposed by Garby and Astrup [21].

Monitoring the amount of independent wheelchair propulsion

In order to quantify the amount of practice between the weekly submaximal exercise tests, participants in the group with a recent SCI continuously wore a set of two activity monitors between the first and the last measurement moment. Activ8 Professional Activity Monitor (2M Engineering Ltd., Valkenswaard, The Netherlands) is a triaxial

accelerometer. One accelerometer was worn on the dorsal side of the dominant wrist and one on the corresponding rear wheel. Each monitor stored the output on a 5s epoch base. The vector counts were used to perform the classification. Classification was performed using custom-written Matlab algorithms, which were validated for detecting independent wheelchair propulsion [12]. Each epoch was classified either as independent wheelchair propulsion (propulsion as a result of arm power of the participant) or as other activity (including but not limited to: being pushed in the wheelchair, reaching movements, general upper body motions). A given epoch was classified as independent wheelchair propulsion if the wheel counts were contained between 31 and 310 counts or if they exceeded 310 and at the same time wrist counts exceeded 98 [12]. In all other cases, an activity was classified as 'other'. The outcome of the activity monitoring was a number of seconds of independent wheelchair propulsion per day. Only full days were included in the data analysis. Participants were asked to keep a diary where they could indicate if they forgot to put on the wrist accelerometer so that those days were not included in the data analysis. The data of all available days in a week was used to calculate a daily average for each given week, which was then used in the analyses. Additionally, the five-week averages of all weekend days (Saturday and Sunday) and all weekdays (Monday to Thursday) were calculated to indicate whether there was a difference in the amount of practice between the days with scheduled therapy and without it. Fridays were not included in the analysis, as Friday was a test day. Participants were not wearing the activity monitors during the tests to not confound the results (longer testing procedure at T1 and T6 could result in more measured activity). Additionally the batteries of the activity monitors needed to charge on Friday.

Wheelchair circuit

The Wheelchair Circuit is a test to assess manual wheelchair skill performance. It consisted of 10 different standardized tasks, 8 tasks originally implemented by Kilkens et al. [13] and 2 tasks (holding a wheelie and propelling in a wheelie) proposed by Cowan et al., in order to attenuate floor and ceiling effects [22]. The tasks were performed in a fixed sequence with 2-min breaks between consecutive items. The tasks, in order of performance, were (1) figure-of-8 shape; (2) .04-m doorstep crossing; (3) .10-m platform ascent; (4) 15.0-m sprint; (5) propelling for 10s on a treadmill with a 3% inclination; (6) propelling for 10s on a treadmill with a 6% inclination; (7) holding a wheelie for 10 seconds; (8) propelling 3m in a wheelie; (9) making a level transfer; and (10) a 3-minute wheeling test on the treadmill. All tests were performed either on a motor-driven treadmill or on an even linoleum floor. The beginning and end point of each test was marked with tape, which was placed on the ground. Participants were instructed to perform the tests as fast as possible. Time score was recorded manually with a stopwatch. Time was recorded from the moment the participant began to drive until the front wheels of the wheelchair passed the finish line. The results of the Wheelchair Circuit consisted of two test scores: ability score and performance time. The ability score is a sum of points awarded per task. Each task is scored either 0 (not able to perform) or 1 (able to perform) point. Three tasks i.e. doorstep crossing, platform ascent and transfer, can be awarded 0.5 point. The ability score ranges from 0 to 10. The performance score is a sum of the performance time of the figure-of-8 and the 15-m sprint.

Work capacity

Bimanual maximal isometric force test

The maximal isometric test is a wheelchair-specific test meant to measure the maximal force that a user can apply to the handrim while the wheelchair remains stationary. The participant, while sitting in the wheelchair, tries to push forward as hard as possible. The wheelchair remains stationary due to a cable, which connects the force transducer with the wheel axle [23]. Each participant performed this test 3 times at a given measurement occasion. The last attempt was used in the data analysis.

Peak graded exercise test

This test consisted of 1-min exercise blocks where the velocity of the treadmill belt was held constant and the workload increased every 60 s by increasing the inclination of the treadmill (1 step each minute) [24]. Velocity equaled the velocity chosen for the submaximal test. The test ended when the participant could no longer maintain his or her position on the belt as a consequence of exhaustion, or when the participant indicated that he/she wanted to stop. Oxygen uptake and heart rate were monitored continuously using Quark K4β2. Highest 30-s mean was calculated to acquire the values of peak oxygen uptake and peak heart rate. The peak power output achieved during the highest inclination maintained for at least 30 s was noted based on the results of the drag test.

Statistical analysis

All statistical analysis was performed using IBM SPSS Statistics version 21.0 (SPSS Inc., Chicago, IL, USA).

Longitudinal analysis in the group with a recent SCI

Data in the group with a recent SCI was not normally distributed and therefore non-parametric testing was used. If there was one missing data point for a certain participant for a given variable, the mean from the two adjacent data points was used to replace the missing value. If there was more than one missing data point, the participant was excluded from the analysis. The reasons for the missing data were: malfunction of the testing devices, participant being unable to complete a test because of spasms or in case of one participant, unwillingness to perform the peak graded exercise test. Total number of participants per variable is provided in the results section.

To analyze the longitudinal change (6 measurement moments per participant) in mechanical efficiency, propulsion technique variables and the amount of independent wheelchair propulsion, Friedman's test was used. The difference in the amount of active propulsion during the average of weekend days and weekdays was determined using a Wilcoxon Signed Rank test.

Since the peak graded exercise test, wheelchair circuit and maximal isometric strength test were only performed at the first and the six measurement occasion, the change in the outcomes of those test was compared using Wilcoxon Signed Rank test.

Comparison between the participants with a recent SCI and experienced wheelchair users

Data used for the between group comparison was normally distributed. Independent t-test was used to check for initial differences in continuous data between the recent SCI and experienced group. Chi square was used to check for initial differences in categorical data (gender, lesion completeness, lesion level). Since relative power output during the submaximal test differed significantly between the groups, it was used as a correction factor as it influences both the propulsion technique and the mechanical efficiency [15,16]. Other outcomes i.e. work capacity and wheelchair skills were not corrected for differences in power output because it is not defined whether and how the power output influences all those outcome measures. One-way ANCOVA with a fixed factor (group) and covariate (relative power output) was implemented to compare the propulsion technique and mechanical efficiency between the experienced users and the group with a recent SCI at discharge (T6). To allow the reader an independent interpretation of the results, both analysis: with and without the covariate is presented in the results section. Significance for all above-mentioned tests was set at $p < 0.05$.

RESULTS

The personal and lesion characteristics for both groups are presented in Table 2.

Longitudinal analysis in the group with a recent SCI

Propulsion technique and mechanical efficiency during submaximal exercise test

All participants in the group with a recent SCI (N=8) completed the testing protocol (Table 3). Power output during propulsion at a submaximal intensity remained constant throughout the experiment (p=0.952). On the group level, there were no changes in any of the propulsion technique variables or mechanical efficiency across time. Individual moment around the wheel axis during the first and the last measurement occasion is presented per participant in Figure 4.

Amount of independent wheelchair propulsion

The amount of independent wheelchair propulsion did not change throughout the 5 weeks of active SCI rehabilitation (p=0.282) (Table 3). Participants were more active during the weekdays (Monday to Thursday) than in the weekend (Median = 6870 s (Range=3684 s) vs 4999 s (7415 s), p=0.049).

Wheelchair circuit

Participants showed a borderline improvement in the ability score (9 (4.5)à 9.5 (3), p=0.066) and a significant decrease in the performance time of the Figure-of-8 and 15m sprint (17.6 s (11.2 s)à 16 s (8.6 s), p=0.012) (Table 4).

Table 2. Personal and lesion characteristics for the group with a recent SCI (N=8) and the experienced group (N=16).

Recent SCI										
ID	**Lesion level ASIA (motor)**	**Lesion completeness ASIA A-E**	**TSI (years)[a]**	**Age (years)**	**Gender[b]**	**Height (m)**	**Body mass (kg)**	**Wheel size (inch)**	**Velocity (m/s)[c]**	**Inclination (treadmill step)[d]**
1	T12	B	0.2	39	M	1.76	72	25	1.11	1
2	T5	A	0.3	54	F	1.66	58	25	1.11	1
3	T12	C	0.2	21	M	1.85	58	25	1.11	1
4	C7	D	0.3	56	F	1.76	66	24	0.83	0
5	T12	A	0.2	53	F	1.63	60	25	1.11	1
6	T5	A	0.2	19	M	1.8	76	25	1.11	1
7	T3	A	0.2	22	M	1.88	80	25	1.11	1
8	L3	D	0.2	53	M	1.83	83	25	1.11	1
Mean ± SD	-	-	**0.2 ± 0.05**	**40 ± 17**	-	**1.76 ± 0.10**	**69 ± 10**	-	-	-
Experienced										
1	T4	D	3.8	50	M	1.83	120	26	1.11	1
2	T6	A	3.8	27	M	1.9	95	26	1.11	1
3	T5	A	2.5	22	M	1.97	95	25	1.11	1
4	T9	D	4.2	59	M	1.95	100	25	1.11	1
5	C5	D	3.9	38	F	1.78	87	25	0.55	0
6	T12	C	9.1	44	M	1.69	75	25	1.11	1
7	T5	A	7.3	45	M	1.8	95	25	1.11	1
8	T3	A	9.1	42	M	1.9	104	24	1.11	1
9	T3	A	23.2	45	M	1.78	80	25	1.11	1
10	T7	D	3.3	27	F	1.67	96	24	1.11	1
11	T3	A	7.3	50	M	1.68	100	25	1.11	0
12	C8	B	6.6	26	M	2.01	120	26	1.11	0
13	T11	A	2.5	55	F	1.69	65	25	1.11	1
14	T6	A	8.6	32	M	1.88	95	25	1.11	1
15	T11	A	8.8	53	M	1.91	100	25	1.11	1
16	T9	A	6.3	35	M	1.72	68	24	1.11	1
Mean ± SD	-	-	**6.9 ± 5.0**	**41 ± 11**	-	**1.82 ± 0.11**	**93 ± 16**	-	-	-
P value	**0.450[e]**	**0.887[f]**	**<0.001[g]**	**0.864[g]**	**0.181[g]**	**0.226[g]**	**0.001[g]**			

[a] TSI calculated as number of years between injury and the first measurement. [b] M, male; F, female. [c] Preferred treadmill velocity for the submaximal and peak graded exercise tests. [d] Preferred treadmill inclination for the submaximal and peak graded exercise tests. [e] p value of Chi-Square Test. [f] p value of Fisher's Exact Test. [g] p value of an Independent Samples T-test

Table 3. Longitudinal course (T1-T6) in mechanical efficiency and propulsion technique in the group with a recent SCI.

	Median (Range)[a]						p value	N
	T1	T2	T3	T4	T5	T6	Time effect[b]	
Propulsion technique								
Push frequency (push/min)	60 (35)	58 (46)	54 (44)	54 (51)	55 (58)	53 (55)	0.434	8
Contact angle (°)	77 (37)	74 (34)	78 (29)	78 (31)	77 (34)	76 (38)	0.734	8
Positive work per push (J)	8.9 (7.5)	8 (8.3)	8.8 (8)	9.1 (8.7)	8.3 (9.5)	9.1 (9.4)	0.266	8
Braking moment (Nm)	-0.23 (0.71)	-0.14 (0.64)	-0.24 (0.99)	-0.24 (0.6)	-0.21 (0.31)	-0.19 (0.72)	0.794	8
Peak force (N)	53 (18)	52 (11)	59 (18)	61 (27)	54 (24)	59 (26)	0.060	8
FEF (%)	72 (39)	72 (41)	65 (39)	71 (46)	68 (56)	64 (53)	0.106	8
Mechanical efficiency (%)	6.6 (4.2)	6 (3.5)	6 (3.8)	5.7 (3.6)	6.5 (3.1)	6.1 (2.2)	0.789	7
Heat rate (beats/min)	106 (20)	106 (28)	104 (30)	108 (26)	105 (28)	109 (37)	0.762	8
Power output (W)	14.2 (9.6)	13.8 (7.9)	13.4 (9.3)	13.8 (9.5)	13.8 (10.7)	14.3 (9.5)	0.952	8
Energy expenditure (W)	211 (76)	246 (69)	219 (89)	222 (92)	224 (81)	231 (75)	0.176	7
Amount of independent propulsion (s/day)	T1-T2	T2-T3	T3-T4	T4-T5	T5-T6			
	5630 (4098)	6223 (3395)	5642 (6167)	6944 (4645)	6801 (4148)		0.282	8

[a] Average of two exercise blocks per measurement occasion. [b] Friedman Test for the time effect

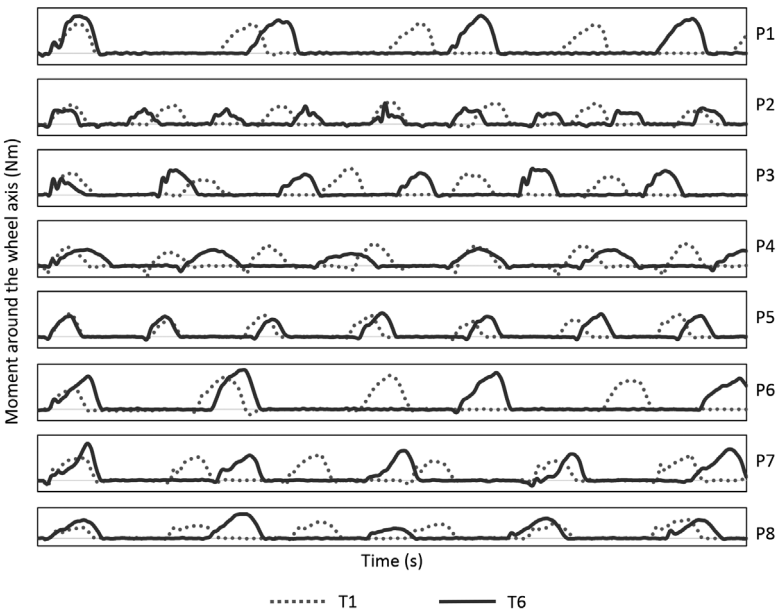

Figure 4. Individual moment around the wheel axis during the first and the last measurement occasion for each participant in the group with a recent SCI (N=8).

Work capacity

Maximal isometric force test

The group with a recent SCI managed to generate higher peak (589 N (467 N) → 621 N (488 N), p=0.036) and mean forces (501 N (457 N) → 579 N (480 N), p=0.012) during the maximal isometric force test at the last measurement.

Peak graded exercise test

Participants increased the peak power output between the first (40 W (51 W)) and the last measurement (48 W (56 W); p=0.028) (Table 4). Peak VO2 and peak heart rate remained unchanged.

Table 4. Results of the wheelchair skill tests, maximal test and maximal force test performed in the group with a recent SCI at the pre- (T1) and the post-test (T6). Significant results are presented in bold.

	Pre	Post	p value Wilcoxon Signed Rank Test	N
	Median (Range)			
Wheelchair circuit				
Ability score [a]	9 (4.5)	9.5 (3)	0.066	8
Performance time score (s) [b]	17.6 (11.2)	16 (8.6)	**0.012**	8
Work capacity				
Maximal isometric force test [c]				
Peak force (N)	589 (467)	621 (488)	**0.036**	8
Mean force (N)	501 (457)	579 (480)	**0.012**	8
Peak graded exercise test				
Peak VO^2 (ml/min)	1200 (712)	1199 (1045)	0.080	5
Peak power output (W)	40 (51)	48 (56)	**0.028**	6
Peak heart rate (beats/min)	167 (89)	170 (87)	0.686	5

[a] The ability score of all 10 skill tests. [b] Sum of the time score of the figure-of-8 and the 15 m sprint.
[c] The final (third) trial of the maximal force test was used to compare the pre- and the post-test values

Comparison between the participants with a recent SCI and experienced wheelchair users

The majority of the personal and lesion characteristics did not differ at baseline between the groups. The only parameter that was different was body mass, which was significantly higher in the experienced group when compared to the participants with a recent SCI (93 kg ± 16 kg vs 69 kg ± 10 kg).

Propulsion technique and mechanical efficiency during submaximal exercise test

Relative power output in the people with a recent SCI was approximately 33% higher when compared to the experienced group (respectively 0.21 W/kg ± 0.03 W/kg vs 0.16 W/kg ± 0.04 W/kg, p=0.006) (Table 5). Absolute power output did not differ between the group with a recent SCI and the experienced group (14.4 W ± 3.0 vs 14.9 W ± 4.4 W, p=0.790).

Both with and without the inclusion of the covariate, there were no differences in propulsion technique between the recent SCI and the experienced group. In contrast, the difference in mechanical efficiency approached significance without correction and was higher in the group with a recent SCI (6.1% ± 0.7% vs 5.1 ± 1.3 %, p=0.077). After correcting for the difference in relative power output, the corrected mean mechanical efficiency was significantly higher in the experienced group (5.2 % ± 0.2 % vs 5.5%

± 0.2%, p<0.001). Difference in heart rate during submaximal intensity propulsion approached significance (with as well as without the covariate) and was higher in the group with a recent SCI. Energy expenditure was significantly higher in the experienced group independent of whether the covariate was used or not.

Table 5. Results of the between group comparison. Effects with and without the relative power output correction. Significant results are presented in bold.

	No correction [e]			**Relative power output correction**[e]		
	Group Mean (SD)		p value	Model Estimated Mean (SE)		p value
Submax test	Recent N=8	Experienced N=15		Recent N=8	Experienced N=15	
Relative power output (W/kg)	0.21 (0.03)	0.16 (0.04)	**0.006**			
Power output (W)	14.4 (3.0)	14.9 (4.4)	0.790			
Propulsion technique						
Push frequency (push/min)	56 (18)	51 (13)	0.448	53 (6)	52 (4)	0.473
Contact angle (°)	74.4 (14.0)	77.9 (13.7)	0.565	72.0 (5.6)	79.2 (3.9)	0.566
Positive work per push (J)	8.9 (3.7)	9.6 (2.9)	0.652	7.9 (1.2)	10.2 (0.8)	0.188
Braking moment (Nm)	-0.25 (0.23)	-0.33 (0.42)	0.609	-0.39 (0.14)	-0.26 (0.1)	0.114
Peak force (N)	56.9 (9.4)	61.3 (12.8)	0.402	56.5 (4.9)	61.6 (3.3)	0.698
FEF (%)	65 (18)	63 (13)	0.678	61 (6)	65 (4)	0.252
Mechanical efficiency (%) [a]	6.1 (0.7)	5.1 (1.3)	0.077	5.2 (0.2)	5.5 (0.2)	**<0.001**
Heat rate (beats/min)	107.6 (11.9)	93.5 (17.6)	0.055	103.4 (6.3)	95.7 (4.3)	0.063
Energy expenditure (W) [a]	229.5 (31.9)	289.8 (41.8)	**0.003**	220.1 (16.4)	294.2 (10.6)	**0.007**
Wheelchair circuit	Recent N=8	Experienced N=16				
Ability score [b]	8.9 (1.3)	9.5 (1.1)	0.261			
Performance time score (s)[c]	16.6 (3.3)	15.5 (3.5)	0.463			
Work capacity						
Peak graded exercise test	Recent N=6	Experienced N=16				
Peak VO^2 (ml/min)	1232 (414)	1616 (568)	0.148			
Peak power output (W)	45.1 (20.4)	57.6 (22.7)	0.253			
Peak heart rate (beats/min)	163 (32)	165 (26)	0.912			
Maximal isometric force test[d]	Recent N=8	Experienced N=16				
Peak force (N)	552 (202)	623 (171)	0.375			
Mean force (N)	510 (188)	539 (146)	0.678			

[a] For mechanical efficiency and energy expenditure for the recent group N=7. [b] The ability score of all 10 skill tests. [c] Sum of the time score of the figure-of-8 and the 15 m sprint. [d] The final (third) trial of the maximal force test was used to compare the pre- and the post-test values. [e] Univariate analysis of variance without or with the inclusion of a covariate (Relative Power Output).

Wheelchair circuit

The level of wheelchair skills was similar in both groups. The ability score in the group with a recent SCI (8.9 ± 1.3) did not differ significantly from the one in the experienced group (9.5 ± 1.1, p=0.261). Both groups needed a similar amount of time to perform the 15 m sprint test and a Figure-of-8 (recent SCI 16.6 s ± 3.3s vs experienced 15.5 s ± 3.5 s, p=0.463).

Work capacity

Maximal isometric force test

The peak isometric force (recent SCI 552 N ± 202 N vs experienced 623 N ± 171 N, p=0.375) and mean isometric force (recent SCI 510 N ± 188 N vs experienced 539 N ± 146 N, p=0.678) that participants could generate did not differ between the groups.

Peak graded exercise test

There were no differences between the recent SCI and experienced group in the peak VO2 (1232 ml/min ± 414 ml/min vs. 1616 ml/min ± 568 ml/min, p=0.148), peak power output (45.1 W ± 20.4 W vs 57.6 W ± 22.7 W, p=0.253) and the peak heart rate (163 beats/min ± 32 beats/min vs 165 beats/min ± 26 beats/min, p=0.912).

DISCUSSION

The group with a recent SCI did not show improvements in the primary outcome measures of this study, the mechanical efficiency and propulsion technique, despite significant improvements on the wheelchair circuit performance score and in physical work capacity over the period of active rehabilitation and 5 weeks after. Moreover, the differences between the group with a recent SCI and experienced participants were less pronounced than hypothesized, with the only significant difference found in mechanical efficiency and no differences in propulsion technique, work capacity and on the wheelchair circuit scores.

1. Propulsion technique and mechanical efficiency during the submaximal exercise test

1.1 Longitudinal analysis in the group with a recent SCI

Contrary to our hypothesis, we found no improvements in propulsion technique and mechanical efficiency during 5 weeks of active inpatient rehabilitation in individuals with a recent SCI. This finding was surprising as in the previous studies, mechanical efficiency showed to improve in the first 3 months of active rehabilitation [10,25] and between the beginning and end of active SCI rehabilitation [26]. A possible explanation for the lack of improvement in ME in the current study could be its duration, in total 5 weeks. The previous studies looked at changes after 3 months and then at discharge. This would not be possible here as the whole period of active rehabilitation for our participants was no longer than 10 weeks, since the length of stay in the rehabilitation center has been shortening progressively over the last years, due to policy changes and financial incentives [27]. Future studies should consider extending the measurements beyond the discharge from active rehabilitation. This could help to observe the long-term changes in ME.

In previous literature, propulsion technique and mechanical efficiency showed to be sensitive to change in the early stages (12 min to 7 weeks) of learning in able-bodied participants [5,7,15,16]. This motivated our choice to initiate the measurements at the start of active rehabilitation. It is however important to realize, that in contrast to the able-bodied individuals [5,7,15,16], participants in the group with a recent SCI were not totally naïve to the task of wheelchair propulsion at the onset of the study as they received a wheelchair before the inclusion. Since even very short (12 min) and low-intensity practice can elicit significant changes in mechanical efficiency and propulsion technique [7], it cannot be excluded that the rapid short-term changes took place before the onset of the present study. Perhaps starting measuring even earlier, for example from the moment when participants receive a manual wheelchair, would be able to capture the very early improvements in technique and efficiency. It is however arguable whether such study design would be feasible and ethically responsible.

Another explanation for the lack of group-level changes in propulsion technique could be the heterogeneity of the group with a recent SCI and resulting inter-individual differences in learning. The presence of individual learning trajectories in wheelchair propulsion was documented before [6]. When inspecting Figure 4, it is apparent that two out of eight

participants, P2 and P3 showed a different course of propulsion technique over the weeks than others. When comparing the torque signal around the wheel axis, it is visible that P2 and P3 increased their push frequency and decreased the contact angle between T1 and T6. This direction is opposite to the one observed in the remaining 6 participants. It also contradicts previous literature which found group-level decrease in push frequency and increase in contact angle of the hand on the handrim in early stages of motor learning process in novice able-bodied wheelchair users [5,7,15]. The heterogeneity of changes in propulsion technique is difficult to interpret, especially considering the small group size in this study. It is however interesting to explore what caused these two individuals, presented with an identical task, to choose various movement strategies. Understanding the inter-individual differences in motor learning is a prerequisite to creating individualized therapies targeting the improvement in wheelchair skill.

1.2 Comparison between the participants with a recent SCI and experienced wheelchair users

The differences between the group with a recent SCI and experienced participants were less pronounced than hypothesized, with the only significant difference found in mechanical efficiency. It is quite unexpected that, independent of the relative power output correction, there were no differences in the wheelchair propulsion technique between the group with a recent SCI and the experienced participants. The mean and standard deviation values for all propulsion technique variables were very similar in both groups. This finding is very surprising as previous studies found differences in propulsion technique between novice and expert users, both while propelling on the ergometer as during over-ground propulsion [28,29]. It should however be considered that these two mentioned studies looked at differences between experienced wheelchair users and able-bodied persons with no previous wheelchair experience. As mentioned previously, the group with a recent SCI was not totally naïve to the task of wheelchair propulsion.

Propulsion technique did not change across active rehabilitation in the group with a recent SCI and there were no differences in technique between the groups with a recent and long-term SCI. Moreover the overall values of frequency and contact angle in both groups resembled those reported in other studies [28,30-33]. Those findings support the earlier discussion point that at least some of the improvement in the propulsion technique in the group with a recent SCI could have taken place before the onset of the study.

Mechanical efficiency, in contrast to propulsion technique, was different between the groups. The interpretation of this difference is, however, difficult as it completely changed direction after the relative power output correction. Without the power output correction, the mechanical efficiency in the group with a recent SCI (6.1%) was borderline significantly higher than in the experienced group (5.1%). This finding was unexpected as mechanical efficiency is known to be higher in experts [34]. After the correction for the difference in relative power output between the groups, the direction of difference changed. Model estimated mean mechanical efficiency in the experienced group (5.5%) was significantly higher than in the group with a recent SCI (5.2%). This

result requires some explanation. First of all we attempted to find out where the large difference in relative power output between the groups came from. Potential sources included: participants' body mass, wheelchair mass and quality or fitting of a wheelchair to the person. We discovered that power output and body mass showed only a moderate correlation, r=0.36 (Figure 5). Based on this we concluded that the much higher body mass in the experienced group (93 kg vs 69 kg), did not explain the difference in relative power output between the groups. We then looked into the state of the wheelchair and its fitting to individual participants. The group with a recent SCI propelled in wheelchairs provided by the rehabilitation center while the experienced users propelled in their own custom-made wheelchairs. We concluded that in the experienced group, each wheelchair was fitted to the individual participant, while in the group with a recent SCI the fitting was often limited to choosing between the few available wheelchairs. Subsequently, no fitting of the foot support, the width or the height of the seat, for/aft seat position or backrest was performed. Additionally, the wheelchairs in the group with a recent SCI were in general less well maintained as evident from factors such as: frame deformations, disturbed rolling of the front wheels, rolling out asymmetrically. As a result of those factors, despite the much higher body mass, the experienced group propelled at a lower relative power output. This result is unexpected but clinically, very relevant. The fact that a good wheelchair with a proper fitting might be at least partially capable of offsetting the effect of 25 kg of body mass emphasizes the need to provide properly fitted wheelchairs to patients as early as possible, with a goal of improving efficiency but also preventing shoulder overload injuries which are very common in individuals who use manual wheelchairs for mobility [35-38]. As a matter of fact, improper wheelchair fitting and maintenance could be some of the reasons why shoulder pain develops already in the early stages of inpatient rehabilitation [39].

1.3 Amount of independent wheelchair propulsion

The amount of independent wheelchair propulsion across 5 weeks of active rehabilitation in the group with a recent SCI did not increase. This is in contrast to another study which found that the level of dynamical activities increased during inpatient rehabilitation [11]. Measurements in that study were obtained at the start of active rehabilitation, 3 months later and at discharge. The lack of change in our study could be explained as we measured across a much shorter period of time. Also, the absolute amount of activity per day was different in our study. Van den Berg-Emons et al. [11] found a level of dynamic activities at the beginning of active rehabilitation to be 3.4 +/- 2.2 % of a day (49 min +/- 32 min), which is lower than in our study (94 min +/- 68 min). The difference could be explained by the fact that the study of Van den Berg-Emons et al. excluded maneuvering from their results [40] which constituted a substantial part of total activity in our study. We included maneuvering as the goal of this study was to quantify the amount of independent wheelchair propulsion practice and maneuvering is a part of that.

Next to the total amount of independent wheelchair propulsion per week we also looked at the difference between the weekend days and weekdays as there is no therapy scheduled during the weekend and participants spent roughly every weekend at home. We found

that participants were more active during the weekdays compared to the weekend. It could be that participants are less active during the weekends due to a lack of motivation or possibility to safely perform various activities. It could be that intervention specifically targeting amount of activity during periods when therapy is not provided is crucial for individuals with SCI to prevent a deterioration in overall wheelchair capacity. This suggestion is supported by Berg-Emmons et al [11], who reported that the amount of dynamical activities decreased after discharge from rehabilitation.

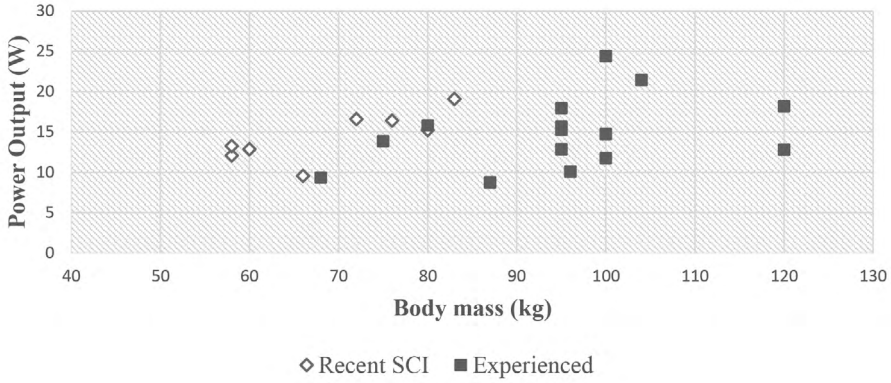

Figure 5. Scatter plot illustrating the relationship between body mass and absolute power output during submaximal exercise test in the group with a recent SCI (N=8, $\bar{x}$=14.4 W ± 3.0 W) and the experienced group (N=16, $\bar{x}$=14.9 W ± 4.4 W). With the large difference in body mass (24kg), this leads to a respective relative power for the recent and experienced group of 0.21W/kg and 0.16W/kg (P=0.006).

2. Wheelchair circuit

The difference between T1 and T6 in scores on the wheelchair circuit showed that the group with a recent SCI improved the performance of functional wheeled-mobility skills. Although the improvement agrees with other studies [13,41], the differences in absolute scores between the studies are remarkable. Median performance time score in the current study was much better, both at T1 (17.6 s) and at T6 (16 s) when compared to the mean scores acquired at the beginning of rehabilitation (28.7 s) and at discharge (19.4 s) in individuals with paraplegia in a previous study [13]. It is interesting to add that the time between T1 and discharge in the previous study was on average 172 days [13] while in the current study the period between T1 and T6, was 5 weeks, so only 35 days. Time since injury at T1 did not differ between the studies.

Contrary to our hypothesis the experienced group did not score better on the wheelchair skill tests than the group with a recent SCI. The mean ability score differed by merely 0.6 point between the groups with both groups scoring high (recent SCI 8.9/10; experienced 9.5/10). Similarly, the mean performance time difference between the groups was 1.1 s. It is therefore safe to assume that this difference would have little effect on the functional capacity of the participants. Wheelchair circuit scores were reported previously to exhibit ceiling effect [41]. This could be related to a fact that the pass/fail scoring

system may not be sensitive enough to quantify the differences in wheelchair skill level across rehabilitation or between various groups with varying experience. It is however remarkable that the ceiling effect in the group with a recent SCI was found already at the start of rehabilitation and despite the fact that we added two relatively difficult skills: stationary wheelie and riding in a wheelie. Without the addition of those two tasks, using the scoring range of Kilkens et al. [13] from 0 to 8, the difference between the recent SCI and experienced group would be even smaller (7.6 vs 7.7) Altogether, the results of wheelchair circuit suggest that the group with a recent SCI included in this study was quite skilled, already at the onset of rehabilitation and the chosen 10 skill tests did not allow to discriminate between the groups.

3. Work capacity

Generally speaking, all work capacity outcomes in both groups do not deviate from values reported for similar populations by other studies [42,43]. Work capacity, operationalized as wheelchair-specific isometric force and outcomes of the peak graded exercise test, improved over the period of 5 weeks in the group with a recent SCI. Increase in both peak and mean isometric force between T1 and T6 is a desired outcome. It shows that participants improved force production and its application to the handrim. Additionally, they improved the peak power output during the peak graded exercise test, which is considered to be an important measure for overall wheelchair capacity and skill. Higher peak power output relates to an increased chance for return to work after suffering a SCI [44] and better quality of life [45].

Surprisingly the difference in work capacity between the recent SCI and experienced group turned out to be smaller than expected. Even though there is a visible trend in all outcome measures favoring the experienced group, none of the differences were significant. This could be related to a heterogeneity within the groups which potentially masked some of the differences.

Future recommendation

Apart from the findings that this study reported, there are two aspects that could be addressed in future studies and clinical practice to make sure that patients with SCI receive the best possible and evidence-based care. First of all, this study pointed out how different the current rehabilitation reality is when compared to that approximately 15 years ago. The length of stay in inpatient rehabilitation is progressively shortening which makes the results of studies conducted 10-15 years ago very difficult to use in rehabilitation programs. The same will most likely be true for the current study. The policy changes are galloping and considering the time needed to gather data for a study like the present one from one rehabilitation center (nearly 2 years) we must ask each other whether this kind of studies are justifiable. Furthermore, we should consider alternative approaches with a goal of developing and updating scientific knowledge in order to provide material for evidence-based therapy. An alternative approach could include a use of wheelchair-mounted, multisensory activity monitors that could be used very early in the rehabilitation setting without putting too much burden on the participants.

Additionally, working towards fixed protocols documenting the progress of wheelchair skill throughout rehabilitation and implementation of those in multiple centers, could allow to build much bigger data sets and form ecologically valid results [46].

The second recommendation relates to the large relative power output difference between the two groups. It is worth adding that if we did not standardize the tire pressure to 6 bar, the difference between the groups would be even more striking as the tires in the group with a recent SCI tended to be less inflated than in the experienced group. This suggests that the state of the wheelchair and its fitting to the participant should probably receive more attention in early rehabilitation.

Limitations

As mentioned previously, the limitation of this study is the small sample size of the group with a recent SCI. The N could ideally have been higher, especially to improve the statistical power by offsetting the heterogeneity of the group. It was, however, not feasible to include more participants from one rehabilitation center during the duration of the current study and given the time intensive measurements for both the participants and the research team. Another limitation is the inclusion bias which is often an issue in studies which include vulnerable groups. Our results may not be representative of the whole population with SCI, as it is reasonable to think that considering the effort participants needed to put in this study, only the relatively fit persons volunteered to participate. Lastly, it should be kept in mind that this study was performed in a single rehabilitation center in the Netherlands. It may therefore not be fully representative of other rehabilitation centers in the Netherlands and definitely of those around the world.

CONCLUSION

Despite improvements on the wheelchair circuit and in work capacity, the group with a recent SCI did not show improvements in the primary outcome measures of this study, the mechanical efficiency and propulsion technique. It could be that learning curves for ME and propulsion technique are different than those of the other reported parameters. It may be that the most rapid changes in both parameters took place before the onset of the study. Additionally, our study may have not been long enough to capture further optimization.

The differences between the group with a recent SCI and experienced participants 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. Propulsion technique was so similar between the groups that based on our results, there is no ground to think that the findings would be different with a larger sample size. Contrary to that, differences in work capacity and on the wheelchair circuit were not significant, but showed a unanimous trend favoring the experienced group.

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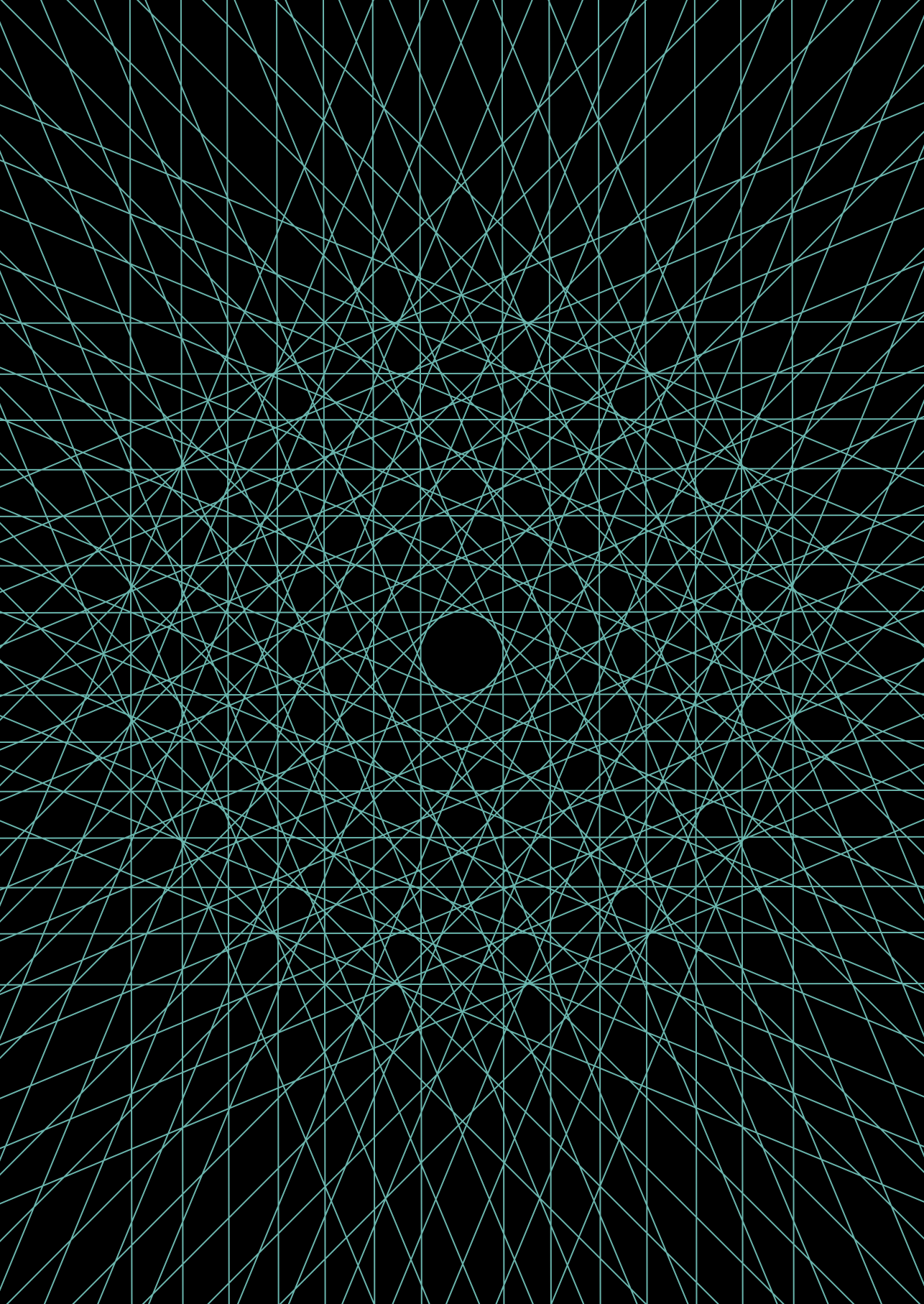

7

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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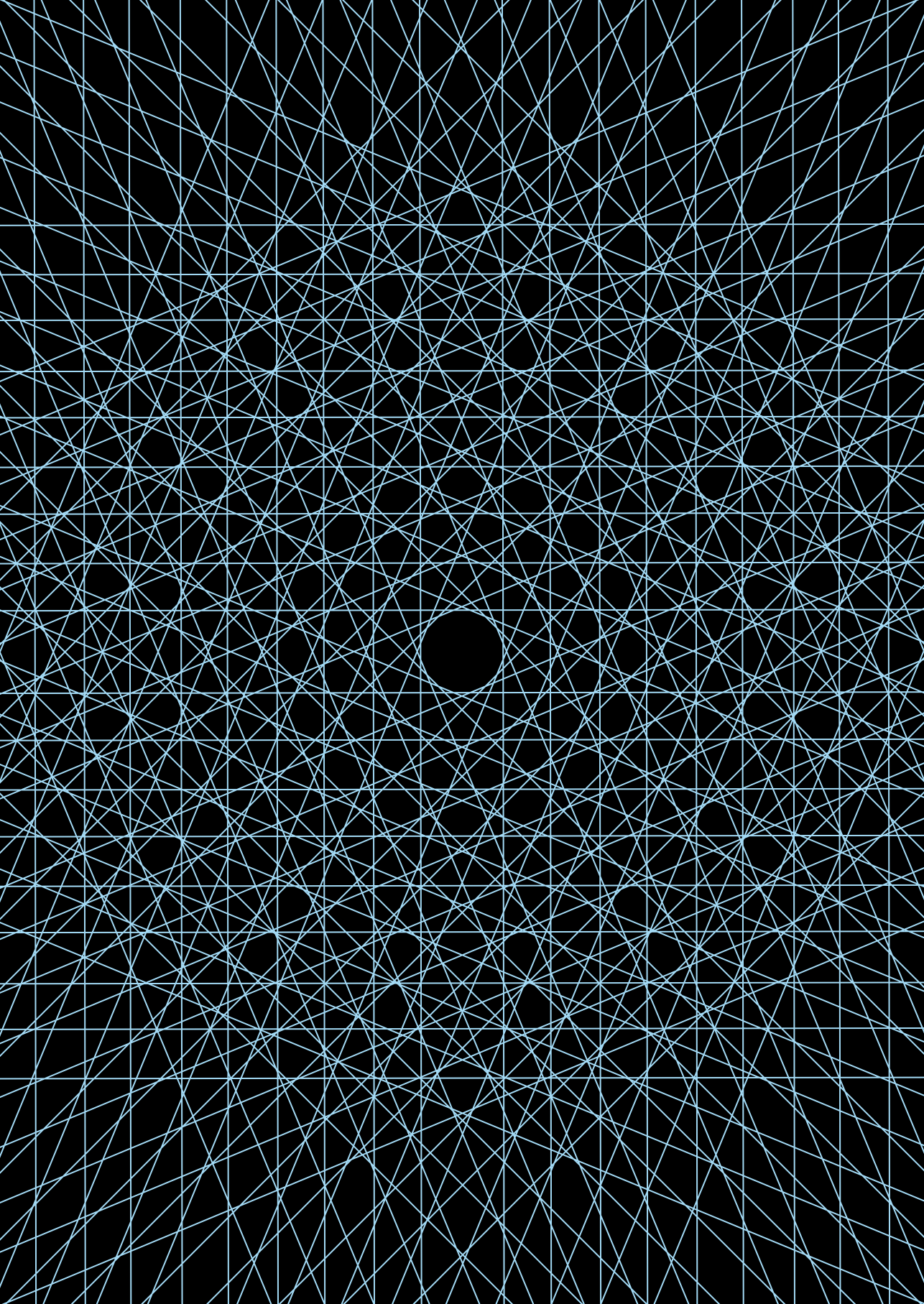

8

APPENDICES:

- SUMMARY IN ENGLISH
- SUMMARY IN DUTCH
- ACKNOWLEDGMENTS
- ABOUT THE AUTHOR
- SCIENTIFIC OUTPUT
- CONFERENCE CONTRIBUTIONS
- RESEARCH INSTITUTE SHARE

SUMMARY IN ENGLISH

Proficiency in wheelchair propulsion is a key to independence among many individuals with a spinal cord injury (SCI). While low levels of wheelchair skill relate to social isolation and dependence on others, high levels of skill correspond to higher independence, participation and quality of life. Even though the motor learning process of handrim wheelchair propulsion is considered highly important, it is still not well understood. The goal of this thesis is to widen the understanding of the motor learning process in handrim wheelchair propulsion. The knowledge gathered in this thesis is anticipated to contribute to evidence-based guidelines concerning wheelchair skill acquisition, which on the long term will enhance the quality of life and participation among wheelchair-dependent persons. The primary outcomes of motor learning in this thesis were the mechanical efficiency (ratio of power output and energy expenditure) and kinetic aspects of the wheelchair propulsion technique measured at the level of the handrim.

Chapters 2 and 3 examined the influence of various forms of variable practice on the motor learning process of handrim wheelchair propulsion in able-bodied participants. The implementation of variable practice was motivated by recent experimental findings in various tasks, including handrim wheelchair propulsion. Those studies claimed that intra-individual movement variability may be a manifestation of motor exploration and is suggested to enhance the outcomes of the motor learning process by allowing to find a more optimal task solution.

Chapter 2 aimed to increase the variability of practice by providing real-time visual feedback on the propulsion technique in a controlled lab-based environment. This 80-min experiment on a motor driven treadmill led to improvements in wheelchair propulsion technique, but they were not greater than in a natural practice group which received the same practice dose, but without visual feedback. Moreover, only the natural practice group increased the mechanical efficiency between the pre- and the post-test. These results suggested that feedback-induced variability on a motor driven treadmill was not beneficial for the improvement in mechanical efficiency.

Chapter 3 introduced a different form of variable practice to a group of novel able-bodied wheelchair users, i.e. uninstructed practice in a free environment. Variable practice consisted of five wheelchair-skill tasks and a 30 min wheelchair basketball game. The results were compared with a no-practice control group which performed exclusively the pre- and the post-test. Compared to the control group, variable practice resulted in an increase in mechanical efficiency. Interestingly, the large relative improvement in mechanical efficiency was concomitant with only moderate improvements in the propulsion technique, which were not significantly different between the groups.

Previous studies observed simultaneous improvements in mechanical efficiency and propulsion technique during the natural motor learning process, when no instruction or feedback was provided to the able-bodied participants. Chapters 2 and 3 showed that

this relationship does not necessarily hold when participants receive an intervention targeting the propulsion variability. Additionally the direction of changes in both primary parameter sets may strictly depend on the task and the environmental constraints as is suggested by the opposing effects of two various types of variable practice on the motor learning process of handrim wheelchair propulsion.

Chapter 4 re-evaluated a part of the data of the participants from Chapter 2 to analyze the concomitant changes in wheelchair propulsion technique and shoulder load. Shoulder pain frequently occurs in wheelchair-users affecting up to 80% of all manual wheelchair users after long-term use. The Clinical Practice Guidelines for preservation of upper limb function following SCI suggest that using a proper wheelchair propulsion technique could minimize the shoulder injury risk. Yet, the exact relationship between the wheelchair propulsion technique and shoulder load is not well understood. This study found that despite homogenous changes in propulsion technique measured at the level of the forces and torques applied to the handrim, the kinematic solution to the task varied widely among the participants, as did the model-based shoulder loads. This experiment also suggested that extreme values of the propulsion technique variables e.g. very high contact angle or very low push frequency may not be beneficial for the load on the shoulder. This suggests that current clinical practice guidelines may be too simplistic and that their advice to use long pushes at low frequency, in some cases, may lead to an increase in shoulder overload risk.

Chapter 5 was a preparatory experiment aiming to study the validity of an activity monitor (Activ8) for wheeled mobility to quantify the daily amount of independent wheelchair propulsion. The Activ8 system proved to be suitable for distinguishing between active wheelchair propulsion and other non-propulsive wheelchair-related activities in able-bodied participants during a set of standardized wheeling tasks. However, the ability of the current system and algorithms to distinguish five various wheelchair-related activities is unsatisfactory. The system should, therefore, not be used in the current configuration to distinguish between various wheelchair-related tasks.

Chapter 6 aimed to describe the motor learning process in actual wheelchair users as they undergo inpatient rehabilitation following SCI. Their outcomes at discharge from active rehabilitation were compared to a group of experienced community-dwelling wheelchair users with a SCI. This study had an observational character and took place within 'care as usual', introducing regular measurement moments, but not intervening in the regular rehabilitation schedule. The group with a recent SCI did not improve on the primary outcomes of the motor learning process - mechanical efficiency and propulsion technique - across five weeks of active rehabilitation. They did, however, exhibit significant improvements on the wheelchair circuit and in work capacity between the first week of active rehabilitation and discharge. It could be that the most rapid changes in efficiency and propulsion technique took place already in the days or weeks before the onset of the study. This emphasizes the need to start measuring even earlier during rehabilitation to understand early phases of motor skill acquisition, preferably using non-invasive

continuous monitoring during the activities of daily living, decreasing the need for extra measurement moments. The differences in skill proficiency between the group with a recent injury at discharge from inpatient rehabilitation and experienced wheelchair users were surprisingly small. The only significant difference between the groups was found in mechanical efficiency, which was higher in the experienced group, but only after the correction for the difference in relative power output (W/kg) between the groups. The difference in relative power output was possibly related to the difference in maintenance and fitting of the wheelchairs which was much better in experienced users. This, despite a significantly higher body mass in the experienced participants, led to a lower relative power output in this group. This finding is clinically relevant and emphasizes the need to provide well-fitted and well-maintained wheelchairs to the patients in active rehabilitation as soon as possible as it may influence not only their motor learning process, but even more important, may also help to prevent overload injuries of the shoulder complex.

Chapter 7 provided a general discussion of the findings of this thesis, discussing their implications for clinical practice, as well as for future studies to further develop knowledge about the motor learning process in handrim wheelchair propulsion. This thesis showed once again that motor learning in wheelchair propulsion is a very complex process with numerous interconnected aspects. The emergent movement pattern is a result of an interplay between the person, the task and the environment. Any changes in one or more of those may lead to different motor solutions. Current practice does not yet have a proper understanding of this important process, which makes the provision of individualized evidence-based care to the patients impossible. Implementation of wheelchair propulsion laboratories was proposed as a possible solution to this. 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.

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SUMMARY IN DUTCH

Vaardig zijn in het aandrijven van een hoepelrolstoel is belangrijk voor onafhankelijk functioneren voor veel personen met een dwarslaesie. Een onvoldoende niveau van rolstoelvaardigheid kan leiden tot sociaal isolement en afhankelijkheid van anderen, daarentegen leidt een hoog niveau van vaardigheid tot een grotere onafhankelijkheid, participatie en kwaliteit van leven. Hoewel het motorisch leerproces van het rijden in een hoepelrolstoel als zeer belangrijk wordt beschouwd, is er nog weinig wetenschappelijke kennis over beschikbaar. Het doel van dit proefschrift is om meer kennis te verkrijgen van het motorisch leerproces van rijden in een hoepel- aangedreven rolstoel. De kennis verzameld in dit proefschrift zal naar verwachting bijdragen aan op evidentie gebaseerde richtlijnen met betrekking tot het motorisch leerproces van rolstoelrijden, wat op de lange termijn participatie en de kwaliteit van leven van rolstoelafhankelijke personen zal kunnen verbeteren. De primaire uitkomstmaten van motorisch leren in dit proefschrift waren de mechanische efficiëntie (d.i. de verhouding van het extern geleverde vermogen (vooral bepaald door snelheid en de rijweerstand) en de daarvoor benodigde metabole energie) en de kinetische aspecten van de rolstoelaandrijftechniek, gemeten op het niveau van de hoepels met een geinstrumeteerd meetwiel.

Hoofdstukken 2 en 3 beschreven de invloed van verschillende vormen van variabel oefenen op het motorisch leerproces van hoepelrolstoelrijden bij gezonde proefpersonen. Variabel oefenen werd in beide hoofdstukken op verschillende wijzen en in een verschillende taakomgeving geimplementeerd. De keuze voor variabel oefenen was gemotiveerd door recente wetenschappelijke bevindingen die suggereren dat intra-individuele bewegingsvariabiliteit een uiting van motorische verkenning kan zijn en belangrijk is om het motorisch leerproces te ondersteunen door een meer optimale taakoplossing te laten vinden.

Hoofdstuk 2 had als doel de variabiliteit van het oefenen te vergroten door real-time visuele feedback te geven op de aandrijftechniek van de proefpersonen op de lopende band in een gecontroleerde (laboratorium) omgeving. Dit 80 minuten durende experiment, leidde tot verbeteringen in de rolstoelaandrijftechniek, maar deze waren niet groter dan in een groep die dezelfde oefenvorm en -dosis ontving, maar dan zonder visuele feedback. Bovendien verhoogde alleen de groep die oefende zonder feedback de mechanische efficiëntie tussen de voor- en de nameting. Deze resultaten suggereerden dat de door visuele feedback geïnduceerde variabiliteit op een loopband niet bevorderlijk was voor de verbetering van de mechanische efficiëntie.

Hoofdstuk 3 introduceerde een andere vorm van variabel oefenen in een rolstoel voor een groep onervaren gezonde proefpersonen, d.w.z. oefenen zonder expliciete instructie in een vrije omgeving. De variabele oefening bestond uit vijf rolstoelvaardigheidstesten en een rolstoelbasketbalwedstrijd van 30 minuten. De resultaten werden vergeleken met een controlegroep die uitsluitend de pre- en de posttest uitvoerde. In vergelijking met de controlegroep leidde de variabele oefening tot een toename van de mechanische

efficiëntie. In tegenstelling tot de grote verbetering in mechanische efficiëntie, verbeterde de aandrijftechniek echter slechts matig en niet significant verschillend tussen de groepen. Eerdere studies observeerden gelijk met elkaar oplopende verbetering in mechanische efficiëntie en aandrijftechniek tijdens het natuurlijke motorische leerproces, dus wanneer er geen instructie of feedback werd gegeven aan de gezonde deelnemers die laag-intensief oefenden. Hoofdstukken 2 en 3 hebben aangetoond dat deze positieve verandering in zowel mechanische efficiëntie als aandrijftechniek niet noodzakelijkerwijs geldt wanneer proefpersonen een interventie ontvangen die gericht is op de aandrijftechniekvariabiliteit. Bovendien kan de richting van veranderingen in beide primaire uitkomstmaten strikt afhankelijk zijn van de taak en de omgevingskenmerken, zoals wordt gesuggereerd door de tegengestelde effecten van twee verschillende soorten variabele oefeningen op het motorische leerproces in de experimenten van Hoofdstukken 2 en 3.

In **Hoofdstuk 4** werd een deel van de data van de deelnemers uit hoofdstuk 2 wat betreft de veranderingen in rolstoelaandrijftechniek en schouderbelasting nader geanalyseerd. Schouderpijn komt vaak voor bij rolstoelgebruikers, vooral na langdurig (jaren) rolstoelgebruik, en treft tot 80% van alle handbewogen rolstoelgebruikers. De klinische praktijkrichtlijnen voor het behoud van de functie van armen en schouders na een dwarslaesie stellenen dat het gebruik van een goede rolstoelaandrijftechniek het risico op schouderletsel kan minimaliseren. De exacte relatie tussen de rolstoelaandrijftechniek en schouderbelasting is echter nooit goed onderzocht. Een potentiele risicofactor voor schouderklachten is een hoge schouderbelasting tijdens alledaags rolstoelrijden. De studie in hoofdstuk 4 toonde aan dat ondanks homogene veranderingen in aandrijftechniek, gemeten op het niveau van krachten en draaimomenten van de hand op de hoepel, de kinematische oplossing voor de taakuitvoering sterk uiteenliep tussen de deelnemers. Dit leidde ook tot verschillen in schouderbelasting die geschat werden met een mathematisch computermodel. Dit experiment suggereerde ook dat extreme waarden van de aandrijftechniekvariabelen, bijvoorbeeld een zeer grote contacthoek of een zeer lage duwfrequentie, mogelijk niet bevorderlijk zijn voor de belasting op de schouder. Dit betekent dat huidige klinische praktijkrichtlijnen mogelijk te eenvoudig zijn en dat door hun gegeven advies, om een lange slag en lage duwfrequentie te gebruiken, in sommige gevallen de kans op schouderoverbelasting kan vergroten.

Hoofdstuk 5 beschrijft een experiment onder niet-rolstoelgebruikers en onderzocht de validiteit van een activiteitenmonitor (Activ8) om de dagelijkse hoeveelheid onafhankelijke rolstoelaandrijving te kunnen kwantificeren. Het Activ8 systeem bleek geschikt om onderscheid te maken tussen actieve rolstoelaandrijving en andere rolstoel-gerelateerde activiteiten bij gezonde proefpersonen tijdens een reeks gestandaardiseerde rolstoeltaken. Het huidige systeem was echter onvoldoende in staat om vijf verschillende rolstoel-gerelateerde activiteiten te onderscheiden. Het systeem moet daarom in de huidige configuratie niet worden gebruikt om verschillende rolstoelgerelateerde taken te onderscheiden.

Hoofdstuk 6 heeft het motorisch leerproces bij rolstoelgebruikers met een dwarslaesie in de actieve klinische dwarslaesierevalidatie bestudeerd via meerdere metingen over de tijd. Hun resultaten bij ontslag uit actieve revalidatie werden vergeleken met een groep ervaren rolstoelgebruikers met een dwarslaesie. Deze observationele studie vond plaats binnen de klinische dwarslaesiebehandeling van revalidatiecentrum Beatrixoord, UMCG, waarbij op zes vaste meetmomenten binnen het reguliere revalidatieschema gestandaardiseerde rolstoeltesten werden uitgevoerd, ondermeer op een lopende band en gebruikmakend van zuurstofopnameapparatuur en het geinstrumenteerde meetwiel. De groep met een recente dwarslaesie verbeterde niet wat betreft mechanische efficiëntie en aandrijftechniek gedurende de eerste vijf weken van actieve revalidatie. Zij lieten echter wel significante verbeteringen zien op een rolstoelcircuit en hun maximale rolstoelfitheid in geleverd piek vermogen nam toe tussen de eerste week van actieve revalidatie en ontslag. Het kan zijn dat de snelste veranderingen in mechanische efficiëntie en aandrijftechniek al in de dagen of weken voor de start van onze studie hadden plaatsgevonden. Dit benadrukt de noodzaak om al vroeg tijdens de revalidatie te beginnen met het vastleggen van kenmerken van het rolstoelvaardigheid, bij voorkeur met behulp van niet-invasieve continue monitoring tijdens de dagelijkse activiteiten met sensortechnologie waardoor er minder behoefte is aan extra meetmomenten. De verschillen in rolstoelvaardigheid tussen de groep met een recente dwarslaesie bij ontslag uit klinische revalidatie en de ervaren rolstoelgebruikers waren verrassend klein. Het enige significante verschil tussen de groepen betrof de mechanische efficiëntie, die hoger was in de ervaren groep, maar alleen na de correctie voor het verschil in het relatieve vermogen (W/kg) waarop beide groepen reden op de lopende band. Het verschil in het relatieve vermogen leek enerzijds gerelateerd aan kwaliteit in onderhoud, materiaal en afstelling van de rolstoelen, die in het voordeel lijken te zijn van de ervaren rolstoelgebruikers. Anderzijds was er een aanzienlijk hoger lichaamsgewicht voor de ervaren deelnemers (+25 kg gemiddeld), dat per definitie leidt tot een lager relatief vermogen in deze groep. Deze bevinding is klinisch relevant en benadrukt de noodzaak om zo snel mogelijk een op de persoon afgestelde en goed onderhouden rolstoel aan te bieden aan patiënten tijdens de actieve revalidatie, omdat dit niet alleen hun motorisch leerproces kan beïnvloeden maar, nog belangrijker, ook kan helpen om overbelastingschade aan het schoudercomplex te voorkomen.

Hoofdstuk 7 gaf een algemene discussie van de bevindingen in dit proefschrift. Implicaties voor de klinische praktijk en voor toekomstige studies werden besproken, om onder andere de kennis over het motorisch leerproces in hoepelaangedreven rolstoelrijden verder te ontwikkelen in praktijk en wetenschap. Dit proefschrift liet opnieuw zien dat het motorisch leren bij rolstoelaandrijving een zeer complex proces is met tal van onderling verbonden aspecten. Het bewegingspatroon is het resultaat van een wisselwerking tussen de persoon, de taak en de omgeving. Elke verandering in één of meer van deze domeinen kan leiden tot verschillende motorische oplossingen en de optimalisatie daarvan. In de huidige praktijk heeft men nog onvoldoende zicht op dit belangrijke en complexe proces, waardoor het verstrekken van geïndividualiseerde, op evidentie gebaseerde zorg aan de rolstoelgebruikers met een dwarslaesie lastig is. De implementatie van rolstoellaboratoria werd voorgesteld als een mogelijke oplossing

hiervoor. De beschikbare technologie biedt nieuwe mogelijkheden voor het bouwen van een efficiënt multi-centrum netwerk van rolstoellaboratoria om clinici te assisteren bij het bieden van een geïndividualiseerde diagnose, rolstoelpassing en behandeling rond vaardigheid en fitheid. Uiteraard moeten deze multi-centrum verzamelde meetgegevens worden gedeeld voor verdergaand functionaliteit-gestuurd wetenschappelijk onderzoek.

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Marika



ABOUT THE AUTHOR

I was born on October 15th, 1986 in Poland, as the first child of Ewa and Włodzimierz Klimczak. Already during my early education, I have developed an interest in the human body and biology. Curious to find out more about it I chose a renowned high school in my hometown, Kalisz, with an advanced profile in biology and chemistry. Subsequently I went on to study physical therapy at the University School of Physical Education in Poznan. Motivated by my fascination in other cultures and languages, I chose to spend a semester abroad in Tampere, Finland where I got a chance to work with patients at various rehabilitation hospitals and clinics. After graduation, I moved to Groningen, the Netherlands where in 2015 I graduated the master program of Human Movement Sciences with specialization in Rehabilitation and functional recovery with a cum laude distinction. Because of a successful publication of a research paper in a top-tier peer-reviewed journal during my master program, I was awarded a fully-funded PhD position at the University Medical Center Groningen.

During my PhD, I worked in an international and multidisciplinary environment which greatly enriched my scientific skills and allowed me to understand the reality and challenges of rehabilitation care. Additionally, I was involved in a number of teaching and student supervision activities as well as management tasks within the SHARE Research Institute and the Graduate School of Medical Sciences at the University Medical Center Groningen. Moreover, parallel to my PhD, for six months I took on a role of academic advisor for the bachelor and master students.

At the moment I continue my academic career by working as a junior teacher at the Center for Human Movement Sciences.

SCIENTIFIC OUTPUT

Leving MT, Vegter RJ, Hartog J, Lamoth CJ, de Groot S, van der Woude LH. Effects of visual feedback-induced variability on motor learning of handrim wheelchair propulsion. PLoS One. 2015;10: e0127311.

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MANUSCRIPTS IN PROGRESS

Vegter RJK, Paulson T, Morrissey D, Mason B, **Leving MT**, van der Scheer J, Bru B, van der Woude LHV, Goosey-Tolfrey V. Understanding propulsive shoulder forces and scapular kinematics during manual wheelchair use.

De Groot S, Cowan RE, MacGillivray M, **Leving MT**, Sawatzky BJ. Reliability of measuring wheelchair propulsion technique in people with a spinal cord injury: a G- and D-study.

CONFERENCE CONTRIBUTIONS

2018: 6th International REHABMOVE State-of-the-art congress, Groningen, The Netherlands, **Oral presentation**

2018: World Congress of Biomechanics, Dublin, Ireland, **Oral presentation**

2017: Progress in Motor Control, Miami, USA, **Poster presentation**

2017: Annual Dutch Congress of Rehabilitation Medicine, Maastricht, The Netherlands, **Poster presentation**

2016: VvBN PhD Day, Maastricht, The Netherlands, **Oral presentation**

2016: Symposium Physical strain, work capacity and mechanisms of restoration of mobility in the rehabilitation of individuals with a spinal cord injury, Enschede, The Netherlands, **Oral presentation**

2016: Annual Dutch Congress of Rehabilitation Medicine, Maastricht, The Netherlands, **Poster presentation**

2016: American College of Sports Medicine Annual Meeting, Boston, USA, **Poster presentation**

2015: 1st Conference on Motor Skill Acquisition at Kisakallio, Finland, **Oral presentation**

2014: 4th International Congress on Complex Systems in Sports and Healthy Ageing, Groningen, The Netherlands, **Oral presentation**

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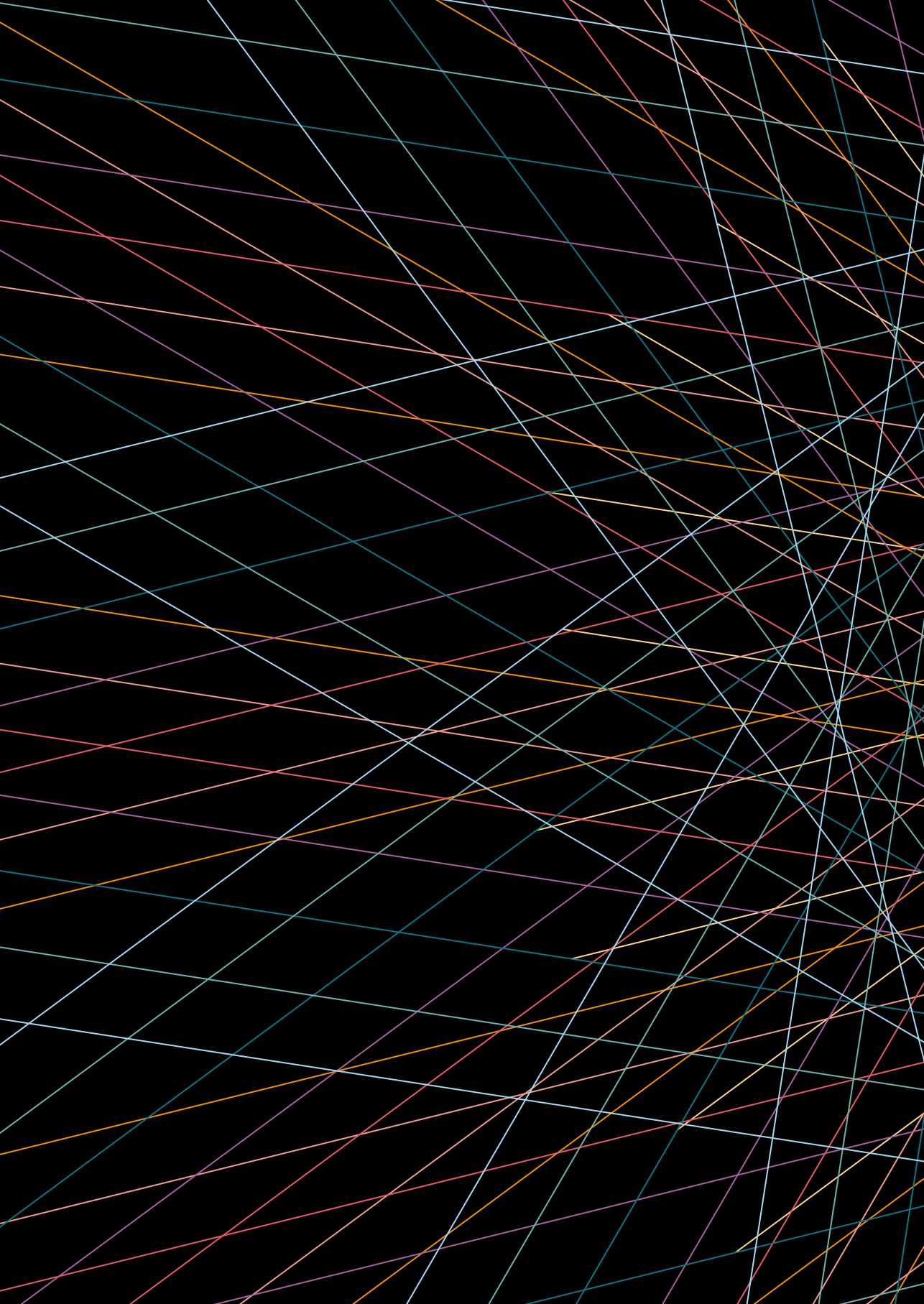

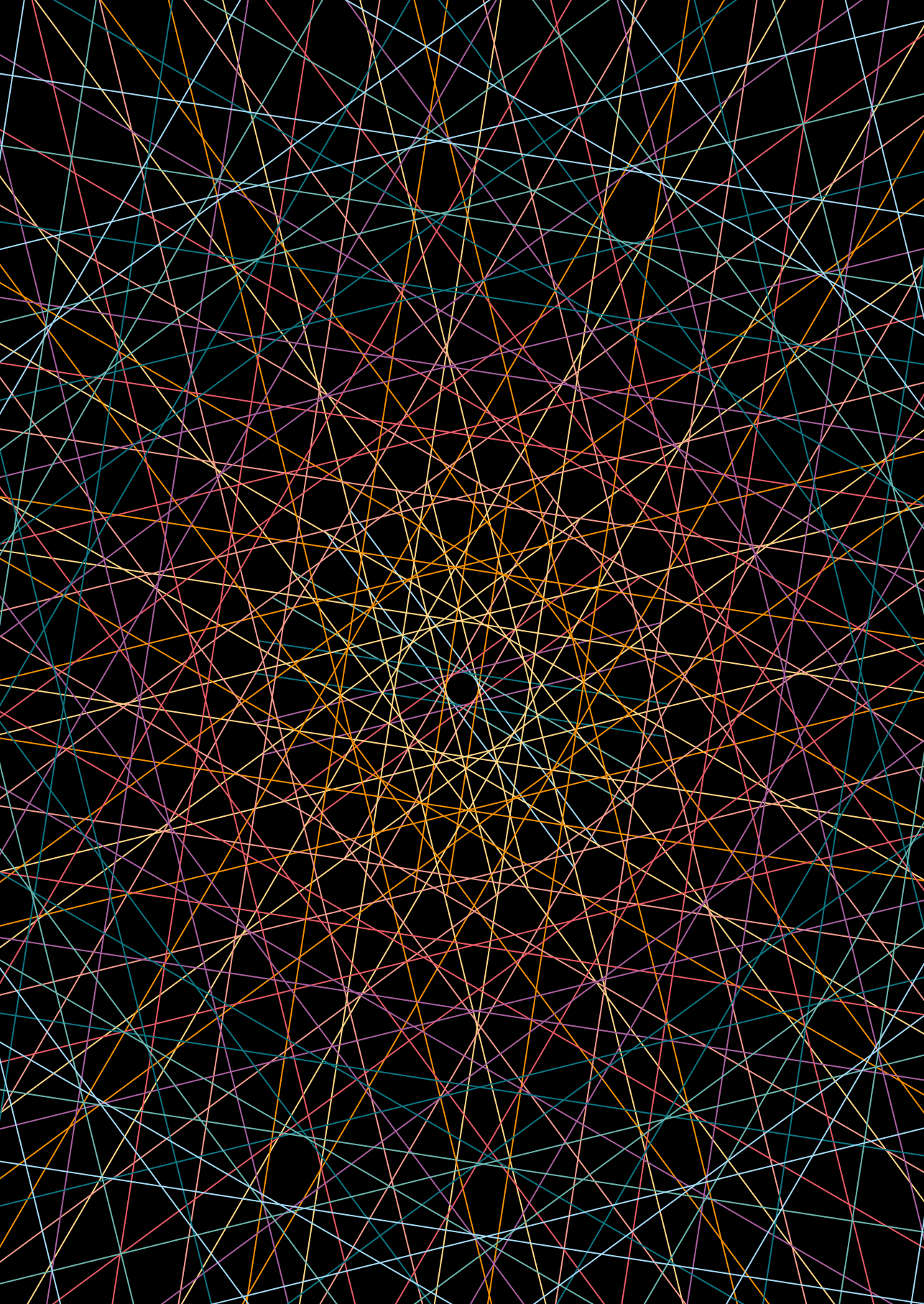



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