KEEP ON ROLLING

Functional evaluation of power-assisted wheelchair use

Marieke Kloosterman

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FUNCTIONAL EVALUATION OF POWER-ASSISTED WHEELCHAIR USE

Marieke Kloosterman

ADDRESS OF CORRESPONDENCE
Marieke Kloosterman
Roessingh Research and Development
PO Box 310
7500 AH Enschede
The Netherlands
0031 53 4875777
mariekekloosterman83@gmail.com

The publication of this thesis was financially supported by:
Indes BV, Sunrise Medical en Roessingh Research and Development

COLOPHON
ISBN: 978-90-365-4120-6
DOI number: 10.3990/1.9789036541206
Printing: Gildeprint, Enschede, The Netherlands
Cover design: Martijn Hoppenbrouwer, iX Studios digital design (www.ixstudios.nl)

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FUNCTIONAL EVALUATION OF POWER-ASSISTED WHEELCHAIR USE

PROEFSCHRIFT

ter verkrijging van
de graad van doctor aan de Universiteit Twente,
op gezag van de rector magnificus,
prof. dr. H. Brinksma,
volgens besluit van het College voor promoties
in het openbaar te verdedigen
op donderdag 23 juni 2016 om 16.45 uur

door

Marieke Geertruida Maria Kloosterman
geboren op 19 juli 1983
te Oldenzaal

DIT PROEFSCHRIFT IS GOEDGEKEURD DOOR

Prof. dr. J.S. Rietman (eerste promotor)
Prof. dr. L.H.V. van der Woude (tweede promotor)
Dr. J.H. Buurke (assistent promotor)

ISBN: 978-90-365-4120-6

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TABLE OF CONTENTS

1

General introduction

BACKGROUND

A wheelchair increases independent mobility for people with lower limb impairments.[1] 10% of the global population have disabilities, approximately 10% of these people require a wheelchair.[2] Thus, more than 70 million people should have access to an appropriate wheelchair. In The Netherlands approximately 0.9 % of the total population uses a wheelchair,[3] that is about 153.000 people. The hand-rim wheelchair is the most common type of wheelchair used by subjects with lower limb impairments in the Western world, and 90% of the prescribed wheelchairs are hand-rim wheelchairs.[4] The effects of wheeled mobility are of fundamental importance; not just for health, but also for independence and quality of life.[5]

Independent hand-rim wheelchair mobility can be compromised not onlyby arm injury or pain (prevalent in 30 - 73% of the spinal cord injury population[6]), insufficient arm strength, low cardiopulmonary reserves or inability to maintain posture,[1] but also by physically challenging environments (for example high pile carpets or steep inclines).[7] These can be conquered using alternative modes of ambulation such as an attendant pushing the wheelchair, a powered wheelchair, or a mobility scooter.[1] The risk created by these alternatives is the possibility of developing a less physically active lifestyle which may predispose to many long term health problems such as obesity, diabetes and cardiovascular problems.[4, 8] To remain physically active in a wheelchair, crank or lever-propulsion can be considered.[4] These propulsion techniques are more efficient than hand-rim wheelchair propulsion, however less appropriate for use indoors due to size and limited maneuverability. For about a decade the transition to a power-assisted hand-rim wheelchair has also been an option. This might be an interesting alternative in the context of preservation of upper extremity function as well as the need to remain physically active.[1, 8]

Figure 1 - The power-assisted wheelchair (**Mid**) is an intermediate between the powered (**Left**) and hand-rim wheelchair (**Right**).

The power-assisted wheelchair is an intermediate between hand-rim and powered wheelchairs (Fig. 1). It consists of a hand-rim wheelchair with electro-motors embedded into the wheels or wheelchair frame. When a subject exerts power on the rim, the motor is activated and augments the delivered power,[9] similar to e-bikes that provide pedal-assist.

A new type power-assist wheelchair wheel is being developed within our project group: Active Assistive Devices, research line of the MIAS project (Major Innovations for an Aging Society) funded by INTERREG, The Netherlands and Germany (European Regional Development Fund of the European Union, grant no.34 Interreg IVA). The new function of these power-assist wheels, compared with already existing power-assist wheels as the Alber E.Motion (Ulrich Alber GmbH, Albstadt-Tailfingen Germany) or Yamaha JWII-systems (Yamaha Moto Company, Shizuoka, Japan), is the possibility to drive completely powered. The wheels have two rims: a large rim that provides power-assist during the push and a small rim that provides continuous support, like a powered wheelchair (Fig. 2). For both rims, the amount of support can be adjusted between 3 modes (amount of assistance provided by the wheelchair), dependent of the environment or subjects own needs. The wheels fit on most hand-rim wheelchair frames, and have a removable battery pack and a motor positioned around the axis. The wheels developed within this project are commercially available as the WheelDrive: http://nl.sunrisemobility.eu/producten/mobility/mobiliteistoplossingen/hulpaandrijving/wheeldrive/c-281/c-267025/p-7162.

Figure 2 - Left - Mounting mechanism for attachment to varying wheelchair frames. **Mid -** Motor and removable battery pack positioned around the axis. **Right -** Upper rim for power-assisted propulsion, lower rim for completely powered propulsion. For both rims the amount of additional power can be switched between 3 modes.

AIM AND OUTLINE OF THE THESIS

Aim

To determine the added value of a power-assisted wheelchair in comparison to a hand-rim wheelchair on shoulder load, daily activities and participation.

Research questions

1. What is the current knowledge of power-assisted wheelchair propulsion?
2. Who might benefit from power-assist wheels?
3. What are the wheelchair characteristics of the prototype and what are the differences with a hand-rim wheelchair, specifically rolling resistance, propulsion efficiency and energy expenditure?
4. Is the assumption of the effectiveness of power-assisted propulsion in reducing potential risk factors for shoulder overuse injuries correct?
5. Are power-assist wheels beneficial in daily situations, and what are the users' opinion about the prototype power-assist wheels?

Outline

Firstly, in **chapter 2** an overview is given of the scientific literature so far available. This systematic review is based on the International Classification of functioning, disability and health (ICF-model)[10], especially on: 1) body functions and structures; 2) activities; and 3) social participation (Fig. 3).

To explore the characteristics of the wheels used in our research, in **chapter 3** we investigated the differences in rolling resistance, propulsion efficiency and energy expenditure required by the user during power-assisted and regular hand-rim propulsion. Different tyre pressures and different levels of motor assistance were tested. Rolling resistance is one of the main forces impairing wheelchair propulsion, in daily life, and thus affecting the external load on the upper extremities.

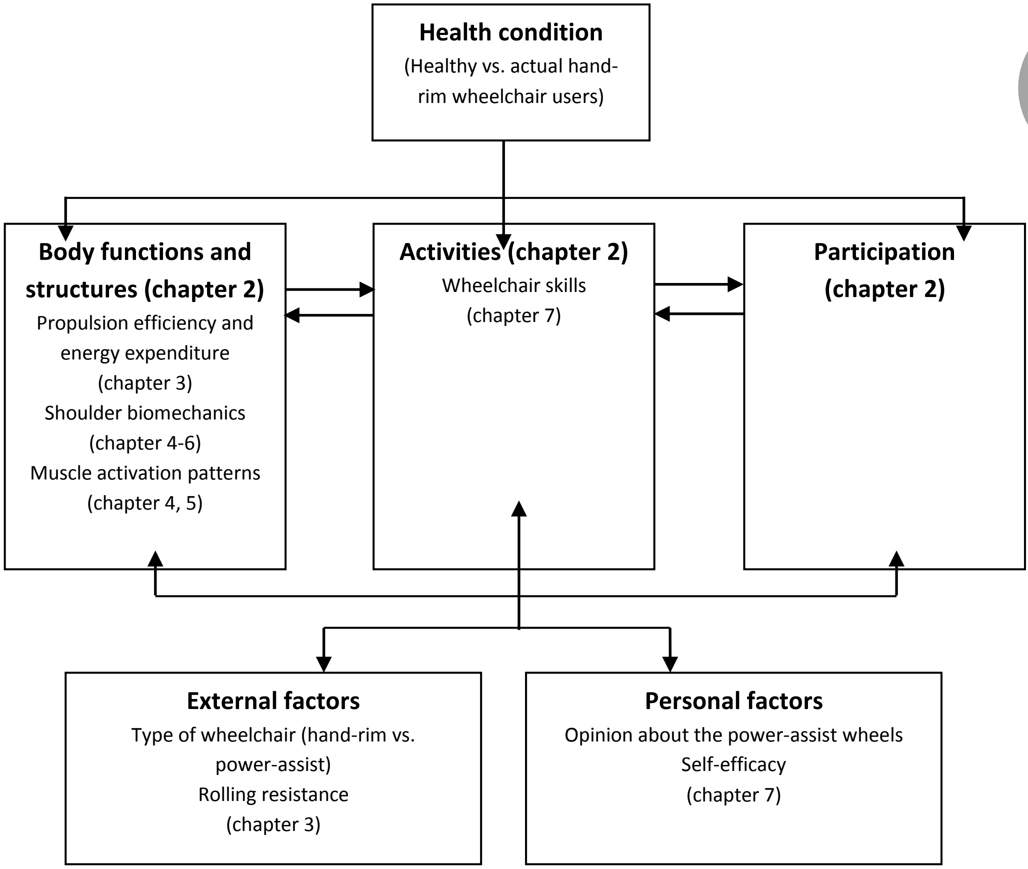

Figure 3 - Place of this thesis within the ICF-model, only the outcome measures were classified.[10]

Incidences of shoulder overuse injuries among hand-rim wheelchair users are high, with figures varying between 30-73% in the chronic spinal cord injury population.[6, 11, 12] It is suggested that part of the risk factors of overuse originate in wheelchair propulsion itself. Characteristics of hand-rim propulsion related to shoulder overuse injuries are, the intensity of mechanical loading of the shoulder during the push phase, the highly repetitive nature of propulsion motions and force generation in extremes of shoulder motion.[6, 13-17] Although the intensity of shoulder loading during hand-rim wheelchair propulsion seems to be one of the causes of shoulder injury, to our knowledge no previous research described the change in upper extremity kinetics between hand-rim and power-assisted propulsion. Therefore, in **chapter 4** a pilot study, with healthy subjects, was performed to explore the theoretical framework for the effectiveness of power-assisted propulsion in reducing shoulder overuse injuries. In this pilot study, the changes in upper extremity kinematics, kinetics and muscle activation patterns during propulsion with and without power-assist were investigated. To translate this concept into clinical practice, in **chapter 5** this study was repeated with experienced hand-rim wheelchair users.

The measurements in chapter 4 and 5 were performed at 0.9 m/s. However, short and slow bouts of activity dominate daily wheelchair usage.[18-20] The acceleration during start-up requires more force than maintaining a constant velocity. Based on previous research, the external stresses on the upper extremities are 2 - 3.5 times higher during acceleration than during constant velocity propulsion.[21] Therefore, we investigated in **chapter 6** whether power-assisted propulsion was beneficial to shoulder load during start-up.

To actually benefit from the power-assist wheels an advantage in daily life should also be present. In **chapter 7**, we investigated these potential benefits in wheelchair users, by means of wheelchair skills and self-efficacy during purely hand-rim and power-assisted propulsion. Besides this, we asked subjects their opinion about the power-assist wheels.

Finally in **chapter 8**, the main findings and conclusions of this thesis were discussed, along with suggestions for clinical implications and future research.

2

A systematic review on the pros and cons of using a pushrim-activated power-assisted wheelchair

Marieke G.M. Kloosterman
Govert J. Snoek
Lucas H.V. van der Woude
Jaap H. Buurke
Johan S. Rietman

Clinical Rehabilitation. 2013;27(4): 299-313

ABSTRACT

Objective: To determine the (dis)advantages of transition to a power-assisted wheelchair, and derive the clinical implications for its use or prescription.

Data Sources: Relevant articles published prior to May 2012 were identified using PubMed, Cochrane Library, REHABDATA, CIRRIE and CINAHL databases.

Review methods: Clinical or (randomized) controlled trials, published in a peer-reviewed journal, comparing power-assisted wheelchair use and hand-rim or powered wheelchair use were eligible. Data quality and validity were assessed by two reviewers independently using the Checklist for Measuring Quality developed by Downs and Black.

Results: A systematic search yielded 15 cross-over trials with repeated measurement design and one qualitative interview. Methodological quality scored between 9 and 15 points out of the maximum score of 32. Ten studies measuring body function and structure reported reduced strain on the arm and cardiovascular system during power-assisted propulsion compared to hand-rim propulsion. Twelve studies measuring activities and social participation reported precision tasks easier to perform with a hand-rim wheelchair and tasks which require more torque were easier with a power-assisted wheelchair. Social participation was not altered significantly by the use of a hand-rim, powered, or power-assisted wheelchair.

Conclusion: Power-assisted propulsion might be beneficial for subjects in whom independent hand-rim wheelchair propulsion is endangered by arm injury, insufficient arm strength, or low cardiopulmonary reserves. Also, subjects who have difficulty propelling a wheelchair in a challenging environment can benefit from power-assisted wheelchair use. Caution is warranted for the additional width and weight in relation to the usual mode of transportation and access to the home environment.

INTRODUCTION

A wheelchair increases independent mobility for people with lower limb impairments.[1] Independent hand-rim wheelchair mobility can be endangered by arm injury, pain, insufficient arm strength, low cardiopulmonary reserves, inability to maintain posture,[1] but also a physical challenging environment (for example carpets or steep inclines).[7] To overcome these debilities and challenging environments, alternatives such as an assistant pushing the wheelchair, transition to a powered wheelchair, or use of a mobility scooter might be preferred.[1] The risk of these alternatives is the possibility to develop a less physically active lifestyle which may predispose to many long term health problems.[4, 8] To remain physically active in a wheelchair, crank or lever-propulsion can be considered. This propulsion technique is more efficient than hand-rim wheelchair propulsion, however, less useful for indoors.[4] Nowadays, transition to a power-assisted wheelchair is also an option. This might be an interesting alternative in the context of preservation of arm function as well as the need to remain physically active.[1, 8]

Pushrim-activated power-assisted wheelchairs have been topic of scientific rehabilitation research for about a decade. Gradually these wheelchairs become available for use in clinical practice.[7] The power-assisted wheelchair is a hybrid between hand-rim and powered wheelchairs. It consists of a hand-rim wheelchair with electro-motors embedded into the wheels or wheelchair frame. When a subject exerts power on the hand-rim, the motor is activated and augments the delivered power.[9]

The transition to a power-assisted wheelchair may influence not only the arm function or the cardiopulmonary system of the subject,[4] but also, for instance, performance of daily activities and social participation. For example, the wheels are heavier than normal manual wheelchair wheels (approximately 10 kg per wheel), which might influence transportation possibilities and car transfers. In addition, because the control mechanism differs from the usual way of propulsion, the additional power and possible delay in applying additional power might influence the control over the wheelchair.[4]

In this systematic review we intend to present the current knowledge about transition from a hand-rim or powered wheelchair to a power-assisted wheelchair. The pros and cons of transition to a power-assisted wheelchair and their clinical implications are important information for the wheelchair user to make a deliberate choice about a possible transition to a power-assisted wheelchair. For healthcare professionals and healthcare policy this information is necessary to underpin their advice about use, prescription or reimbursement of a power-assisted wheelchair.

METHODS

This review was based on a systematic literature search of studies published till May 2012 in the following databases: PubMed, the Cochrane Library, REHABDATA (produced by National Rehabilitation Information Center for Independence), CIRRIE (Center for International Rehabilitation Research Information and Exchange) and CINAHL (Cumulative Index to Nursing and Allied Health Literature). We used the following search strategy in PubMed:

1. Wheelchair AND power assist*
2. Wheelchair [MeSH] AND power assist*
3. Wheelchair AND power support
4. Wheelchair [MeSH] AND power support
5. PAPAW

where * indicates a wildcard search; [MeSH], Medical Subject Headings; PAPAW, pushrim-activated power-assisted wheelchair.

The other databases were searched with line 1, 3 and 5 of this search strategy, so without the MeSH terms. In addition, we checked the references of the included studies for relevant additional publications.

We based the initial selection of articles on title and abstract. Two reviewers (MK, GS) independently selected and extracted data from the studies and scored their methodological quality using a systematic approach and checklist. The reviewers met regularly to discuss their findings and decisions. If consensus was not reached, a third reviewer could be consulted (HR).

A study was included in this review when it:

- investigated the effect of power-assisted wheelchair propulsion on human functioning compared to hand-rim or powered wheelchair propulsion;
- was a clinical trial or (randomized) controlled trial;
- was published as a full-length paper in a peer-reviewed journal in the English language.

We excluded studies which focused on engineering, for example studies testing a power-assisted wheelchair to ANSI/RESNA standards[9] or describing the control mechanism.[22, 23] To enable the most comprehensive review of the current literature, we included studies involving wheelchair users as well as healthy subjects.

The “Checklist for Measuring Quality” of Downs and Black[24] was used to assess the methodological quality of the included studies. This checklist is a valid and reliable checklist suitable for the assessment of randomized as well as non-randomized studies.[24, 25] The checklist consists of 27 questions covering five areas of methodological quality: reporting, external validity, bias (internal validity), confounding (internal validity), and power.[24] All areas were assessed and a total score was calculated with a maximum score of 32. For inclusion in this review no minimum score for methodological quality was required.

We scanned the general contents of the studies for: methodology, design, study population, types of wheelchairs used, intervention, measurements, and main findings. The main findings were grouped into part 1: functioning and disability, and part 2: contextual factors, of the ICF (International Classification of Functioning Disability and Health) model. Both parts comprised two components: (1a) body functions and structure, (1b) activities and participation, (2a) environmental factors, (2b) personal factors.[10] The results of the comparison between propulsion in a hand-rim or powered wheelchair and propulsion in a power-assisted wheelchair were considered to be positive if there was a significant difference, as calculated by an appropriate statistical test. For studies without statistical analysis, or without statistical significant results, the main findings according to the aim of this study were presented.

RESULTS

The systematic literature search in PubMed resulted in the identification of 264 studies. Fifteen of these studies fulfilled the selection criteria, and were included in the present review. Additional searches in databases of the Cochrane Library, REHABDATA, CIRRIE and CINAHL resulted in one additional inclusion. Checking the reference list of relevant publications did not result in new inclusions. Figure 1 depicts the literature search which resulted in 16 eligible studies for this review.[18, 26-40]

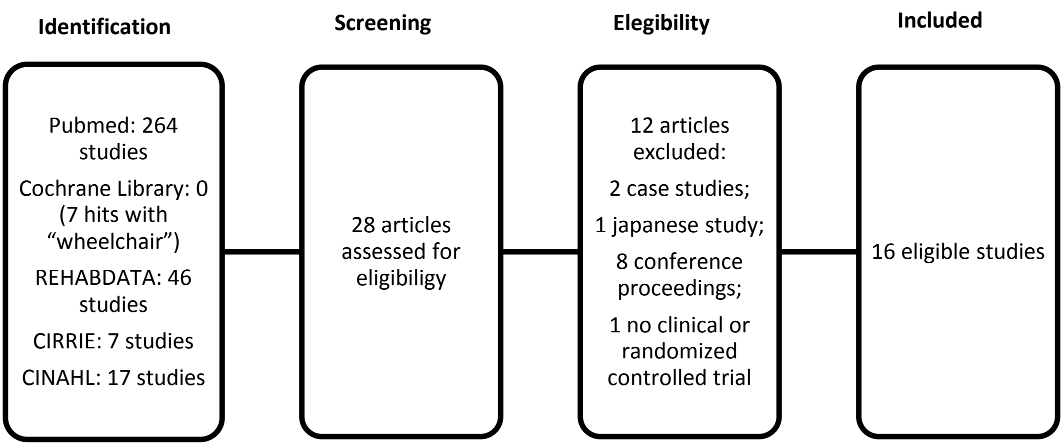

Figure 1 - Flowchart showing the systematic literature search process.

Fifteen studies were cross-over trials with a repeated measurements design, comparing power-assist to hand-rim or powered wheelchair use.[18, 26-34, 36-40] One study consisted of multiple qualitative interviews.[35] Two studies did not perform a statistical analysis.[35, 39] Complete agreement about the scoring of the methodological quality was reached in 375 of the 405 scores (92.6 %). Entire consensus was attained by discussion. The studies scored between 9 and 15 points out of the maximum score of 32 (Table 1). The methodological quality of the study of Kloosterman et al.[27] is not rated and the content is not extensively reported in this study because of conflicting interest.

Table 1 - Methodology quality according to the Checklist for Measuring Quality.[24]

	Domains Checklist for Measuring Quality					
	Report	**External validity**	**Internal validity**		**Power**	**Total**
			Bias	Confounding		
Maximum score:	11	3	7	6	5	32
First author						
Algood (2005)[26]	7	0	4	1	1	13
Algood (2004)[28]	7	0	4	11	1	13
Arva (2001)[29]	7	0	4	1	0	12
Best (2006)[30]	7	0	4	1	2	14
Cooper (2001)[31]	7	0	4	1	0	12
Corfman (2003)[32]	7	0	4	1	2	14
Ding (2008)[33]	7	0	3	1	0	11
Fitzgerald (2003)[34]	5	0	3	1	0	9
Giacobbi (2010)[35]	5	1	3	0	0	9
Giesbrecht (2009)[36]	7	1	3	1	0	12
Levy (2010)[18]	8	1	5	1	0	15
Levy (2004)[37]	7	0	4	1	0	12
Lighthall Haubert (2009)[38]	7	0	4	1	0	12
Lighthall Haubert (2005)[39]	5	0	3	1	0	9
Nash (2008)[40]	7	1	4	1	0	13

A detailed overview of the articles is presented in Table 2, below a summary of the main findings of the included studies.

The power-assisted wheelchairs used were Yamaha JWII[26, 28, 29, 31-34, 38, 39] (Yamaha Motor Company, Shizuoka, Japan. Available in the USA as Quickie Xtender, SunriseMedical, Longmont, Colorado), Alber E.motion[18, 30, 35, 36, 39, 40] (Ulrich Alber GmbH, Albstadt-Tailfingen, Germany), Delta Glide[37] (DeltaGlide Inc., Hamden, Connecticut, was available from Independence Technology as the iGLIDE (Independence Technology, Warren, New Jersey), no longer available) and a prototype power-assisted wheelchair[27] (Indes Holding B.V., Enschede, The Netherlands, not yet available). The Alber E.motion and the Yamaha JWII systems are power-assisted wheels which fit on most of the hand-rim wheelchair frames. The DeltaGlide is an integrated system of motor and chair. The control system of the Yamaha JWII differs from the control system used by Alber E.motion and DeltaGlide. The Yamaha JWII gives proportional assistance. For more demanding tasks more power is added by the system. The assistance given by the Alber E.motion or DeltaGlide depends on the chosen setting. The amount of power remained the same regardless the demands of the task.

Thirteen studies were performed in the USA.[18, 26, 28, 29, 31-35, 37-40] Seven of them were carried out at the University of Pittsburgh and the Human Engineering Research Laboratory of Pittsburgh, Pennsylvania.[26, 28, 29, 31-34] The three studies performed outside the USA were performed in Canada[30, 36] and The Netherlands.[27] In the USA the Medicare policy determines that an individual receives one wheeled mobility device every five years.[18] This makes it impossible to use a power-assisted wheelchair next to a hand-rim or powered wheelchair or mobility scooter, which is a possibility in the Netherlands.

Movement analysis of the arm during power-assisted propulsion compared to hand-rim propulsion resulted in a significantly decreased wrist ulnar-radial deviation and flexion-extension.[32] At the shoulder, flexion-extension[27, 32] and internal-external rotation[27, 28] significantly decreased. Shoulder abduction tended to decrease, however, this was not significant.[28, 32] The results on push frequency were not unambiguous.[28, 31, 32, 38, 39] Muscle activation patterns were compared between regular hand-rim and power-assisted propulsion[27, 37, 38] with different test protocol and measurement techniques (surface[27, 37] and fine wire electromyography[38]), therefore summarization of the results is difficult. However, all studies reported a significant decreased activity in the pectoralis major and in two studies activity in the tricpes brachii significantly decreased[27, 37] during power-assisted propulsion. Lighthall-Haubert et al.[38] found similar supraspinatus activity during hand-rim and power-assisted propulsion, probably because the available power-assisted wheelchair had a seat 18-inches (48 cm) wide, whereas for propulsion in the standard hand-rim wheelchair a seat width of 16 or 18 inches (41 or 48 cm) was selected based on the size of the subjects. This may have required increased glenohumeral abduction during power-assisted propulsion.[38]

Power-assisted propulsion tends to reduce the cardiovascular and respiratory strain compared to hand-rim propulsion. Heart rate was lower during power-assisted propulsion compared to hand-rim propulsion on an activities of daily living (ADL) course,[26] and at particular speed and resistance combinations in the dynamometer trials.[28, 31] During propulsion on different surfaces, increase of heart rate from rest was significantly lower with a power-assisted wheelchair.[37] A study comparing propulsion in three different brands of power-assisted wheelchairs with hand-rim propulsion reported a reduced heart rate in four of the five subjects during power-assisted propulsion, regardless of brand.[39] Significantly lower oxygen consumption was detected during power-assisted propulsion compared to regular hand-rim propulsion on the dynamometer and stationary rollers.[28, 29, 31, 40] During propulsion on a test track the oxygen consumption was significantly decreased for the Xtender and E.motion (not for the iGlide) compared to the regular hand-rim wheelchair.[39] Perceived exertion for propulsion[37, 40] was significantly lower for power-assisted propulsion compared to hand-rim propulsion. In qualitative interviews, 16 out of 20 people reported less fatigue with a power-assisted wheelchair.[35]

Measuring daily activities on a test track showed that carpet, dimple strips, ramp, and curb are significantly easier to complete with power-assist[26] and removing and replacing wheels was significantly more difficult.[31] Best et al.[30] identified no significant differences. However, the healthy participants ranked the hand-rim wheelchair as more effective for tasks which require greater control such as turns, moving through a doorway, and wheelie skills. The power-assisted wheelchair seemed easier for tasks which required more force, such as curbs, irregular surface and ascent-descent.[30] Based on questionnaires, powered wheelchair users preferred the powered wheelchair for activities outdoors, whereas the power-assisted wheelchair was preferred for tasks performed in a confined space.[36]

Measurements in the home environment comparing power-assisted wheelchair use with hand-rim or powered wheelchair use reported no significant differences on activity (in example daily duration of wheelchair use, involvement in occupational activities), social participation and psychosocial impact,[33-36] except for faster traveling[33] and travelling longer distances with a power-assisted wheelchair.[18]

Qualitative analysis showed that subjects experienced increased ease of propulsion with a power-assisted wheelchair (respectively 73% (*n* = 11/15[33]; *n* = 8/11[37]); 85% (*n* = 6/7) of the participants[34]). Mainly power-assisted propulsion on level and inclines (91% (*n* = 10/11)) and carpet (82% (*n* = 9/11)) were rated as (very) easy compared to hand-rim wheelchair propulsion.[37] In addition, 43% (*n* = 3/7) reported an improved ability to climb hills.[34] Maneuvering a power-assisted wheelchair in confined spaces was a limitation for 20% of the participants.[33] The additional width of the power-assisted wheelchair made it difficult to manoeuvre indoors.[33, 34] Difficulties with taking the power-assisted wheelchair wheels in and out of a vehicle was also reported.[33, 35] The car transfer, which required taking off and putting on the wheels, was not possible for 50% (n = 5/10) of the subjects when using the power-assisted wheelchair.[31] Individuals with the capacity to transport the chair with ease, for instance with a lift, spouse, public transport or other assistance, reported superior benefits from the power-assisted wheelchair.[35] Positive experiences with a power-assisted wheelchair, including access to new and different activities, was perceived in 65% (n = 13/20) of the participants.[35] Also 65% (n = 13/20) experienced the use of a power-assisted wheelchair as less burdensome and experienced greater independence.[35] More independence was also experienced in 40% (n = 6/15) of the participants in the study by Ding et al.[33]

Table 2 - The details of eligible studies. The outcome measures are classified according to the four components of the ICF model: body functions and structure; activities and participation; environmental factors; and personal factors

First author (year) *n* = Size and pathology of population **I** = Intervention **M** = Measurements	Quality score total Design	Significant changes in the outcome measurements Body functions and structure	Activities and participation	Environmental factors Wheelchairs used Setting comments	Personal factors
Algood (2005)[26] *n* = 15; cervical SCI **I**: self-developed ADL course with 18 tasks. Own MWC <-> PAPAW **M**: Heart rate, time to complete tasks, questionnaires (difficulty of completing obstacles; ergonomics both wheelchairs)	13 Cross-over trial with RM	Using PAPAW: lower heart rate	With PAPAW obstacles carpet, dimple strips, ramp, and curb cut easier to complete In third trial compared to first trial carpet, ramp, bump, curb cut, toilet, bathroom sink, turning on kitchen faucet and bus docking space easier to complete	PAPAW: Yamaha JWII on Quickie 2 Pittsburgh, Pennsylvania PAPAW easier to propel than MWC	N/A
Algood (2004)[28] *n* = 15; cervical SCI **I**: Dynamometer propulsion 0.9 m/s, with 10, 12 and 14 W resistance. Own MWC <-> PAPAW **M**: Velocity, energy consumption, heart rate, push frequency, ROM shoulder, elbow, wrist	13 Cross-over trial with RM	Using PAPAW: Lower energy consumption; *14 W:* lower HR; higher mean velocity; all ROMs decreased except shoulder ab-adduction. *10 and 12 W:* lower push frequency less ROM shoulder flexion-extension, internal-external rotation, horizontal flexion-extension, and wrist ulnar-radial deviation; *12 W* in addition less ROM in pro-supination.	Higher velocity with PAPAW at 14 W resistance	PAPAW: Yamaha JWII on Quickie 2 Pittsburgh, Pennsylvania	N/A

Arva (2001)[29] *n* = 10; 9x SCI T2-T12, 1x MS **I**: Dynamometer propulsion 0.9 m/s with 9, 12 and 13 W and 1.8 m/s with 24 and 30 W resistance. Own MWC <-> PAPAW **M**: Torque hubs and physiological data	12 Cross-over trial with RM	Using PAPAW: lower metabolic power (W) and user power (W applied to the dynamometer)	N/A	PAPAW: Yamaha JWII on Quickie 2 Pittsburgh, Pennsylvania PAPAW higher mechanical efficiency.	N/A
Best (2006)[30] *n* = 30; able-bodied **I**: Wheelchair Skill Test[41] (after 2 hours of training). MWC <-> PAPAW **M**: Total scores, skill success scores	14 Cross-over trial with RM	N/A	No significant differences in wheelchair skill scores	PAPAW: E.motion on Quickie LXI MWC: Quickie LXI Halifax Canada	N/A
Cooper (2001)[31] *n* =10; 9x SCI T2-L2, 1x MS **I**: Dynamometer propulsion own MWC <-> PAPAW: 0.9m/s with 10, 12, and 14 W and 1.8 m/s with 25, and 30 W resistance. ADL course of DiGiovine et al. [42] **M**: Metabolic energy consumption, ADL evaluation with: subjects rating, time to complete, heart rate, and ergonomics	12 Cross-over trial with RM	Using PAPAW: lower oxygen consumption all conditions; *1.8 m/s-30W and 0.9 m/s-12 W* lower heart rate; *0.9m/s-10 and 12W* higher ventilation	Lower score on car transfer: taking of / putting on the wheels PAPAW trial 3 compared to PAPAW trial 1 lower completion time and higher rating large speed bump	PAPAW: Yamaha JWII on Quickie 2 Pittsburgh, Pennsylvania PAPAW higher score on stability	N/A

2

Corfman (2003)[32] *n* = 10; 9x SCI T2-T12, 1x MS **I**: Dynamometer propulsion 0.9 m/s with 10, 12 and 14 W and 1.8 m/s at 25 and 30 W resistance. Own MWC <-> PAPAW **M**: Arm ROM, push frequency	14 Cross-over trial with RM	Using PAPAW: *0.9 m/s (12 and 14 W) and 1.8 m/s at 30 W:* decreased shoulder flexion/extension, horizontal flexion/extension and wrist ulnar/radial deviation; *0.9 m/s, 14 W and 1.8 m/s, 25 W:* decreased elbow flexion/extension and wrist flexion/extension	N/A	PAPAW: Yamaha JWII on Quickie 2 Pittsburgh, Pennsylvania	N/A
Ding (2008)[33] *n* = 15; cervical SCI **I**: Normal wheelchair use: 2 weeks MWC <-> 2 weeks PAPAW **M**: Data logger recorded mobility; Daily questionnaires on activities, 2-weekly PIADS (psychosocial impact)	11 Cross-over trial with RM	N/A	Using PAPAW faster traveling No significant differences in community participation and psychosocial impact	PAPAW: Yamaha JWII on Quickie 2 or Quickie GP Pittsburgh, Pennsylvania No significant differences in wheelchair satisfaction	No significant differences in psychosocial impacts
Fitzgerald (2003)[34] *n* = 7; SCI (T3-T12) I: Normal wheelchair use: 2 weeks MWC <-> 2 weeks PAPAW **M**: Data logger recorded mobility; Weekly questionnaires on activities	9 Cross-over trial with RM	N/A	No significant differences in activities between MWC and PAPAW usage	PAPAW: Yamaha JWII on Quickie Pittsburgh, Pennsylvania. Weather did not impact whether the persons left the house or not	Personal reasons as illness did not impact whether the person left the house or not

Giacobbi (2010)[35] *n* = 20; varying pathologies **I**: Normal wheelchair use 4 weeks own MWC -> 8 weeks PAPAW -> 4 weeks own MWC **M**: Qualitative interviews	9 Interview	Qualitative interviews, no test statistics performed.	Qualitative interviews, no test statistics performed	PAPAW: E.motion on own MWC Tucson, Florida	Qualitative interviews, no test statistics performed
Giesbrecht (2009)[36] *n* = 8 dual users (MWC and PWC); varying pathologies **I**: Normal wheelchair use: 3 weeks own PWC <-> 3 weeks PAPAW **M**: Questionnaires on activity and social participation: QUEST, FEW, PIADS, COPM	12 Cross-over trial with RM	N/A	No significant differences on activity and social participation between PWC and PAPAW use	PAPAW: E.motion on own MWC or Sunrise Quickie 2 Manitoba, Canada	Using PAPAW lower score on self-esteem
Levy (2010)[18] *n* = 20 elderly; varying pathologies **I**: normal wheelchair use: 4 weeks own MWC -> 8 weeks PAPAW -> 4 weeks own MWC **M**: Bicycle computer recorded distance	15 Cross-over trial with RM	N/A	Using PAPAW further traveling compared with both baseline and follow-up phases Travelled distances in weeks 1-2 lower than in weeks 3-4 and 7-8	PAPAW: E.motion on own MWC Gainsville, Florida	N/A

Levy (2004)[37] *n* = 11; elderly; varying pathologies **I**: Propulsion on a linoleum floor (100 m), a thick polyester carpet (21 m), and an incline (6 m). Own MWC <-> PAPAW. **M**: sEMG extensor carpi radialis, triceps brachii, anteromedial deltoid, posteromedial deltoid, pectoralis major, latissimus dorsi, rectus abdominus, and erector spinae, HR, questionnaires: PAS-LI, FSI, SIP, FIM, CAPAW	12 Cross-over trial with RM	Using PAPAW: lower heart rate rise, and perceived exertion, reduced sEMG activity in extensor carpi radialis, triceps brachii, pectoralis major, latissimus dorsi	N/A	PAPAW: DeltaGlide on a Colours in Motion wheelchair Gainsville, Florida	N/A
Lighthall Haubert (2009)[38] *n* = 14; SCI C6 or C7, ASIA grade A or B **I**: propulsion at a stationary ergometer during free, fast and graded resistance (4% or 8%) propulsion Own MWC <-> PAPAW **M**: fine wire EMG sternal or clavicular part pectoralis major, anterior deltoid, supraspinatus and infraspinatus; cycle length; cadence	12 Cross-over trial with RM	Using PAPAW: Decreased peak intensity all muscles and conditions except for the supraspinatus during free propulsion Decreased median EMG intensity during fast and graded propulsion and for pectoralis major, anterior deltoid during fee propulsion Less perceived exertion	Using PAPAW: lower velocity and cadence with increased cycle length during fast propulsion. Higher velocity and increased cycle length during graded trial	PAPAW: Quickie Xtender Downey, California	N/A

Lighthall Haubert (2005)[39] *n* = 5; complete SCI C6, C7, T12 **I**: 20 minutes of continuous propulsion on SS speed over 126 m outdoor cement track Own MWC <-> 3 PAPAW's **M**: propulsion characteristics metabolic demands	9 Cross-over trial with RM	Descriptive statistics	Descriptive statistics	PAPAW: iGlide, Xtender, and E.motion, last 2 were mounted on a Quikie 2 Downey, California	N/A
Nash (2008)[40] *n* = 18; 12x paraplegia and 6x tetraplegia (ASIA A or B) confirmed shoulder pain **I**: 6 min steady state propulsion without resistance and 12 min intensity graded propulsion on stationary rollers; both at greatest attainable speed **M**: Metabolic energy consumption, RPE, questionnaire WUSPI	13 Cross-over trial with RM	Using PAPAW lower energy costs. RPE only significant lower during resisted propulsion	Using PAPAW higher velocity	PAPAW: E.motion on own MWC Miami, Florida	N/A

Kloosterman (2012)[27] *n* = 9 healthy subjects **I**: Propulsion at a treadmill at 0.9 m/s Own MWC <-> PAPAW **M**: shoulder kinematics; kinetics at rim and shoulder; sEMG anterior, middle, posterior deltoid; sternal head pectoralis major; middle trapezius; long head biceps brachii; long head triceps brachii	N/A Cross-over trial with RM	Using PAPAW: significantly decreased maximum shoulder flexion and internal rotation angles and decreased peak force on the rim resulting in decreased shoulder flexion, adduction and internal rotation moments and decreased forces at the shoulder in the posterior, superior and lateral directions. Muscle activation in the pectoralis major, posterior deltoid and triceps brachii decreased	N/A		PAPAW: prototype, not yet commercial available Enschede, The Netherlands	N/A

Abbreviations: <->, compared to; ->, followed by; ADL, activities of daily living; ASIA, American Spinal cord Injury Association; C, injury on cervical level; CAPAW, Consumer Assessment of Power Assist Wheelchairs; COPM, Canadian Occupational Performance Measure; EMG, electromyography; FEW, Functioning Everyday with a Wheelchair; FIM, Functional Independence Measure; FSI, Jette Functional Status Index; HR, heart rate; MS, multiple sclerosis; L, injury on lumbar level; MWC, manual (hand-rim) wheelchair; N/A, not applicable; PAPAW, pushrim-activated power-assisted wheelchair; PAS-LI, Physical Activity Scale for Persons with Locomotor Impairments; PIADS, Psychosocial Impact of Assistive Devices Scale; PWC = powered wheelchair; QUEST, Quebec User Evaluation of Satisfaction with assistive Technology; RM = repeated measurements desingn; ROM, range of motion; RPE, rate of perceived exertion; SCI, spinal cord injury; sEMG, surface electromyography; SIP, Sickness Impact Profile; T, injury on thoracic level; WC, wheelchair; WUSPI, wheelchair users shoulder pain index.

DISCUSSION

The main results of this systematic review imply that power-assisted propulsion reduced the strain on the arms and cardiovascular system compared to hand-rim wheelchair propulsion. Precision tasks seemed easier with a hand-rim wheelchair, while tasks which require more torque seemed easier with a power-assisted wheelchair. Social participation was not affected significantly by the use of a hand-rim, powered or power-assisted wheelchair.

This review was confounded by a number of factors: First, despite the extensive search we possibly failed to notice relevant publication because the initial selection was done by one of the authors only and four articles were excluded based on language or study design. Second, a meta-analysis was not possible. The relatively small research populations, small number of articles per outcome measure and the variety in methodology made it difficult to make an extensive comparison. Third, the methodological quality of all studies scored less than half of the maximum score on the checklist for measuring quality. The areas with the lowest scores were external validity, confounding and power, warranting caution with generalization of the results. Self-evidently, a first step in investigating a relatively new technology is done within an experimental setting and with a small study population. Also blinding is hardly possible. Hence, to our opinion a randomized controlled trial in which subjects are their own controls is the best feasible protocol to evaluate two different types of wheelchairs. Fourth, the results of this review must be generalized to other hand-rim wheelchair users with care. The majority of the studies assessed subjects with a spinal cord injury, which is a small part of the total hand-rim wheelchair population. The inclusion of studies with healthy subjects[27, 30] as well as hand-rim wheelchair users[18, 26, 28, 29, 31-35, 37-40] or dual users[36] with varying pathology resulted in the description of a population with a large variety in arm function and physical condition. The studies included in this review solved this problem by using a within-subject comparison. Therefore, personal variations such as lesion level and arm strength were tackled as confounders.

Transition from a hand-rim wheelchair to another type of mobility device, such as a powered wheelchair, is induced because of arm injury, pain, insufficient arm strength, low cardiopulmonary reserves or inability to maintain posture.[1] According to this systematic review, power-assisted wheelchair propulsion could have an effect on all these factors, except the inability to maintain posture.

Guidelines for lowering the risk of arm injury during hand-rim wheelchair propulsion focus on the spinal cord injury population.[8, 43] These guidelines recommend minimizing extreme or potentially injurious positions at all joints, especially extreme wrist positions and positions where the shoulder is prone to impingement. The combination of extreme internal rotation with abduction or forward flexion, and maximum shoulder extension combined with internal rotation and abduction should be avoided.[8] The results of this review showed that abovementioned angles decreased during power-assisted propulsion compared to hand-rim propulsion.[27, 28, 32] Two studies[28],[32] reported slightly different results despite a comparable experimental setup. A plausible explanation for these differences might be that Algood et al.[28] measured subjects with a cervical spinal cord injury and Corfman et al.[32] mainly measured subjects with a thoracic spinal cord injury. The spinal cord lesion level influences the kinematics during hand-rim wheelchair propulsion.[38, 44, 45]

Another recommendation to lower the risk on arm injury is to reduce the push frequency as well as the amplitude of forces and moments exerted on the rim and acting on the shoulder. The results for push frequency yielded conflicting results, and only one study with healthy subjects investigated the force applied to the hand-rim during propulsion.[27] The results were promising, however the measurements should be repeated with hand-rim wheelchair users before generalization to the wheelchair user population is possible. With this review no long-term effects on shoulder injuries were identified.

For subjects with insufficient arm strength and low cardiopulmonary results the power-assisted wheelchair seems beneficial. The effort needed to propel a power-assisted wheelchair in comparison with a hand-rim wheelchair is reduced, based on significantly decreased: intensity of muscle activation of the majority of the measured shoulder and arm muscles,[27, 37, 38] heart rate,[26, 28, 31, 37] metabolic costs,[28, 29, 31, 40] and perceived exertion.[37, 40] On the other hand, physical inactivity occurs disproportionately among those with disabilities, contributing to obesity and a cycle of deconditioning and further decline.[18] It is plausible that the physical fitness further declines when travelling with less effort. However, if the transition from a hand-rim to a powered wheelchair can be postponed with a power-assisted wheelchair, subjects retain, at least to some extent, the benefits of exercise by hand-rim wheeling.[29, 32, 37] Currently the long term effects of power-assisted propulsion on the cardiovascular system are unknown.

Power assisted propulsion seemed beneficial for tasks which require more effort and seemed less convenient for tasks which require more control when compared to hand-rim wheelchair propulsion. Three different tests were used to determine wheelchair skills. The Wheelchair Skill Test[41, 46] is a valid and reliable test. The outcome of this test is a series of pass or fail tests. Algood et al.[28] and Cooper et al.[31] both analyzed an ADL-course with a standardized but not validated test. Besides pass or fail, they did a more extensive examination by measuring time to complete the task, heart rate and a visual analogue scale (VAS) score to determine ease of completing the tasks. None of the protocols measured removing and replacing wheels. This is an important task because this is a prerequisite for a car transfer, for instance, and therefore for usability and independence. Because of the additional weight of approximately 10 kg per wheel, it is a challenging task. To increase comparability between studies investigating wheelchair skills, consensus about the included skills and standardization of measurements should be reached.[47, 48]

Activity monitoring in the home environment of the subjects was investigated in four studies.[18, 33, 34, 36] The only significant differences were faster[33] and further travelling with a power-assisted wheelchair compared to a hand-rim wheelchair.[18] Two findings are noteworthy because they might explain the lack of more significant differences. First, in two studies subjects could use their own wheelchair within the power-assisted trial.[33, 34] In the study of Ding et al.[33] subjects in the power-assisted trial used their own hand-rim wheelchair at a similar frequency as the power-assisted wheelchair. For the study of Fitzgerald et al.[34] this factor was unknown. Second, Levy et al.[18] found that the first two weeks could be considered as an adjustment phase in which subjects are less active than in subsequent weeks[18]. Two of the studies measured only two weeks of power-assisted propulsion, and therefore possibly missed an increase in activity.

The number of involved activities[34, 36] as well as occupational performance[34, 36] and quality of life[33] did not change significantly using a power-assisted instead of a hand-rim wheelchair. A possible explanation is that daily activities are more related to changes in behavioural and social routines[34] than to change of wheels. Changing habits is not likely to occur within two weeks, especially when the subject is aware of the fact that the chair must be returned to the investigators.[34] In addition, habit change might also depend on factors such as transportability, social network and personal factors as force, fatigue or physical fitness.

Environmental and personal factors received limited attention in the included studies. Because a wheelchair is often the primary mode of daily mobility, it is essential to take these factors into account when choosing the designated type of wheelchair. Especially access to transportation and the home environment, and ability to transport the power-assisted wheelchair might be an issue due to the additional weight and width of the wheels.

In conclusion, the pros of power-assisted wheelchair propulsion are: reduction of load on the arm, decrease in cardiopulmonary demand, increase in propulsion efficiency, maintained benefit of exercise, easy access to challenging environments and - compared to a powered wheelchair - relatively lightweight and easy to transport. The cons of power-assisted wheelchair propulsion are: difficulty performing tasks which require greater control such as a wheelie, difficulty with car-transfers and access to home environment due to additional weight and width compared to a hand-rim wheelchair, unknown long-term effects on physical fitness and repetitive motion injuries can still be present or have still no time to heal.

Further research is needed to get insight into the influence of power-assisted propulsion on forces and moments exerted on the rim and acting on the shoulder.

Furthermore, a longitudinal study would provide information about the long-term effects of power-assisted wheelchair use on arm injuries and physical fitness. Further research addressing the change of activity profiles after transition to a power-assisted wheelchair is important, because next to the (re)training of function, improvement in activity and social participation are also important focuses in the rehabilitation process.

CLINICAL MESSAGES

- Power-assisted propulsion is promising in reducing load on the arm and cardiovascular system.
- Power-assisted propulsion is most beneficial for tasks that require high levels of effort and is less convenient for tasks requiring greater manoeuvrability.
- A large disadvantage is the weight of the power-assisted wheels.

3

Rolling resistance and propulsion efficiency of manual and power-assisted wheelchairs

Technical note

Efthymia Pavlidou
Marieke G.M. Kloosterman
Jaap H. Buurke
Johan S. Rietman
Thomas W.J. Janssen

Medical Engineering & Physics. 2015;37(11):1105-10

ABSTRACT

Rolling resistance is one of the main forces resisting wheelchair propulsion and thus affecting stress exerted on the upper limbs. The present study investigates the differences in rolling resistance, propulsion efficiency and energy expenditure required by the user during power-assisted and manual propulsion. Different tire pressures (50%, 75%, 100%) and two different levels of motor assistance were tested. Drag force, energy expenditure and propulsion efficiency were measured in 10 able-bodied individuals under different experimental settings on a treadmill. Results showed that drag force levels were significantly higher in the 50%, compared to the 75% and 100% inflation conditions. In terms of wheelchair type, the manual wheelchair displayed significantly lower drag force values than the power-assisted one. The use of extra-power-assisted wheelchair appeared to be significantly superior to conventional power-assisted and manual wheelchairs concerning both propulsion efficiency and energy expenditure required by the user. Overall, the results of the study suggest that the use of power-assisted wheelchair was more efficient and required less energy input by the user, depending on the motor assistance provided.

INTRODUCTION

For the majority of people with mobility impairments who rely on wheelchairs, the effects of wheeled mobility are of fundamental importance; not just for their health, but also for their independence and the quality of life.[5] Repetitive high loads, motion extremes and disproportional muscle load during wheelchair propulsion have been suggested to cause the development of chronic upper-limb injuries.[31] Pain in the upper limbs is a common occurrence in wheelchair users, and a serious limiting factor in everyday life functions.[4, 31, 40, 49-51] Thus, it is important to find the balance between sufficient physical activity, maximum participation, comfort and overload. The optimal choice of wheelchair may play a role in that issue.

A wide variety of mobility devices is available in the market. In this study we focus on options which require user input, maintaining physical activity levels: namely, manual wheelchairs and pushrim-activated power-assist wheelchairs (PAWs).[29, 31, 52] Manual wheelchairs are lightweight, easy to manipulate and to transport.[18] However, manual propulsion is highly inefficient (with mechanical efficiency values ranging as low as 2-10%)[53] and requires power input which is not available by less capable individuals, especially in challenging terrain.[18, 39] Power-assisted wheelchairs are a less energy demanding alternative.[28, 39, 40, 54] They are propelled by the user like manual wheelchairs, but the movement is additionally supported by motors integrated into the wheels that provide different levels of assistance in propulsion.[31, 39, 52] The benefits of power-assisted propulsion have been extensively reported in literature.[18, 28, 29, 31, 39, 40, 54] However, these benefits of PAWs may be influenced by the different types of available PAWs and the level of impairment of the users.[39] Furthermore, commercially available types of PAWs are approximately 20 kg heavier than manual wheelchairs;[18, 39] wheels are not easy to remove and replace, making independent transportation more difficult.[31, 33, 35] The increased weight could also affect rolling resistance.

Rolling resistance is the main force opposing the motion of a tire as it rolls across a surface. It is caused by inelastic deformation of the materials comprising the tire and/or the surface.[55] Numerous studies with manual wheelchairs have described the effects of laden and total weight, tire design and inflation pressure, material composition, internal resistance, wheel alignment and surface type on propulsion.[55-59] Van der Woude et al.[59] reported that physical strain and energy cost are affected by obstacles, floor surfaces and materials. Sawatzky et al.[58] suggested that increases in rolling resistance contribute to additional energy expenditure and deflated tires are associated with higher levels of rolling resistance. Increased weight,[60, 61] mass distribution[62] or weight-tire type interactions[63] seem to increase rolling resistance in manual propulsion. However, the information available on rolling resistance of PAWs is still very limited.

In the present study, we investigated the rolling resistance of a newly-developed power-assisted wheelchair. We made a comparison with manual wheelchairs and examined the effect of different levels of tire inflation on the measured rolling resistance. Furthermore, we evaluated the effects of manual and power-assisted modes of propulsion on the energy input required by the user and on propulsion efficiency. These are metrics commonly used in existing literature to assess wheelchair propulsion.[5, 29, 31, 39, 40, 53] The newly-developed PAW we used, offered the option of two kinds of wheels, providing two different levels of motor support in terms of torque and power. We tested both options to study how the level of motor support affects propulsion efficiency and energy expenditure. The hypotheses were, that (a) power-assisted wheels demonstrate higher levels of rolling resistance compared to manual wheels, (b) deflated tires increase rolling resistance, (c) power-assisted propulsion is more efficient and requires less energy input by the user, compared to manual propulsion, and (d) improved motor assistance increases propulsion efficiency and reduces energy cost.

METHODS

Characteristics of the participants

Ten able-bodied participants, five male and five female, took part in the study after giving their written informed consent. The characteristics of the sample are summarized in Table 1. Participants were volunteers studying at the University of Twente, The Netherlands. None of the subjects had previous experience with wheelchair propulsion. All participants were tested in all conditions, using all wheelchair types in all the configurations of interest. The study protocol was approved by the local institutional review board.

Table 1 - Sample

Participants	*N*	Age (years) ± sd	Height (m) ± sd	Body mass (kg) ± sd
Male	5	29 ± 3	1.74 ± .07	76 ± 14
Female	5	25 ± 2	1.62 ± .07	57 ± 7
Total	10	27 ± 3	1.68 ± .09	66 ± 14

The wheelchair

The same wheelchair frame was used to mount three sets of pneumatic wheels: (a) manual, (b) power-assisted and (c) power-assisted but with a more powerful motor (Fig. 1). All configurations were tested on a treadmill. In this way we could eliminate all factors affecting rolling resistance (surface type, material composition) other than those related to the different wheels. The wheelchair frame was a Legend2, Exigo, Handicare, Moss, Norway, www.handicare.com (seat width 0.41 m, total width 0.59 m, diameter rim

0.028 m). Power-assisted wheels were developed by Indes Holding B.V., Enschede, The Netherlands, www.indes.eu. Both types of power-assisted wheels were experimental: conventional PAW was the first prototype and extra-PAW the second prototype in which torque as well as amount of power were increased. The settings of the second prototype are used in the commercially available WheelDrive wheels, www.handicare.com; a detailed description of the wheels is provided in:
http://www.handicare.com/media/211056/sm_wheeldrive_int.pdf. When the motor is off, the wheels are in 'free-wheel' mode. The software settings of PAW and extra-PAW motors were adjusted by the manufacturer.

Figure 1 - Left Manual wheels; **Mid -** power-assisted wheels with conventional motor, mounted on the wheelchair frame; **Right -** power-assisted wheels with extra-power motor attached.

Experimental setting

First, we measured drag force at three levels of tire inflation for M and PAW wheels: 50%, 75% and 100% of the recommended tire pressure. Subsequently, we measured energy expenditure and propulsion efficiency for three wheelchair configurations: manual (M), conventional power-assisted (PAW) and extra-power-assisted (EP). Within the two parts of the measurements the sequence of testing different wheelchair types and configurations was randomized, to avoid bias and multiple-treatment interference. Participants had a short introductory session to get familiarized with the equipment and were measured in groups of two. As one of them completed each task, the other was in the role of safety assistant (Fig. 2). In this way, participants had rest intervals longer or equal to the duration of each task. The role of the assistants were instructed to make sure the wheelchair would remain streamlined if the user lost control of it. In practice they help was never needed during the measurements, because there was enough space on the treadmill for maneuvers and the belt speed was slow; however, we decided to keep the assistance for moral support of the users.

Rolling resistance: drag test

Rolling resistance is defined as "the required drag force (F_{drag}) that has to be exerted parallel to the floor surface in the line of coasting of the wheelchair", as described by Van der Woude and colleagues:[59] $F_{drag} = c*m*g*sin(\alpha)$, where c= coefficient of friction, dependent on tire and floor characteristics, m=system mass, g=gravitational acceleration and α=inclination angle of the treadmill.

Figure 2 - Execution of the 6-min propulsion on the treadmill.

Drag force was determined using a drag test, executed on a treadmill. The measurements took place with a complete wheelchair-user system and thus included internal friction. The participants were passively seated in a wheelchair connected with a rope to a force transducer on a treadmill. Tests were performed on manual and power-assisted wheels. Speed was kept constant but the angle of the treadmill was increased gradually and drag force (F_{drag}) was measured in three different slopes (2%, 4% and 8%). Based on the results, linear regression was applied to calculate the drag force levels at zero inclination. The test was repeated for three different tire inflation levels (50-75-100%).

Energy expenditure and propulsion efficiency

The focus of the study was to qualitatively assess the impact of different levels of assistance on the energy requirements placed on the user, rather than the performance of the motor. The users were asked to produce the same power output using different wheelchairs, manual and conventional/extra power-assisted; the level of their participation was measured directly as energy expenditure. Propulsion efficiency calculations were based on that energy expenditure.

Participants performed one 6-minute propulsion test for each wheelchair configuration (M, PAW and EP), at standardized slope (0%), inflation level (75%) and power output (*PO*) to allow comparability of the results. We calculated *PO* based on the formula described in Tropp et al.[64]: $PO = F_{drag} \times V$, where V is the speed of the treadmill belt and F_{drag} (at zero inclination, for 75% inflation level) was measured during the drag test. In order to decide on the target PO levels, we performed a series of preparatory trials with volunteers different to the ones that participated in the actual measurements. This choice was made to ensure that all participants of our study were equally inexperienced in wheelchair propelling. At the trial sessions we noticed that not all volunteers could control the manual wheelchair at speeds higher than 3 km/h. We used this level as an upper threshold for the speed applied in our experiment. This speed level falls within the speed range applied by Van der Woude et al.[65] for both experienced and non-experienced manual wheelchair users. Using the F_{drag} values we had measured at the drag test, we calculated that $PO=5.5W$ can be safe enough target level. This power output resulted to manual propulsion efficiencies between 3% and 6%, which fall within the range reported by Arva et al.[29] and Van der Woude et al.[53] for non-wheelchair users (2-10%).

For the actual measurements each participant was requested to propel for 6 minutes at a horizontal level using three wheelchair configurations (manual, PAW, extra-PAW). Different speeds were applied for every wheelchair configuration, based on F_{drag} values we had previously calculated at the drag test, in order to maintain the 5.5 W target power output. During each 6-minute propulsion, oxygen consumption (VO2) was measured with the Cosmed K4b2 portable telemetric gas analysis system (Cosmed K4b2, Cosmed, Rome, Italy) (Fig. 2). Total energy expenditure (power input) was calculated based on the average respiratory exchange ratio (*RER*) and VO_2 of the last minute of the propulsion, based on the formula by Garby and Astrup:[66] $P_i=(4940\ RER+16040)(VO_2/60)$, where Respiratory Exchange Ratio (RER) stands for the ratio VCO_2/VO_2. RER values above 1.00 were attributed to buffering of H^+-ions by bicarbonate and were treated as equal to 1.00. Resulting power input was used for propulsion efficiency calculations.

Propulsion efficiency was calculated using the formula described by De Groot et al.[63]: $PE= (PO/P_i)x100\%$ where PE=propulsion efficiency; PO=Power Output; P_i=Power input(energy expenditure) as measured above. This PE is not the same as the gross mechanical efficiency, because the PO delivered by the motor is included as well, while the energy expenditure from the motor is not. The PE therefore represents the energy expenditure that is needed from the user to overcome a certain task, assisted or not by the motor.

Data analysis

Statistical analysis of the results was based on a repeated measures ANOVA design, with Wheelchair type (M, PAW, EP) and inflation level (50%, 75%, 100%) as within-subjects factor, as applicable according to the parameter studied. Partial η^2 was used to determine the effect size and the 95% confidence intervals for the mean differences were also calculated. The assumption of normality was based on visual inspection of *q-q* plots and homogeneity of variance was checked using the Levene's test. The significance level was set at .05.

RESULTS

Drag force

Drag force at zero inclination revealed a significant effect of wheelchair type and tire inflation level, but no interactions of the above factors. Manual wheelchairs displayed significantly (p=.002) lower drag force values than the PAWs (Fig. 3, left). Pair-wise comparisons between the inflation conditions showed higher levels of drag force for 50% inflation, compared to 75% and 100% inflation (Fig. 3, right). However, these differences were statistically significant only between inflation levels of 100% and 50% (p=.046).

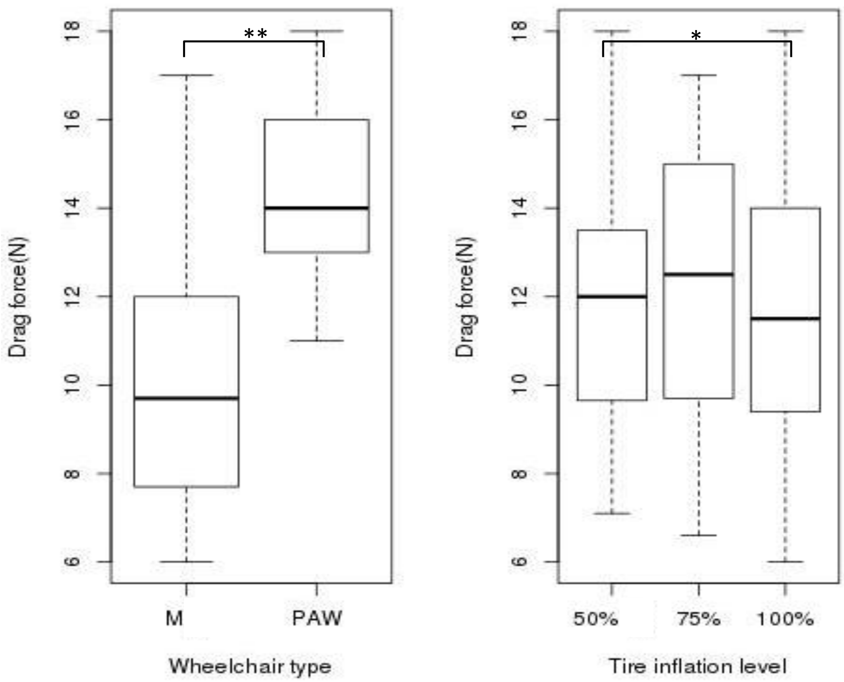

Figure 3 - Drag force values (Newton) summarized by wheelchair type (on the left panel, M = manual and PAW = power-assisted wheelchair) and inflation level (right panel).
* = p < .05; ** = p < .01.

Energy expenditure

There was a significant effect of wheelchair propulsion mode ($F[2,16] = 8.969$, $p = .002$, $\eta^2 = .529$) on the measured energy expenditure. Pair-wise comparisons between the three wheelchair propulsion modes revealed a significant difference between Manual and Extra-Power assisted wheelchairs ($p = .006$), with the manual wheelchair propulsion requiring higher energy consumption (Fig. 4). Energy required for EP propulsion was also significantly lower compared to conventional PAW propulsion($p = .013$). Finally, only a tendency towards a lower energy expenditure was found for conventional PAW compared to manual wheelchair use ($p = .072$).

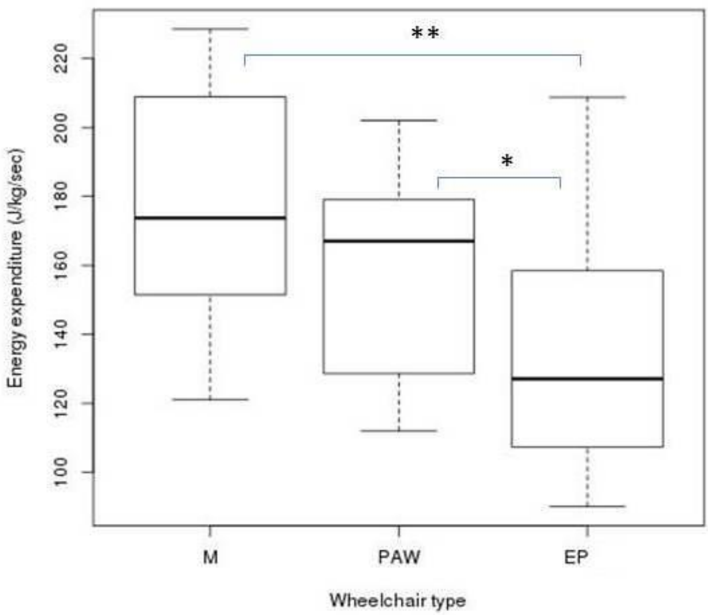

Figure 4 - Energy expenditure (J/kg/sec) summarized by wheelchair type (M = manual, PAW = power-assisted, EP = extra-power assisted wheelchair). * = p < .05; ** = p < .01

Propulsion efficiency

In the case of propulsion efficiency, significant effects were noted for wheelchair propulsion mode ($F[2,16] = 9.336$, $p = .002$, $\eta^2 = .539$). Pair-wise comparisons showed that the use of Extra-Power Assisted Wheelchair was significantly more efficient than Manual and conventional PAWs ($p = .008$ and $p = .001$ respectively), while there was no significant difference between manual wheelchairs and PAWs ($p = .227$) (Fig. 5).

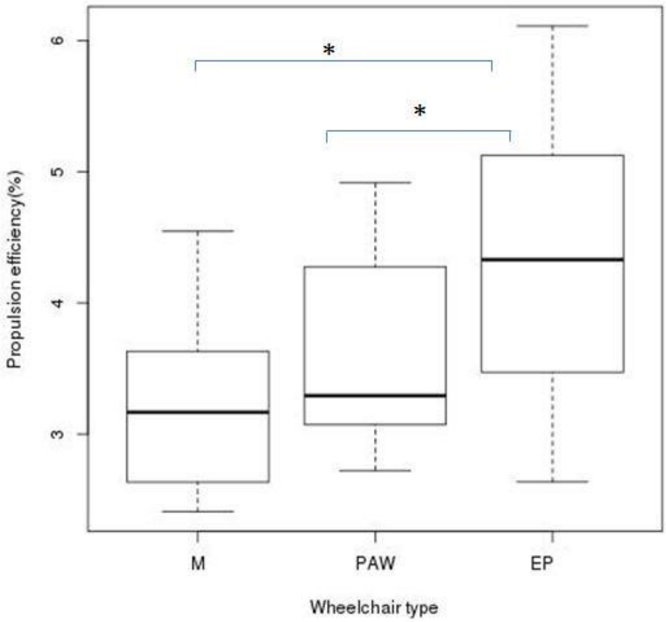

Figure 5 - Propulsion efficiency levels summarized by wheelchair type (M = manual, PAW = power-assisted, EP = extra-power assisted wheelchair). * = p<.01.

DISCUSSION

The present study aimed to contribute to our still incomplete knowledge on rolling resistance of power-assisted propulsion. We reported rolling resistance of a newly-developed power-assisted wheelchair at different tire inflation conditions, and we compared the results with those of a manual wheelchair. Furthermore, we investigated the role of motor assistance in wheelchair propulsion, in terms of propulsion efficiency and energy input required by the user.

Our results confirmed the hypotheses that deflated tires and power-assisted wheelchairs face higher levels of rolling resistance. Significant differences were noticed only between the 100% and 50% inflation conditions. Sawatzky et al[67] had already mentioned dramatic increases in rolling resistance of deflated tires in manual wheelchairs; they also mentioned increased energy cost of propulsion starting with tire pressures 50% lower than recommended but not in the 75% inflation case. The present study confirmed the same effect of inflation level in the case of rolling resistance of PAWs, and showed that the latter demonstrate higher drag force values than manual wheelchairs.

During our measurements the wheelchair frame and the surface were the same; the only difference between configurations was the type of wheels mounted. A possible candidate contributing to the increased rolling resistance of PAWs might be the increased internal friction: despite the freewheel mode of the PAW wheels when the motor is turned off, it is likely that there is more internal friction in PAWs than in the manual wheelchair. Another potential contribution might come from the increased weight of power-assisted wheels (PAW's approximately 20 kg heavier than the manual wheelchair). Sauret[62] has previously mentioned that rolling resistance is affected by the system's mass, as well as by its distribution between the rear and the front part of the wheelchair. Other indirect indications of the potential effects of weight on wheelchair propulsion can be found in Beekman et al.[60], who measured greater speed and travelled distance with the use of ultra weight wheelchairs, and Cowan et al[61] who reported that a 9-kg weight increase resulted in lower self-selected propulsion velocity and increased peak forces during propulsion on different surfaces.

Our study confirmed also our hypothesis that improved motor assistance in terms of increased torque and power lead to higher propulsion efficiency and required less energy input. Indeed, the extra-power-assisted propulsion was the most efficient and least energy demanding mode of propulsion. It is interesting to note that there was no significant difference in efficiency between propulsion with the manual wheelchair and the conventional PAW, nor in energy expenditure. A potential reason for this might be the increased rolling resistance of the power-assisted wheels, which the motor assistance of the conventional PAW was just enough to compensate for without offering any further benefit. This finding may be supported by, and extend, the work of Lighthall-Haubert et al.[39] who mentioned that during propulsion on a test track the oxygen consumption depended on PAW-type. The authors commented that push-rim sensitivity and power assistance can influence effective propulsion of a PAW, adding that this influence may vary depending on the impairment and abilities of the user. In our study all participants were non-disabled and novice in wheelchair propulsion, and we observed statistically significant positive influence on energy expenditure and propulsion efficiency only with the extra-PAWs. This is an indication that the amount of torque and power delivered by the motor should be considered when selecting and programming a PAW. Our study was not designed to distinguish the role of the two (torque and power assistance); more research would be required in that respect. On the other hand, the benefits of using the extra-PAW were clear on both propulsion efficiency and energy requirements. These observations are in accordance with previous findings. Arva et al.[29] reported an average of 80% increase in efficiency when using power assistance, and

many researchers have measured significantly lower oxygen consumption during power-assisted propulsion on a dynamometer and stationary rollers.[28, 29, 31, 40]
Participants reported that propelling the extra-power assisted wheelchair was easier, although during the trials some of them had difficulty maintaining a straight course when using PAWs at higher speeds. These observations agree with Best et al.[30] who reported ease of performance with PAWs but better control when using a manual wheelchair. In the case of control, the motor may be accentuating the natural difference in strength between the left and right arm without compensating for the additional resistance. Another possible explanation could be a delay between the power exerted on the rim and the onset of the support of the motor. More research is needed to confirm these remarks. Another interesting issue for future study could be the potential differences in the propulsion patterns employed by the participants, when they use the different types of wheelchair. Since the information available on the control algorithms of the motors or the details of their design was limited, it would be useful to examine these technical specifications in more detail and make comparisons with other commercially available models of PAWs.

Potential limitations of our experimental design lie in the application with able-bodied participants and in the choice of treadmill as a test setting. The use of able-bodied, novice wheelchair users prevents experience in a propulsion system from affecting the results. A potential learning-effect[68] on the results has been limited by the randomization of the testing sequence. However, results might differ in case of application of the same protocol to different populations of actual wheelchair users, and this would be a field for future research. In terms of experimental setup, the use of a test track is the most realistic choice. However, for practical considerations we chose the treadmill as artificial test environment. Although the absence of air drag might be affecting the external validity of the results, van der Woude et al[53] mention that propulsion on a treadmill is mechanically comparable to propulsion over ground, and using a treadmill is the second best option to measure wheelchair propulsion.

Conclusions

Power-assisted wheelchair rolling resistance was measured on a treadmill and found to be higher compared to the rolling resistance of a manual wheelchair. Deflated tires increase rolling resistance in both manual and power-assisted wheelchairs, and could impose unnecessary physiological charges during propulsion. Motor assistance during propulsion significantly increases propulsion efficiency and decreases the energy expenditure required by the user, but these benefits are measured only with sufficiently high levels of motor contribution in terms of torque and power assistance.

4

Comparison of shoulder load during power-assisted and purely hand-rim wheelchair propulsion

Marieke G.M. Kloosterman
Hilde Eising
Leendert Schaake
Jaap H. Buurke
Johan S. Rietman

Clinical Biomechanics. 2012;27(5): 428-35

ABSTRACT

Background: Repetitive forces and moments are among the work requirements of hand-rim wheelchair propulsion that are related to shoulder injuries. No previous research has been published about the influence of power-assisted wheelchair propulsion on these work requirements. The purpose of our study was therefore to determine the influence of power-assisted propulsion on shoulder biomechanics and muscle activation patterns. We also explored the theoretical framework for the effectiveness of power-assisted propulsion in preventing shoulder injuries by decreasing the work requirements of hand-rim wheelchair propulsion.

Methods: Nine non-wheelchair users propelled a hand-rim wheelchair on a treadmill at 0.9 m/s. Shoulder biomechanics, and muscle activation patterns, were compared between propulsion with and without power-assist.

Findings: Propulsion frequency did not differ significantly between the two conditions (Wilcoxon Signed Rank test/significance level/effect size:4/.314/−.34). During power-assisted propulsion we found significantly decreased maximum shoulder flexion and internal rotation angles (1/.015/−.81 and 0/.008/−.89) and decreased peak force on the rim (0/.008/−.89). This resulted in decreased shoulder flexion, adduction and internal rotation moments (2/.021/−.77; 0/.008/−.89 and 1/.011/−.85) and decreased forces at the shoulder in the posterior, superior and lateral directions (2/.021/−.77; 2/.008/−.89 and 2/.024/−.75). Muscle activation in the pectoralis major, posterior deltoid and triceps brachii was also decreased (2/.038/−.69; 1/.015/−.81 and 1/.021/−.77).

Interpretation: Power-assist influenced the work requirements of hand-rim wheelchair propulsion by healthy subjects. It was primarily the kinetics at rim and shoulder which were influenced by power-assisted propulsion. Additional research with actual hand-rim wheelchair users is required before extrapolation to routine clinical practice.

INTRODUCTION

Hand-rim wheelchair users rely extensively on their upper extremities, not only for mobility but also for other activities of daily living like transfers and weight relief lifts.[14, 69] This causes considerable strain on the upper extremities.[4, 6, 14] Consequently, upper extremity complaints among wheelchair users are common, especially shoulder injuries (30 % to 73% in the chronic spinal cord injury population)[6, 11, 12] and carpal tunnel syndrome (49%-73% of the manual wheelchair users).[43] These complaints influence activities such as self-care and community participation.[4, 70]

Risk factors for wheelchair-related overuse injuries are divided into three domains: (1) individual factors (physical capacity, posture, skill level), (2) environmental factors (floor surface, incline, wheelchair fit), and (3) work requirements (magnitude and frequency of the load applied, direction of force, time of exposure, rest periods).[71] In contrast to the two other risk factor domains, work requirements can be changed by altering the type of wheelchair propulsion or the propulsion technique.[8, 43]

Work requirements related to shoulder overuse injuries include repetitive (high) forces and moments, extremes of motion at the glenohumeral joint, and uneven loading or overloading of upper extremity muscles.[11, 13, 15, 32, 44, 72] It has therefore been recommended that the work requirements of hand-rim wheelchair propulsion should be reduced as much as possible.[8, 15, 43] Guidelines for people with a spinal cord injury recommend using a light wheelchair; avoiding weight gain; ergonomically adjusting of the wheelchair setup; and optimizing the propulsion technique to reduce the risk of overload injuries.[8, 43] One of the guidelines[8] recommends a power-assisted wheelchair as a relatively new means to reduce energy expenditure in hand-rim wheelchair propulsion. Power-assisted wheelchairs have been developed as a hybrid between hand-rim and powered wheelchairs,[73] and can decrease biomechanical[28, 32] and physiological strain associated with hand-rim wheelchair propulsion.[28, 29, 37, 73]

Although high forces and moments are an important risk factor in the development of shoulder overuse injuries, little attention has been given to the influence of power-assisted propulsion on these risk factors. To our knowledge, no previous research has been published about its influence on the forces and moments exerted on the rim and acting on the shoulder. Ideally, such a study should systematically integrate data collection and analysis of kinematics, kinetics and electromyography of the upper extremity, to allow a comparison between purely manual hand-rim and power-assisted propulsion, but the literature offers no example of such a study. Only one study reported on the changes in total power, based on motor torque and velocity.[29] The purpose of our study was therefore to determine the influence of power-assisted propulsion on shoulder kinematics, kinetics and muscle activation patterns, and to compare the results with those of purely manual hand-rim propulsion. The results of our experimental study allow an exploration of the theoretical framework for the effectiveness of power-assisted wheelchair propulsion in preventing shoulder injuries by decreasing the work requirements of hand-rim wheelchair propulsion. We hypothesized that power-assisted propulsion could reduce the work requirements related to shoulder overload injuries during hand-rim wheelchair propulsion. In addition we hypothesized a decrease in the forces and moments exerted on the rim, because the force needed to propel the wheelchair is partly delivered by a motor, reducing forces and moments at the glenohumeral joint and the activation of the push-phase muscles.

METHODS

Subjects

Four men and five women participated in this study, with a mean age of 23 ± 2 years, a height of 1.78 ± 0.10 m and a weight of 74 ± 12 kg. Since we used a prototype power-assisted wheelchair, only healthy volunteers participated in this study. All subjects were non-wheelchair users and had no current wrist, elbow or shoulder complaints. Subjects provided written informed consent before entering the study. The study was reported to the local medical ethics committee of Medical Spectrum Twente, Enschede, The Netherlands. All experiments were performed in a biomechanics laboratory at Roessingh Research and Development, Enschede, The Netherlands.

Instrumented power-assisted wheelchair

The wheelchair used for the measurements consisted of prototype power-assisted wheels (Indes Holding B.V., Enschede, The Netherlands, www.indes.eu) mounted on a hand-rim wheelchair frame (Sopur Starlight, Sunrise Medical, Longmont, Colorado, United States, www.sunrisemedical.com). The power-assisted wheels were manufactured by the project group. A motor was mounted on the wheel axis and piezoelectric sensors were mounted at the points where the hand-rim was attached to the wheel. The signal caused by deformation of the piezoelectric sensor activated the motor, resulting in extra power being delivered to the wheel, additional to the hand-rim power provided by the wheelchair user.

In one wheel, a six degrees of freedom force and torque sensor (Model FT Delta SI-660-60, ATI Industrial Automation, Apex, North Carolina, United States, www.ati-ia.com) was mounted on the axis. The hand-rim was connected to the sensor by a frame (Fig. 1). This arrangement allowed all the forces and moments exerted on the rim to be measured by the sensor.

Procedure
Before the measurements, subjects were given about 15 minutes to get used to hand-rim wheelchair propulsion with and without power-assist. After this familiarization period, the subjects were prepared for the measurements by placing markers and electrodes (see below). This resulted in a rest period of 20 to 30 minutes.

In accordance with previous studies[28, 29, 32, 73] subjects propelled the wheelchair on a large treadmill (Bonte B.V. Zwolle, The Netherlands (company does not exist anymore)) at 0.9 m/s. The treadmill was a single-belt treadmill without inclination. The subjects first propelled without power-assist, followed by a trial with power-assist, and both conditions were repeated twice in the same order. Each trial consisted of approximately one minute of propulsion and two minutes of rest to prevent fatigue. During the experiment, the treadmill was started and its speed increased slowly until the intended speed of 0.9 m/s was reached. Data acquisition was started when the participants had reached a steady propulsion rhythm. Kinematic, kinetic and surface electromyography data were collected simultaneously for 30 to 40 seconds. Because it has been shown that left and right side data are highly correlated during hand-rim wheelchair propulsion,[74] all data were collected unilaterally (subject's right side).

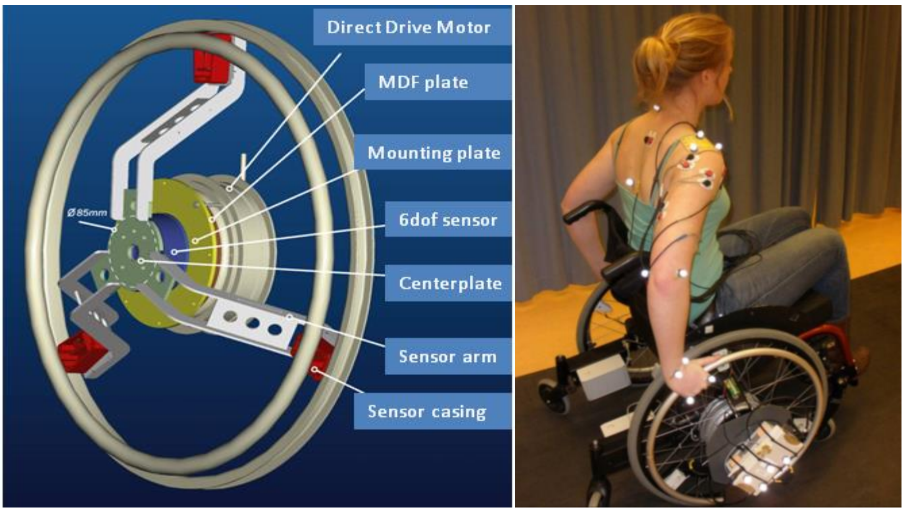

Figure 1 - Left - Schematic depiction of the six degrees of freedom sensor mounted on the wheel axis. The motor was mounted in the axis. A mounting plate and a medium-density fiberboard (MDF) were placed between the motor and the six degrees of freedom (6dof) force and torque sensor. The hand-rim was mounted on the sensor via the sensor casing, sensor arm and center plate. **Right -** as implemented in the prototype used in the study. The picture also shows the reflective markers and surface electromyography electrodes.

We reduced the data volume by selecting 10 sequential propulsion cycles from one trial for data analysis. As a check for consistency between cycles, we used the propulsion cycles with the smallest difference in lateral displacement of the marker on the wheel axis in respect to the treadmill.

All data analysis was performed with Matlab (The MathWorks Inc, Natick, Massachusetts, United States, www.mathworks.com). The total propulsion cycle was defined as 100% and the timing of propulsion characteristics is expressed as a percentage of the propulsion cycle. The propulsion cycle was divided into a push phase and a recovery phase (Fig. 2 Left). The push phase was defined as the part of the cycle with a propulsive hand-rim contact exceeding 0.40 Nm, as proposed by Mulroy et al.[75] The start of the propulsion cycle was the point at which the push phase started (Fig. 2 right). Propulsion frequency was defined as the number of propulsion cycles per minute.

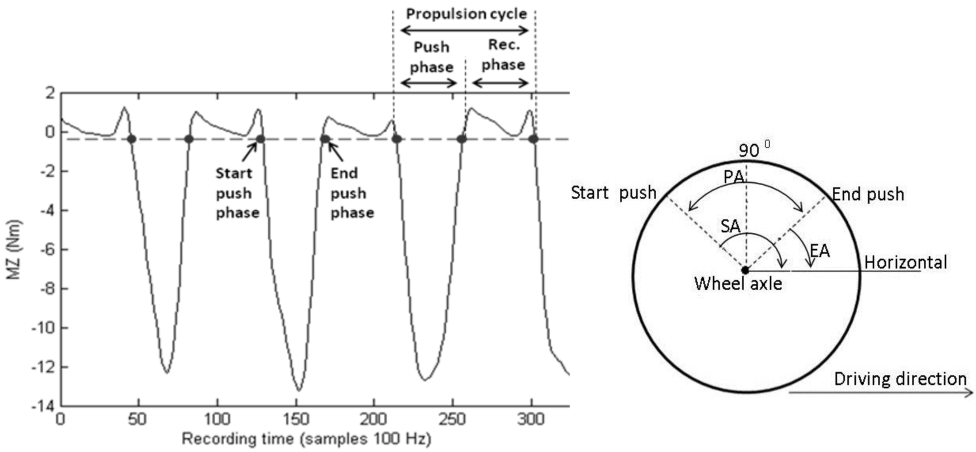

Figure 2 - Left - Determination of the propulsion cycle, divided into a push phase and recovery (Rec.) phase. Both phases were classified by the propulsion moment applied (Mz). **Right** - Definitions of start angle (SA), end angle (EA) and push angle (PA).

Kinematics

Position data for the upper extremity and the wheel were recorded at 100 Hz by means of an infrared 3D-motion analysis system with six cameras (Type MX 13, Vicon-UK Ltd, Oxford, United Kingdom, www.vicon.com), and were low-pass filtered at 40 Hz with a second-order zero-phase Butterworth filter. Reflective markers were placed on the right side of the body at eleven bony landmarks (incisura jugularis, xiphoid process, spinous process of seventh cervical vertebra, spinous process of eighth thoracic vertebra, marker set at acromion, medial and lateral epicondyle humerus, radial styloid process, ulnar styloid process, distal point of second metacarpal joint, distal point of fifth metacarpal joint), and four on the wheel: one at the axis and three around the axis.

In analyzing the collected data, missing marker data of body segments that showed minimal movement, like the trunk, were replaced using Vicon bodybuilder, using the position of the three other markers of the segment to reconstruct the missing marker. Other missing markers were replaced by linear interpolation for periods shorter than 15 samples. When longer periods of marker data were missing, which occurred only in the trials of one subject, these periods were removed from the dataset.

Joint angles were calculated using the methods proposed by the International Society of Biomechanics (ISB),[76] except for the glenohumeral joint rotation center, which was calculated from the marker set on the acromion by regression, as proposed by Campbell et al.[77] We used this method because scapular motion tracking was not possible in this wheelchair. The rotation order of the humerus with respect to the trunk that we chose was the z-x-y order, rather than the y-x-y order, to fit in with to clinical terminology. The anatomical position was taken as the offset position with all angles zero. Flexion, adduction and internal rotation of the shoulder with respect to the thorax were defined as positive angles.

Kinetics

The forces and moments exerted on the hand-rim were measured with the six degrees of freedom force and torque sensor. The data was sampled at 200 Hz, filtered with an eighth-order, zero-phase, low-pass Butterworth filter with a 20 Hz cut-off frequency, and stored on a wireless data acquisition system (Type WLS-9205, National Instruments Corporations, Austin, Texas, United States, www.ni.com). The forces and moments measured at the axis were converted to forces and moments at the point of force application on the rim (second metacarpal joint). The reported parameters were: Fx (forward forces), Fy (downward forces), Fz (radial forces) on the rim, propulsive moment around the wheel axis, peak resultant force with its timing as a percentage of the propulsion cycle, and the corresponding position of the glenohumeral joint.

A linked-segment model between hand, forearm, humerus and thorax, with 7 DOF (shoulder flexion/extension, ab/adduction, internal/external rotation; elbow flexion/extension, forearm pro/supination; wrist flexion/extension, ab/adduction), was constructed in Matlab to calculate forces and external moments at the shoulder joint. Segment lengths were measured for each subject. Segment mass and the center of mass of each segment were adapted from Winter.[78] The maximum and minimum forces and moments at the rim and glenohumeral joint during the complete stroke are reported in this paper. For graphical reasons, the anterior, superior and lateral forces were defined as positive forces and the posterior, inferior and medial forces as negative forces. For the external moments, flexion, adduction and internal rotation were defined positive and extension, abduction and external rotation were defined negative Forces and moments were calculated as a mean of the ten selected strokes.

Electromyography

Bi-polar surface EMG was recorded with a wireless 16-channel EMG amplifier(Type Biotel 99 Glonner Electronic, GmbH, Munich, Germany (company does not exist anymore)). The raw signals were digitized at a sampling rate of 1000 Hz, high-pass filtered at 16 Hz, and stored on the Vicon system, where they were synchronized with the kinematic data. Silver/silver-chloride electrodes (Type ARBO S93SG Tyco Healthcare UK Ltd, Hampshire, United Kingdom, www.tycohealthcare.co.uk) with a 23 mm inter-electrode distance were used. The electrodes were placed on seven muscles of the right arm, which were involved in wheelchair propulsion: the anterior, middle and posterior deltoid; the sternal head of the pectoralis major; the middle trapezius; the long head of the biceps brachii and the long head of the triceps brachii. Placement and preparation were in accordance with SENIAM guidelines.[79]

The signals were band-pass filtered with a fourth-order zero-phase Butterworth filter with 20 and 400 Hz as the cut-off frequencies. Mean power of the EMG signal was determined by the root mean square (RMS) of the signal based on previous studies of cyclic movements.[75, 80, 81] A 10 Hz filter was used to smooth the signal. RMS was calculated over each of the ten selected complete propulsion cycles. Next, the mean of these calculated RMS values was taken, to obtain one value for the mean amplitude of muscle activity. Since the individual RMS values cannot be compared between subjects these RMS values were normalized by calculating the percentage difference in RMS during propulsion with and without power-assist within subjects, setting the RMS of the trial without power-assist at 100%.

Statistical analysis

All parameters were averaged over the ten strokes analyzed for every subject. These averages were then used to calculate a group average and standard deviation. Because of the small sample size and the fact that the data were not normally distributed, the differences between propulsion with and without power-assist were determined with the Wilcoxon Signed Rank test, reporting the test statistic T (smallest of the two sum of ranks), significance (p), and effect size (r). The level of significance was set at $p<0.05$.

RESULTS

Kinematics

Table 1 shows the shoulder kinematics in both conditions. The propulsion frequency did not change significantly with power-assist. Flexion and internal rotation at the glenohumeral joint decreased significantly during power-assisted propulsion. The velocity of the wheelchair for the selected trials without power-assist (range 0.898 to 0.902 m/s), and with power-assist (range 0.896 to 0.904 m/s) did not differ significantly.

Table 1 - Kinematics (n = 9): propulsion frequency and maximal shoulder angles, presented with the results of the Wilcoxon Signed Rank test for the two test conditions.

Kinematic outcome measures	Mean (SD) without PA	Mean (SD) with PA	Wilcoxon (*T/p/r*)
Propulsion frequency (strokes/min)	60.6 (14.1)	63.2 (14.7)	4 /.314 /-.34
Maximal flexion (º)	22.1 (6.8)	14.9 (5.5)	1 /.015*/-.81
Maximal extension (º)	40.4 (6.2)	40.9 (6.9)	3 /.678 /-.14
Minimal abduction (º)	25.8 (4.7)	24.5 (6.2)	4 /.678 /-.14
Maximal abduction (º)	37.7 (5.3)	35.8 (5.2)	4 /.314 /-.34
Maximal external rotation (º)	6.2 (7.7)	9.8 (8.2)	2 /.066 /-.61
Maximal internal rotation (º)	20.4 (12.2)	12.8 (11.3)	0/ .008**/-.89

SD = standard deviation; PA = power-assist; T = test statistic (smallest of the two sum of ranks); p = significance level; r = effect size;* = p < .05; ** = p < .01

Kinetics at the hand-rim

Table 2 presents the kinetics as applied to the hand-rim. The horizontal (Fx) and vertical forces (Fy) exerted on the rim were significantly lower in the power-assist condition, and the moments around the z-axis (Mz) were also significantly smaller during power-assisted propulsion. The peak resultant force was significantly lower, and was reached earlier in the propulsion cycle, with less internal rotation at the glenohumeral joint, during power-assisted propulsion. Figure 3 shows a typical example of forces and moments around the wheel axis during a propulsion cycle.

Table 2 - Forces and moments as applied to the hand-rim (n = 9). The peak resultant force is shown with the timing (% of movement cycle) and shoulder angles during this peak force. All presented with the results of the Wilcoxon Signed Rank test for the two test conditions.

Kinetic and kinematic outcome measures	Mean (SD) without PA	Mean (SD) with PA	Wilcoxon (T/*P*/r)
FX peak (N)	48.3 (9.4)	35.1 (8.0)	1 /.015* /-.81
FY peak (N)	44.8 (7.9)	29.0 (9.0)	0 /.008**/-.89
FZ peak (N)	-12.7 (10.4)	-9.4 (6.6)	3 /.109 /-.53
MZ peak (N·m)	12.5 (1.2)	7.5 (0.7)	0 /.008**/-.89
Peak resultant force on the rim (N)	66.5 (11.8)	47.8 (8.8)	0 /.008**/-.89
Timing of peak force (%)	53.6 (9.1)	47.3 (6.0)	0 /.008**/-.89
Extension angle (º)	10.5 (5.4)	15.2 (8.0)	2 /.110 /-.53
Abduction angle (º)	35.6 (6.0)	33.1 (6.2)	4 /.286 /-.36
Rotation angle (º)	8.6 (9.9)	1.6 (10.2)	1 /.015*/-.81

FX; FY; FZ = force in x; y; or z direction; MZ = moment around z-axis; SD = standard deviation; PA = power-assist; T = test statistic (smallest of the two sum of ranks); p = significance level; r = effect size;* = p < .05; ** = p < .01

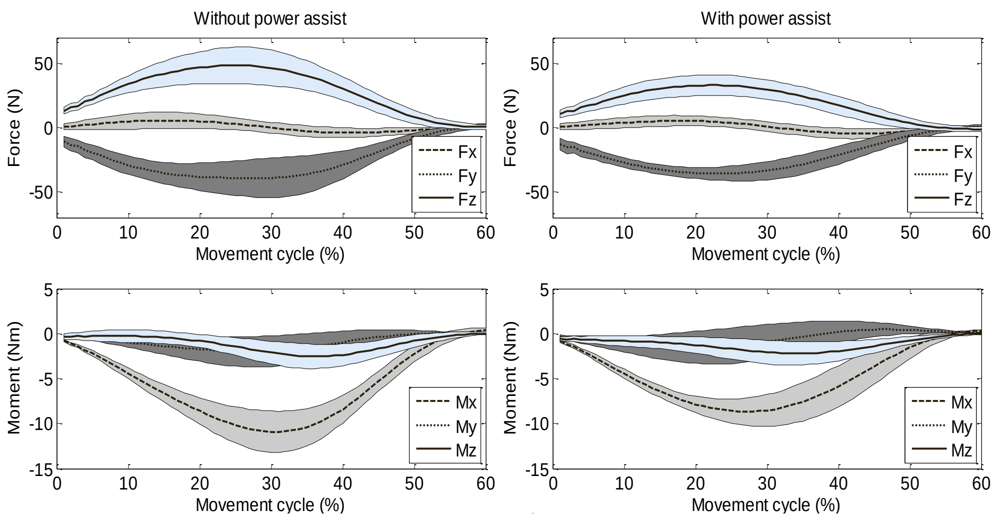

Figure 3 - Left - Three-dimensional hand-rim forces and moments at the wheel axis for propulsion without and **(Right)** with power-assist (mean of ten sequential strokes of subject S8). The plotted line for each parameter represents the mean, while the shading around the line represents the standard deviation. Fx; Fy; Fz = force in x; y; z direction; Mx; My; Mz = moment around x; y; z-axis.

Kinetics at the shoulder

Without power-assist, the flexion moment was the largest shoulder moment, followed by adduction and internal rotation (Fig. 4). These moments were all significantly lower during assisted propulsion. The flexion moment (mean(SD)) decreased from 18.4 (6.5) N·m to 12.8 (5.9) N·m (*T* = 2; *p* = .021; *r* = -.77), the adduction moment from 10.8 (4.7) to 6.5 (2.9) N·m (*T* = 0; *p* = .008; *r* = -.89), and the internal rotation moment from 10.9 (3.1) to 8.0 (2.3) N·m (*T* = 1; *p* = .011; *r* = -.85) without power-assist.

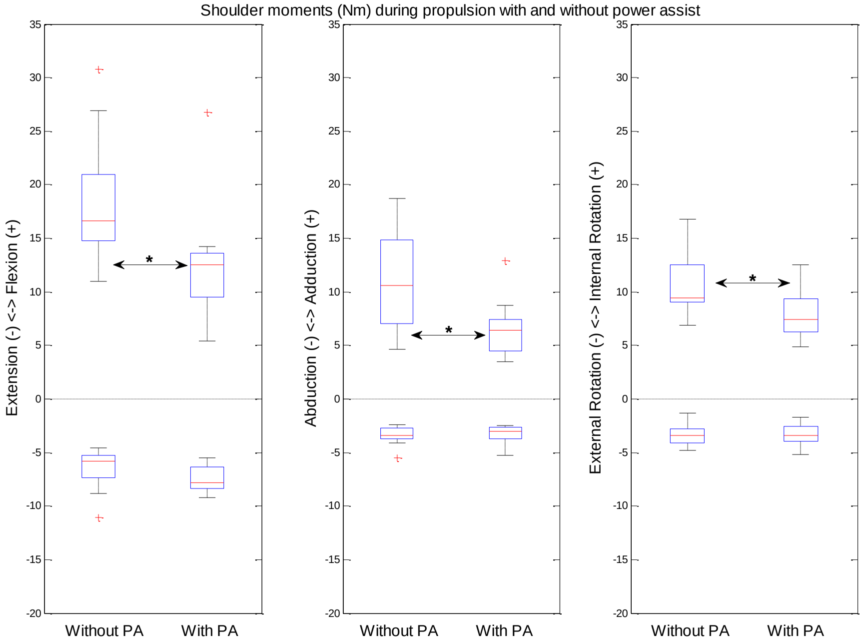

Figure 4 - Peak shoulder moments during a complete propulsion cycle. Propulsion without power-assist is the left part in every plot) and with power-assist is the right part in every plot (mean values over n = 9). + = outlier; * = Significant difference between propulsion with or without power-assist; PA = power-assist.

The forces acting on the glenohumeral joint during propulsion are shown in figure 5. The force in the posterior direction was the largest, followed by that in the inferior direction. The forces in the posterior and lateral directions showed significant decreases, from 50.6 (10.3) N to 36.9 (8.6) N (*T* = 2; *p* = .021; *r* = -.77) and from 15.3 (9.9) N to 11.2 (6.9) N (*T* = 2; *p* = .024; *r* = -.75), respectively, during power-assist propulsion. The superior directed force significantly decreased from 9.3 (6.7) N to an inferior force of 5.4 (9.5) N (*T* = 2; *p* = .008; *r* = -.89). The forces in the anterior, inferior and medial directions peaked through the recovery phase and were not changed significantly by assisted propulsion.

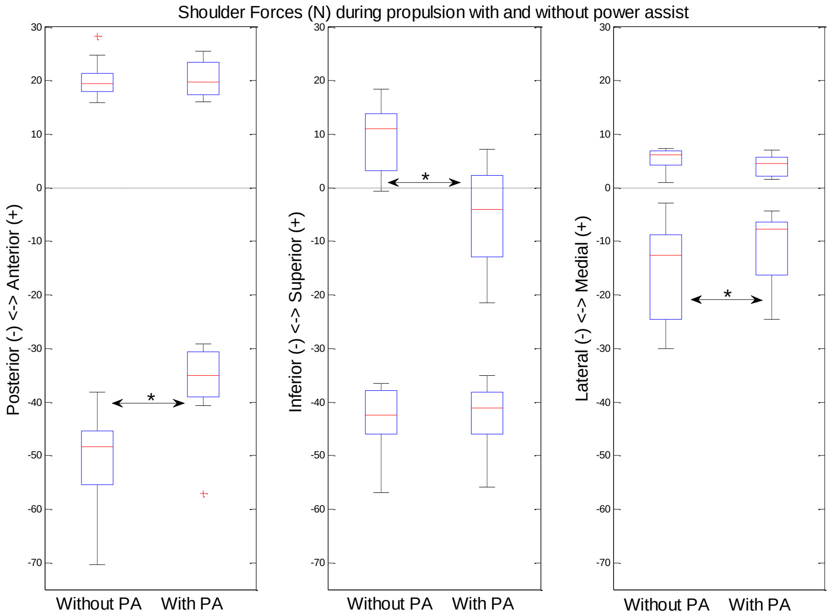

Figure 5 - Net peak shoulder forces during a complete propulsion cycle. Propulsion without power-assist is the left part in every plot) and with power-assist is the right part in every plot (mean values over n = 9). Net peak shoulder forces during propulsion without (left in every plot) and with (right) power-assist (mean values over n = 9). + = outlier; * = Significant difference between propulsion with and without power-assist; PA = power-assist.

Electromyography

Table 3 shows the RMS values of the muscles we measured. The RMS for the posterior deltoid, pectoralis major and triceps brachii decreased significantly with power-assist.

Table 3 - Change in RMS throughout the propulsion cycle (n = 9), between power-assist on and off in terms of percentage (propulsion with PA off set as 100%). All reported with the results of the Wilcoxon Signed Rank test between both test conditions.

Muscles	Mean RMS ± SD without PA (μV)	Mean RMS ± SD with PA (μV)	Change in RMS (%)	Wilcoxon (T/*p*/r)
Anterior deltoid	146.6 (51.9)	130.8 (67.3)	10.8	3 /.260 /-.38
Middle deltoid	101.4 (25.7)	98.9 (30.3)	2.5	3 /.594 /-.18
Posterior deltoid	112.6 (42.3)	98.8 (33.0)	12.3	1 /.015*/-.81
Pectoralis major	70.8 (36.1)	51.7 (18.7)	27.0	2 /.038*/-.69
Trapezius	147.2 (57.0)	137.9 (49.7)	6.4	3 /.314 /-.33
Biceps	91.7 (56.9)	79.3 (46.3)	13.5	2 /.066 /-.61
Triceps	47.0 (11.7)	40.7 (15.3)	13.4	1 /.021*/-.77

RMS = root mean square; SD = standard deviation; PA = power-assist; T = test statistic (smallest of the two sum of ranks); p = significance level; r = effect size; * = p < .05

DISCUSSION

We hypothesized that a power-assisted wheelchair could reduce the work requirements of hand-rim wheelchair propulsion that are related to shoulder overload injuries. The results show considerable decreased shoulder kinetics during power-assisted propulsion, as were shoulder kinematics and intensity of muscle activity, though to a more limited degree.

Imbalance in internal and external rotators can cause impingement of the subacriomial space. Repeated superior forces and internal rotation moments at the glenohumeral joint and the radial forces on the rim are also risks for impingement and should therefore be minimized.[11, 15] Minimizing the peak forces and overall forces necessary to propel a wheelchair has also been recommended to prevent overuse injuries.[8, 43] Our kinetic data showed that power-assisted propulsion significantly reduced the peak resultant force on the rim. At the shoulder joint, this led to significantly decreased forces in the posterior, superior and lateral directions and decreased flexion, adduction and internal rotation moments. Although the radial force on the rim did not change significantly, this force results in a laterally directed force at the glenohumeral joint, which did decrease significantly. To our knowledge, there have been no other studies with which we can compare our results.

The cadence of exerted forces and moments should also be minimized,[8, 43] which means reducing the propulsion frequency. In our study, propulsion frequency was not significantly different in the power-assisted condition; in fact, it, even slightly increased. Although other studies have also measured the propulsion frequency during power-assisted and purely hand-rim wheelchair propulsion, they yielded conflicting results. The results were also difficult to compare because the measurements were performed under different conditions: (1) using a dynamometer with various speed and resistance combinations;[28, 32] (2) using a stationary ergometer during free and fast propulsion and propulsion with graded resistance (4 % and 8 %);[38] (3) using an ADL course[31] and; (4) using a 126 m outdoor test track with three different types of power-assisted wheelchairs.[39] A significantly reduced propulsion frequency was found at 0.9 m/s, 10 and 12 W[28] and during fast propulsion.[38] In the study by Lighthall-Haubert et al.[39] three of the five subjects showed decreased propulsion frequency in all three types of power-assisted wheelchair compared to hand-rim wheelchair propulsion, while the two other studies found no significant change in propulsion frequency.[31, 32] The results seem to depend on the propelled velocity, but also on the measurement setup. Although wheelchair propulsion on a test track is the most realistic experimental setup, performing measurements in this setting is difficult. Motion capturing systems have a limited reach and a constant speed is hard to maintain. To overcome these difficulties, we chose a treadmill as our artificial test environment, which has been suggested as the second best option to measure wheelchair propulsion.[53] Although the absence of air drag reduces its validity, propulsion on a treadmill is mechanically comparable to overground propulsion.[53] Our study found a more variable velocity during power-assisted propulsion than without power-assist. It seems plausible that the subjects had difficulties fine-tuning the amount of torque they had to produce on the hand-rim. More control over the velocity can be reached by making shorter pushes at a higher propulsion frequency.

Our results may also have been influenced by the fact that our participants were healthy subjects, and also by the non-randomized test order. Studies of able-bodied subjects learning wheelchair propulsion showed no changes in gross mechanical efficiency during three 4-minute sessions.[82] Apart from a decrease in the propulsion frequency,[82, 83] they found small changes in kinematics, while an increase was found in the activity and co-contraction of several muscles.[83] Probably, the 12 minutes of practice, like the 15 minutes we gave participants before our measurements, was too short to achieve optimal propulsion frequency, muscle activation and co-contraction patterns.[82, 83] Subjects may also have needed more time to get used to the amount of power-assist delivered by the motor. If a learning effect occurred due to the non-randomized test order, then the above-mentioned results could have influenced the results found during power assisted wheelchair propulsion compared to manual wheelchair propulsion. The effect of 12 minutes of practicing manual wheelchair propulsion is (1) no change in kinetics (2) decreased propulsion frequency and (3) increased muscle activity. The differences found in our study between power-assisted and manual wheelchair propulsion, however, are not in line with the expected results due to a learning effect. Another consequence of a non-randomized test order might be the influence of fatigue. We used a low intensity protocol of one minute of propulsion on a treadmill at 0.9 m/s without resistance or inclination angle, followed by two minutes of rest. In comparison with hand-rim wheelchair research investigating fatigue,[84-86] this is low-intensity propulsion. In the above-mentioned studies, the first three to five minutes are used as warming up or to reach a steady state. Other studies investigating the difference between hand-rim and power-assisted wheelchair propulsion also used 0.9 m/s, though with resistance,[28, 29, 31, 32] and none of them reported fatigue. Therefore, it is unlikely that fatigue influenced our results.

The shoulder is most likely to be injured when forces are delivered at the extremes of the range of motion of the glenohumeral joint. It is especially when extension is combined with internal rotation[32, 44] or dominance of adduction and internal rotation is apparent[13, 72] that this results in abnormal joint translation at the glenohumeral joint. This abnormal joint translation can cause symptomatic joint instability resulting in impingement syndrome and rotator cuff tears.[13, 72] For example, in the first half of the push phase, there is usually a peak resultant force; during this phase, the glenohumeral joint is in extension combined with internal rotation and thus prone to impingement.[32, 44] We found significantly less internal rotation at the shoulder during the peak force at the rim in the power-assisted condition. With regard to extremes of motion, our study showed significantly decreased shoulder flexion and internal rotation during power-assisted propulsion. Two other studies also reported a significantly decreased range of motion of shoulder flexion-extension,[28, 32] and Algood et al. also reported a significantly decreased internal-external rotation range of motion.[28] The differences in range of motion were approximately the same as in our study.

Another risk factor for shoulder injury that has been suggested is uneven loading or overloading of muscles.[13, 72] We found that the activity of all muscles we measured tended to be lower over the complete propulsion cycle in the power-assisted condition. In contrast with our hypothesis, significant decrease in activity was found in muscles which were active during the push as well as the recovery phase, namely the pectoralis major, triceps brachii and posterior deltoid. The pectoralis major contributes to the flexion torque of the shoulder, which was in our study found to be decreased in power-assisted propulsion. The decreased activity of the posterior deltoid and triceps brachii may be a result of the decreased flexion-extension range. Two studies have investigated the effect of power-assisted propulsion on muscle activation patterns.[37, 38] However, their results are not comparable with ours, due to differences in the experimental setup with regard to: (1) surface electromyography[37] versus fine wire electromyography;[38] (2) recording of different muscles and; (3) different test conditions.

Further research should use a sample of long-term hand-rim wheelchair users, to see if the variability in velocity we found during power-assisted propulsion was due to the treadmill or due to the fact that our participants were not used to hand-rim wheelchair propulsion. In addition, hand-rim wheelchair users differ in terms of muscle strength and functionality of the upper extremities and trunk, which means that although the results were promising they are not directly applicable in clinical practice.

Conclusions

This study shows that power-assisted wheelchair propulsion can be effective in reducing the risk factors of wheelchair-related shoulder injuries in healthy subjects. The repetitive high forces at the glenohumeral joint in the posterior, superior and lateral directions decreased significantly, while the flexion, adduction and internal rotation moments also decreased significantly. Less pronounced results were found regarding shoulder kinematics (significant decrease in flexion and internal rotation angles) and muscle activity (RMS significantly decreased in the posterior deltoid, pectoralis major and triceps brachii). It is as yet not possible to translate our results directly into recommendations for hand-rim wheelchair users. Further research with actual hand-rim wheelchair users is necessary to explore the short- and long-term effects of power-assisted propulsion on shoulder injuries in this population.

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Effect of power-assisted hand-rim wheelchair propulsion on shoulder load in experienced wheelchair users: a pilot study with an instrumented wheelchair

Marieke G.M. Kloosterman
Jaap H. Buurke
Wiebe de Vries
Lucas H.V. van der Woude
Johan S. Rietman

Medical Engineering & Physics. 2015;37(10): 961-8

ABSTRACT

This study aims to compare hand-rim and power-assisted hand-rim propulsion on potential risk factors for shoulder overuse injuries: intensity and repetition of shoulder loading and force generation in the extremes of shoulder motion. Eleven experienced hand-rim wheelchair users propelled an instrumented wheelchair on a treadmill while upper-extremity kinematic, kinetic and surface electromyographical data was collected during propulsion with and without power-assist. As a result during power-assisted propulsion the peak resultant force exerted at the hand-rim decreased and was performed with significantly less abduction and internal rotation at the shoulder. At shoulder level the anterior directed force and internal rotation and flexion moments decreased significantly. In addition, posterior and the minimal inferior directed forces and the external rotation moment significantly increased. The stroke angle decreased significantly, as did maximum shoulder flexion, extension, abduction and internal rotation. Stroke-frequency significantly increased. Muscle activation in the anterior deltoid and pectoralis major also decreased significantly. In conclusion, compared to hand-rim propulsion power-assisted propulsion seems effective in reducing potential risk factors of overuse injuries with the highest gain on decreased range of motion of the shoulder joint, lower peak propulsion force on the rim and reduced muscle activity.

INTRODUCTION

Incidences of shoulder overuse injuries among hand-rim wheelchair users are high with figures varying between 30 and 73% in the chronic spinal cord injury population.[6, 11, 12] It is suggested that part of the risk factors for overuse originate in wheelchair propulsion itself. Characteristics of hand-rim propulsion related to shoulder overuse injuries are the intensity of mechanical loading of the shoulder during the push phase, the highly repetitive nature of propulsion motions and force generation in extremes of shoulder motion.[6, 13-17]

To create a better balance between mechanical loading and the work-capacity of the shoulder complex during propulsion, guidelines have been developed.[8, 43] These guidelines recommend minimum: push-frequency; maximum shoulder extension combined with internal rotation and abduction; imbalance in internal and external rotators at the shoulder; peak propulsion forces; and overall propulsion forces. Specifically, the radial directed forces at the rim, high posterior and lateral directed forces at the shoulder, and superior directed forces combined with internal rotation moments at the shoulder are deemed to be potential risk factors and therefore should be minimized.[11, 15]

One of the guidelines[8] recommends a power-assisted wheelchair (hybrid between hand-rim and powered wheelchairs)[9] as a way to reduce energy expenditure in hand-rim wheelchair propulsion. However, research shows that power-assisted wheelchair propulsion applies to more aspects than energy expenditure alone.[87] Several studies compared hand-rim and power-assisted propulsion on kinematic and electrophysiological parameters.[27, 28, 31, 32, 38, 39] The results were promising in reducing the risk-factors of shoulder overuse-injuries. Shoulder flexion–extension[27, 32] and internal–external rotation[27, 28] significantly decreased during power-assisted propulsion. Shoulder abduction tended to decrease, however, this was not significant[28, 32]. The results on push frequency were ambiguous.[28, 31, 32, 38, 39] Muscle activity in the pectoralis major[27, 37, 38] and in the triceps brachii[27, 37] significantly decreased during power-assisted propulsion.

Although high forces and moments are important risk factors in the development of shoulder overuse injuries, little attention has been paid to the influence power-assisted propulsion could have on these risk factors. To our knowledge no previous studies reported the influence of power-assisted propulsion on shoulder kinetics and shoulder angles during peak force in actual hand-rim wheelchair users. Only one study with healthy subjects[27] combined kinematic and electrophysiological parameters with kinetics measured at the rim. This study showed that power-assisted wheelchair propulsion reduced the risk factors of wheelchair-related shoulder injuries in healthy novices.[27] However, before these results can be translated to clinical practice, additional research with experienced wheelchair users is necessary. This is essential, because differences in propulsion technique between experienced wheelchair users and novices are assumed. These differences may emerge from certain impairments (e.g. partly innervated upper extremity muscles, hypertonia) as well as the mere extend of hand-rim propulsion experience. Also, the effects of motor-learning during the measurement period of the healthy novices may cause additional differences [88]. Therefore, in this current study the measurements were done following a period of regular use in the personal daily environment. The aim of the current study was to compare hand-rim propulsion with and without power-assist on shoulder load in a group of experienced wheelchair users, while propelling an instrumented experimental wheelchair on a motor driven treadmill during standardized conditions. To get insight in the potential risk factors of shoulder overuse injuries we quantified shoulder load as: 1) intensity and frequency of forces and moments acting on the rim and the shoulder; 2) shoulder angles during force generation; 3) range of motion of the shoulder during the push; and 4) intensity of upper-extremity muscle activation. It is hypothesized that power-assisted hand-rim propulsion has a reducing effect on the above mentioned outcomes, i.e. potential risk factors for shoulder overuse.

METHODS

Subjects

The sample size was based on our pilot study with healthy subjects,[27] because patient data on our primary objective was lacking.[87] Based on the peak force on the rim, as outcome measure for the total amount of force necessary to propel a wheelchair, a sample size of 6 was deemed to be sufficient to detect changes with an alpha of 0.05 and a power of 0.80. The sample size was calculated with the statistical program G*Power version 3 (Heinrich Heine Universität Düsseldorf). We took into account that data of patients was probably more variable, and subjects might withdraw from the study. Therefore, it was intended to recruit twelve subjects. Eventually eleven hand-rim wheelchair users participated in this study. All participants were able to propel a hand-rim wheelchair bimanually with sufficient trunk stability to maintain posture. Exclusion criteria were the current use of any type of power-assisted wheelchair, extreme shoulder pain, spasticity, or contractures of the upper extremity which made hand-rim wheelchair propulsion for the duration of the measurements impossible. This study was approved by the local medical ethics committee, and registered in the trial register under no. NTR2661. All participants gave written informed consent prior to admittance to the study.

Procedure

All subjects had 1 to 4 weeks of practical use with prototype power-assist wheels (Indes Holding B.V., commercially available as Wheeldrive, Handicare B.V.) on their personal hand-rim wheelchair in their home environment. The weight of the power-assist wheel is 13.3 kg and it has an additional width of 21.5 mm compared to a normal hand-rim wheelchair wheel. Following this familiarization with the power-assist system, experimental measurements were conducted in the instrumented experimental power-assist wheelchair on a motor-driven treadmill. Each measurement was preceded by a short (approximately 1 minute) familiarization period to get used to the measurement set up on a the treadmill. In accordance with available studies[27-29, 31, 32] subjects propelled the instrumented wheelchair on a level single-belt treadmill (Forcelink B.V.; 1.2 x 2.5 m) at 0.9 m/s. From the start of the experiment the speed of the treadmill was slowly increased until the intended speed of 0.9 m/s was reached. The measurements consisted of 2 conditions each with 3 trials of approximately 1 minute propulsion followed by at least 2 minutes of rest to prevent fatigue. Test order was randomly assigned to propulsion with and without power-assist (motor on / motor off). Data acquisition started when the participants reached a stable propulsion rhythm. Kinematics, kinetics and surface electromyography (sEMG) data were measured simultaneously for 30 to 40 s. Because kinematics, kinetics and sEMG data of the left and right side highly correlated during straight hand-rim wheelchair propulsion [74, 89], all data was collected unilaterally at the subject's right side.

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To reduce data volume, ten sequential strokes were selected for data analysis. As a check for consistency between the propulsion cycles, cycles with the smallest deviation of the mean cycle length were selected. The total propulsion cycle was defined as 100% and the timing of propulsion characteristics was expressed as a percentage of the propulsion cycle. The propulsion cycle was divided into a push phase and a recovery phase. The start of the push phase was defined as the turning-point in the velocity data (velocity = 0) followed by forward movement of the radial styloid process. The start of the recovery phase is the next point in the data in which the velocity is equal to zero, however now followed by backward movement of the radial styloid process. Data processing was performed with Matlab.

Instrumented power-assisted wheelchair

The experimental instrumented wheelchair consisted of prototype power-assist wheels (Indes Holding B.V., commercially available as Wheeldrive, Handicare B.V.) with a six degrees of freedom force and torque sensor (Model FT Delta SI-660-60, ATI Industrial Automation) build in the right wheel. The hand-rim was connected to the sensor by a rigid frame (Fig. 1). This arrangement allowed all the forces and moments exerted on the rim to be measured by the sensor. The transmitter was centred at the rigid frame. The instrumented wheel was mounted on a standardized hand-rim wheelchair (Legend2, Handicare, seat width 0.41 m, total width 0.59 m, diameter hand-rim 0.52 m, diameter tube 0.028 m). This setup was used for all subjects and in both conditions: with and without power-assist, respectively motor on/ motor off. Only in the condition when the power-assist was turned on did the signal caused by deformation of the piezoelectric sensor activate the motor. This resulted in extra power being delivered to the wheel axis, additional to the hand-rim power provided by the wheelchair user.

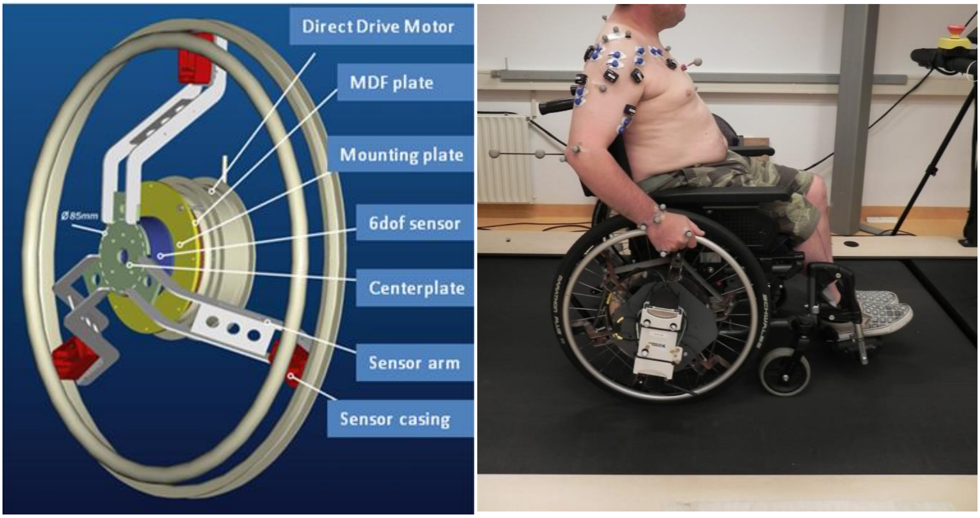

Figure 1 - Left. Schematic the six degrees of freedom sensor mounted on the wheel and axis. The assisting motor was mounted in the axis itself. A mounting plate and a medium-density fiberboard (MDF) were placed between the motor and the six degrees of freedom (DOF) force and torque sensor. The hand-rim was mounted on the sensor via the sensor casing, sensor arm and center plate. **Right.** The instrumented wheel as implemented in the experimental wheelchair used in this study. The picture also shows the reflective markers and electrodes for surface electromyography.

Kinematics

Reflective single markers were placed on the right side of the body at the following bony landmarks: incisura jugularis, xiphoid process, spinous process of 7th cervical vertebrae, spinous process of 8th thoracic vertebrae (pointer in static trial), medial and lateral epicondyle, radial and ulnar styloid process,[76] a marker-set at the acromion,[77] distal point of second and fifth metacarpal joint. Additionally, four markers were placed at the wheel, and four at the treadmill. Position data was sampled at 100 Hz by means of VICON 370 Type MX 13, infrared 3D-motion analysis system with six cameras. Kinematic data was low-pass filtered at 6 Hz with a second order, zero phase Butterworth filter.[90] Joint angles were calculated as proposed by the International Society of Biomechanics.[76] Except for the rotation order of the humerus with respect to the trunk we used the z–x–y rotation order, rather than the y–x–y order, to stay close to clinical terminology. The glenohumeral joint rotation center, was calculated from the marker set on the acromion by regression.[77] In the anatomical position all angles were set at zero. As well as maximum shoulder angles, push-frequency (strokes / minute) and stroke angle (degrees; Fig. 2 - left) were also reported.

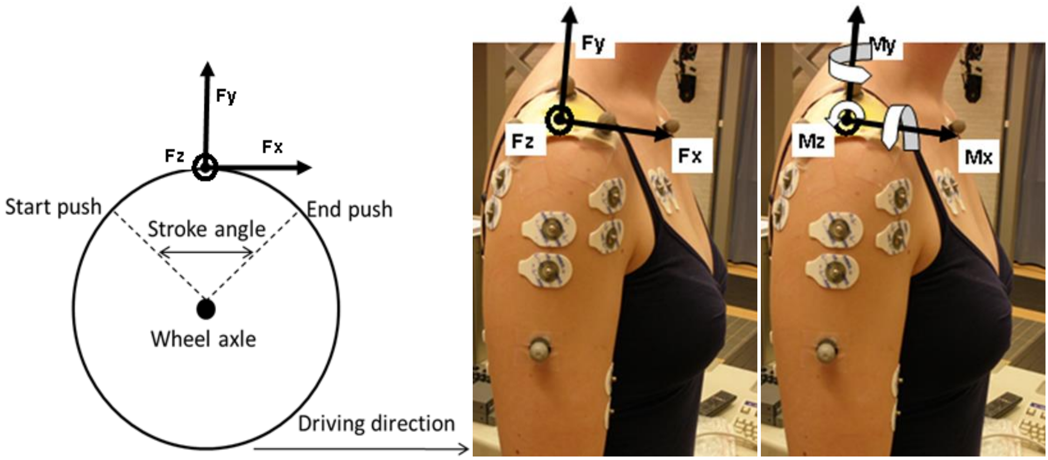

Figure 2 - Left and Mid. The local positive forces FX = anterior, FY = superior and FZ = lateral directed forces at point of force application at the point of force application on the rim (left) and the glenohumeral joint (mid). **Right.** Positive moments MX = adduction moment, MY = internal rotation and MZ = flexion moment at the glenohumeral joint.

Kinetics

The 3D kinetic data from the instrumented wheel was sampled at 200 Hz, low-pass filtered at 10 Hz with a second order, zero phase-shift Butterworth filter, and stored on a wireless data acquisition system (Type WLS-9205, National Instruments Corporation). The kinetic data was down-sampled to 100 Hz and synchronized with the kinematic and sEMG data. The forces and moments measured at the axis were calibrated, corrected for baseline values due to gravity, corrected for rotating axes system and converted to forces and moments at the point of force application (PFA) on the rim in a local reference frame. PFA was defined as the position of the center of mass of the hand[78] on the rim.

A three-dimensional linked-segment model between hand, forearm, humerus and thorax was constructed to calculate net shoulder joint forces and external joint moments at the shoulder joint.[91] The inputs for the model were kinematics of the upper extremity, forces and moments at PFA, segment lengths and estimated segment mass, position center of mass[78] and moments of inertia.[91] Forces and moments were expressed in the local anatomical axis system[91] as a mean of the ten selected strokes. Positive forces represent: FX = anterior, FY = superior and FZ = lateral directed forces (Fig. 2, left and midway). Positive moments around the glenohumeral joint represent: MX= adduction moment, MY = internal rotation and MZ = flexion moment (Fig. 2 right). For graphical reasons and as a consequence of the chosen model, the opposite directions were presented as negative forces and moments. Next to forces and moments at the shoulder, the exerted forces at PFA on the rim (FX_{rim}, FY_{rim}, FZ_{rim}, peak resultant force ($\sqrt{FX_{rim}^2 + FY_{rim}^2 + FZ_{rim}^2}$) and propulsion moment (MZ_{rim}) at the rim were also reported.

Surface EMG

Bi-polar surface EMG was recorded with 16-channel Zero Wire EMG System (Biometrics), sEMG amplifier. The raw signals were digitized at a sampling rate of 2000 Hz with a bandwidth filter of 10 to 1000 Hz. The raw signals were stored on the Vicon system where they were synchronized with the kinematic data. Ag/AgCl electrodes (Type ARBO S93SG Tyco Healthcare) were used, with a 23 mm inter-electrode distance. The electrodes were placed on seven muscles of the right arm involved in wheelchair propulsion: anterior, middle and posterior part of the deltoid, the sternal part of the pectoralis major, the long head of the biceps and triceps brachii, and the middle part of the trapezius.[7, 27, 38, 75] Placement and preparation were in accordance with SENIAM guidelines.[79] Mean power of the EMG signal was determined by the root mean square (RMS) of the signal based on previous studies on cyclic movements.[75, 80, 81] A 10 Hz fourth order, zero phase-shift Butterworth filter was used to smooth the signal. RMS was calculated as the mean RMS of the 10 selected propulsion cycles. Since individual RMS values cannot be compared between subjects the RMS values were normalized within-subjects, by calculating the percentage difference in RMS during propulsion with and without power-assist, setting the RMS of the trial without power-assist at 100%.

Statistical analysis

All parameters were averaged over the ten strokes analyzed for every subject. These averages were then used to calculate a group average with standard deviation. Because of the sample size and the fact that the data were not normally distributed, the differences between propulsion with and without power-assist were determined with the Wilcoxon Signed Rank test, reporting the test statistic T (smallest of the two sum of ranks), significance (p), and effect size (r). A p-value less than 0.05 was considered as statistically significant. Statistical analysis was done in SPSS 19.

RESULTS

Eleven hand-rim wheelchair users, six men and five women with a mean age of 35.6 ± 5.6 years, participated in this study. The hand-rim wheelchair was their primary mode of mobility for 12.2 ± 9.6 years due to incomplete spinal cord injury (n=4; height T1, T7, T9, T10), Ehlers Danlos (n=2), hereditary spastic paraplegia (n=3), cerebral palsy (n=1), and Friedreich's ataxia (n=1). The subjects had a mean height of 1.74 ± 0.11 meters and a mean weight of 67.6 ± 15.3 kilogram.

All participants performed the experiments according to the protocol: two conditions with 3 trials of approximately 1 minute low intensity propulsion. Propulsion on a treadmill at 0.9 m/s without incline resulted in a task load of 9.8 (± 6.7) Watt for the power-off condition. For one subject 0.9 m/s was too fast, therefore in this case 0.6 m/s was used. All subjects had a complete data set except for one subject lacking force data of the trial with power assist due to an error in data transmission. Force data of this subject was not used for statistical analysis. The presented shoulder angles and kinetic parameters were calculated during the push-phase.

Shoulder kinematics

In table 1 the shoulder kinematics for both conditions are presented. During power-assisted propulsion the push-frequency increased significantly, while the stroke angle, maximal shoulder flexion, extension, abduction and internal rotation angles decreased significantly.

Table 1 - Kinematics (n = 11): push-frequency and maximal shoulder angles, presented with the results of the Wilcoxon Signed Rank test for the two test conditions.

Kinematic outcome measures	Mean (SD) without PA	Mean (SD) with PA	Wilcoxon (T/p/r)
Push-frequency (strokes / min)	50.5 (9.4)	56.9 (13.6)	2/.033*/-0.64
Maximal flexion (°)	9.3 (9.9)	4.4 (13.0)	3/.016*/-0.72
Maximal extension (°)	50.8 (12.7)	47.2 (13.0)	1/.008**/-0.80
Minimal abduction (°)	27.4 (5.5)	26.7 (7.0)	5/.790/-0.08
Maximal abduction (°)	39.6 (9.0)	37.4 (10.0)	2/.013*/-0.75
Maximal external rotation (°)	1.9 (8.2)	2.4 (7.9)	5/.722/-0.22
Maximal internal rotation (°)	36.5 (15.6)	29.6 (14.4)	0/.003**/-0.88
Stroke angle (°)	75.3 (7.8)	64.0 (11.7)	1/.004**/-0.86

SD = standard deviation; PA = power assist; ° = degrees; *T = test statistic (smallest of the two sum of ranks); p = significance level; r = effect size;* = p < .05; ** = p < .01*

Kinetics at the rim

When comparing kinetics, peak forward force applied during the push on the rim (FX_{rim}), decreased significantly during power-assisted propulsion. The peak resultant force also decreased significantly and occurred earlier in the propulsion cycle with less abduction and internal rotation at the shoulder, as seen in Table 2.

Table 2 - Peak push forces and moments as applied to the push-rim (local reference frame at point of force application). The peak resultant force is reported with the associated timing and shoulder angles (n = 10), and presented with the results of the Wilcoxon Signed Rank Test between both test conditions.

Kinetic and kinematic outcome measures	Mean (SD) without PA	Mean (SD) with PA	Wilcoxon (T/p/r)
AT PUSH RIM			
Forward force (N)	80.9 (16.7)	64.5 (12.7)	1/.007**/-0.85
Downward force (N)	24.2 (7.3)	19.4 (9.4)	2/.093/-0.53
Inward force (N)	8.0 (2.7)	6.7 (3.2)	2/.093/-0.53
Propulsion moment (N·m)	0.92 (0.88)	1.1 (1.1)	4/.445/-0.24
Peak resultant force (N)	83.4 (15.9)	67.2 (13.5)	0/.005**/-0.89
Timing of peak resultant force (%)	54.6 (7.5)	46.0 (7.1)	1/.037*/-0.66
SHOULDER ANGLES DURING PEAK RESULTANT FORCE AT RIM			
Extension angle (°)	21.5 (12.7)	26.3 (13.6)	1/.059/-0.60
Abduction angle (°)	37.1 (9.1)	35.4(10.0)	1/.009*/-0.82
Internal rotation angle (°)	16.6 (13.1)	3.9 (2.1)	2/.022*/-0.73

SD = standard deviation; PA = power assist; % = percentage of movement cycle; ° = degrees; N = Newton; N·m = Newton Meter; *T = test statistic (smallest of the two sum of ranks); p = significance level; r = effect size;* = p < .05; ** = p < .01*

Kinetics at the glenohumeral joint

At the glenohumeral joint the anterior directed force decreased significantly during power-assisted propulsion, while the posterior directed force increased significantly (Table 3.). No superior directed force occurred, however the minimum inferior directed force (FY) increased significantly during power assisted propulsion. Internal rotation and flexion moments decreased significantly during power-assisted propulsion, while the external rotation moments increased significantly (as seen in Fig. 3). Fig. 4 shows an example of forces and moments at the glenohumeral joint during the push phase.

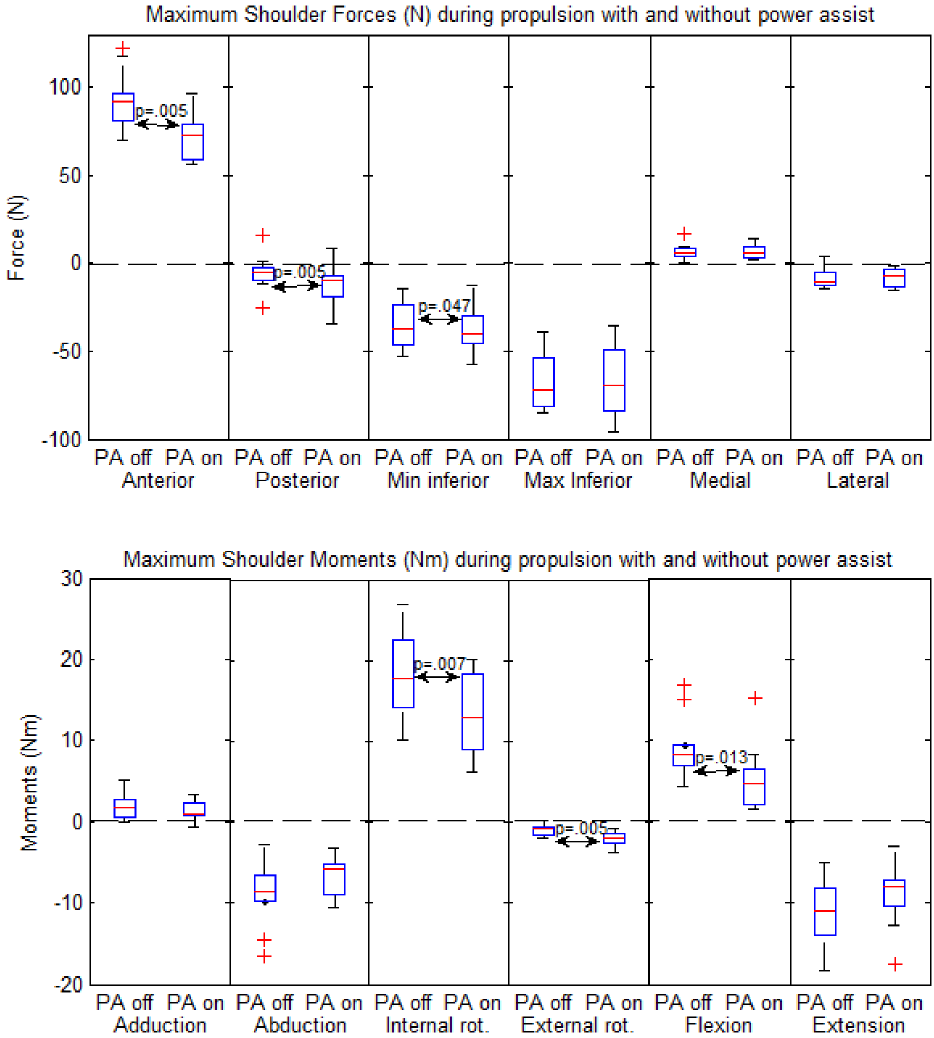

Figure 3 - Maximum shoulder forces (N) and moments (Nm) measured with and without power assist (n=10). In each graph the box plot on the left is without power assist and on the right with power assist. The significant differences between the values with and without power assist are presented with a p-value. + = outlier.

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Table 3 - Peak push forces and moments as calculated in the local reference frame of the glenohumeral joint. The peak resultant force is reported with the associated timing and shoulder angles (n = 10), and presented with the results of the Wilcoxon Signed Rank Test between both test conditions.

Kinetic outcomes: net shoulder forces and moments	Mean (SD) without PA	Mean (SD) with PA	Wilcoxon (T/p/r)
Anterior directed force (N)	91.9 (16.2)	72.7 (12.3)	0/.005**/-0.89
Posterior directed force (N)	4.9 (10.1)	12.0 (11.2)	0/.005**/-0.89
Minimal inferior directed force (N)	33.4 (12.7)	38.7 (13.3)	3/.047*/-0.63
Maximal inferior directed force (N)	67.0 (15.8)	67.4 (19.2)	3/.139/-0.47
Lateral directed force (N)	7.2 (4.3)	6.1 (3.7)	4/.333/-0.31
Medial directed force (N)	7.8 (6.5)	8.1 (5.6)	4/.575/-0.18
Adduction moment (N·m)	1.9 (1.5)	1.3 (1.2)	3/.241/-0.37
Abduction moment (N·m)	8.7 (4.0)	6.5 (2.5)	2/.074/-0.56
Internal rotation moment (N·m)	17.3 (5.4)	13.5(5.0)	1/.007**/-0.85
External rotation moment (N·m)	0.9 (0.7)	2.1 (0.9)	0/.005**/-0.89
Flexion moment (N·m)	9.3 (3.9)	5.4 (4.0)	1/.013*/-0.79
Extension moment (N·m)	11.5 (4.3)	8.8 (4.0)	1/.059/-0.60

SD = standard deviation; PA = power assist; % = percentage of movement cycle; º = degrees; N = Newton; N·m = Newton Meter; *T = test statistic (smallest of the two sum of ranks); p = significance level; r = effect size;* = p < .05; ** = p < .01*

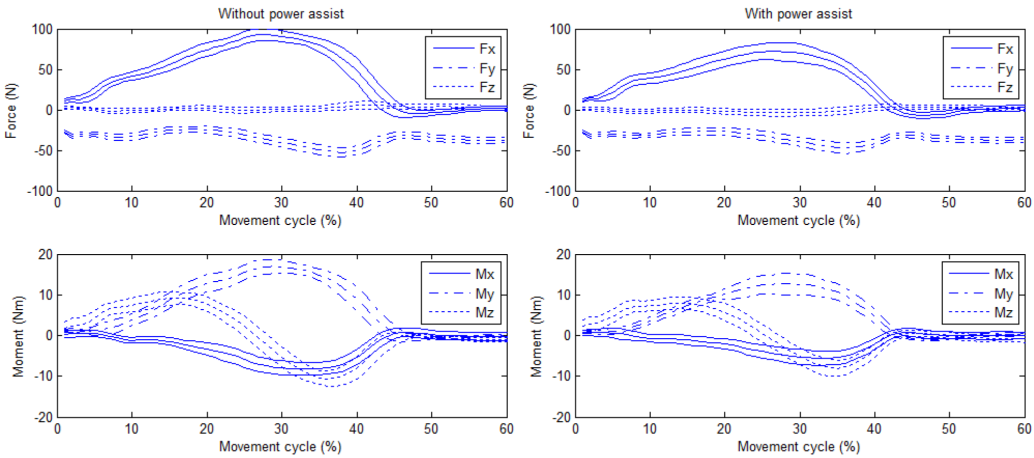

Figure 4 - Three dimensional shoulder forces and moments during the push phase. The plotted line for each parameter represents the mean of ten sequential strokes with standard deviation for one subject. Fx, Fy, Fz = force in respectively x, y and z direction; Mx, My, Mz, moment around respectively x, y and z axis. **Left -** during propulsion without power assist. **Right -** during propulsion with power assist.

Electromyography

In Table 4 the percentage change in RMS values of the measured muscles are presented. The RMS for the anterior deltoid and pectoralis major decreased significantly with power-assist.

Table 4 - Percentage change in RMS between propulsion with and without power-assist throughout the propulsion cycle (n = 11), reported with the results of the Wilcoxon Signed Rank test between both test conditions. Propulsion without PA is set as 100%.

Muscles	Change in RMS (%)	Wilcoxon (T/*p*/r)
Anterior deltoid	-42.3	2/0.050*/-0.59
Middle deltoid	-6.8	5/.424/-0.24
Posterior deltoid	-0.2	4/.722/-0.11
Pectoralis major	-37.3	3/.033*/-0.64
Trapezius	+ 2.3	5/.790/-0.08
Biceps	-24.7	2/.062/-0.56
Triceps	-21.8	5/.248/-0.35

RMS = root mean square; % = percentage change relative to RMS during propulsion without power assist; T = test statistic (smallest of the two sum of ranks); p = significance level; r = effect size; * = p < .05

5

DISCUSSION

In this article shoulder load between hand-rim and power-assisted hand-rim propulsion were compared, while propelling an instrumented experimental wheelchair on a motor driven treadmill under standardized conditions. A comparison was made of 1) intensity and frequency of forces and moments acting on the rim and the shoulder; 2) shoulder angles during force generation; 3) range of motion of the shoulder during the push; and 4) intensity of upper-extremity muscle activation. To our knowledge, points 1 and 2 were not previously measured during power assisted propulsion in actual hand-rim wheelchair users, even though these parameters are indicted as important parameters in the development of shoulder overuse injuries.[6, 13-17] It is therefore hypothesized that hand-rim propulsion with power-assist reduces potential risk factors of overuse injuries: intensity of loading, the highly repetitive nature of propulsion motions, and force generation in extremes of shoulder motion. The majority of the results confirm this hypothesis. There is a considerable decrease in peak resultant force at the push-rim, shoulder range of motion and muscle activity during power-assisted propulsion. Shoulder kinetics also showed decreased figures during power-assisted wheelchair propulsion, although to a lesser extent.

Intensity of shoulder loading decreased during power-assisted propulsion, which is in accordance with our study on healthy subjects.[27] Guidelines recommended decreasing the intensity and frequency of peak force and propulsion forces.[8, 43]

Specifically, the radial directed forces at the rim, high posterior and lateral directed forces at the shoulder, and superior directed forces combined with internal rotation moments at the shoulder are deemed to be potential risk factors and therefore should be minimized.[11, 15] The peak propulsion force decreased, and from the afore specified directional forces and moments only the internal rotation moments decreased. Additionally, at the glenohumeral joint the anterior directed force and flexion moments decreased significantly during the push. In contrast however, the posterior and minimal inferior directed forces increased significantly, as did the push-frequency. Although the increase in the posterior and minimal inferior directed force in absolute number is small (7.1 N and 5.3 N respectively), the reason for the increase is unclear. Possible explanations are that a higher push-frequency with a smaller stroke angle results in a higher acceleration / deceleration of the arm, and slowing down the arm and meanwhile stabilizing the glenohumeral joint might result in higher posterior forces and minimum inferior forces. Another possibility is that the instrumented wheelchair reacts slightly differently than the prototype used at home. Possibly, propulsion with different wheels than subjects were used to combined with propulsion on a fixed speed on a treadmill, which has a confined space, results in shorter propulsion strokes to gain more control. This strategy might be comparable to the initial phase of learning hand-rim wheelchair propulsion.[82, 88] In previous research the effect of power-assisted propulsion on push-frequency led to ambiguous results.[28, 31, 32, 37-39] Four studies measured, among others, push-frequency on a dynamometer. In two studies the push-frequency decreased during power-assisted propulsion[28, 38] in the other two studies no significant differences were found.[31, 32] Two studies measured this during over-ground propulsion. In the study of Lighthall-Haubert et al.[39] 2 subjects showed increased push-frequency and 3 showed decreased push-frequency during power-assisted propulsion. Levy et al.[37] reported decreased push-frequency during 100 meter power-assisted level propulsion and no significant changes on carpet and incline.

For glenohumeral kinematics, the guidelines recommended to decrease the maximum extension combined with internal rotation and abduction and reduce the imbalance in internal and external rotators.[8, 43] Power-assisted propulsion, in this study, had a positive influence on maximum shoulder angles during force generation. During the peak resultant force, abduction and internal rotation decreased significantly, which also seems to be a mechanism in healthy subjects.[27] The range of motion of the shoulder during the push-phase also decreased. The maximum shoulder extension, internal rotation and abduction angles decreased significantly, these three angles were all mentioned as provocative for shoulder injuries.[8, 43] These results were in accordance with previous research, reporting a significantly decreased shoulder flexion-extension,[27, 32] a decreased internal-external rotation range of motion,[27, 28] and a tendency to decrease the shoulder abduction during power-assisted propulsion.[28, 32] Our study showed that during power-assisted propulsion there is still twelve times more external rotation than internal rotation (without power-assist this was nineteen times higher). However, with the significantly decreased internal rotation moments and increased external rotation moments during power-assisted propulsion, the balance in internal and external rotators at the shoulder seemed improved.

The significant changes in shoulder kinematics are relatively small (2-7 degrees). However, when you keep in mind the number of pushes during the day, these results might be clinically important. Notably, this results in a few degrees less abduction and extension movement some 1800 bimanual pushes per hour[4] and as a result a reduction in force necessary to hold the arm against gravity. Whether these changes were indeed clinically significant cannot be answered with this cross-sectional pilot study, a longitudinal study with more subjects would be necessary.

The intensity of upper-extremity muscle activation tended to decrease over the complete propulsion cycle in the power-assisted condition in 6 of the 7 muscles measured. Significant decreases in activity were found in the pectoralis major, and the anterior deltoid muscles which were active during the push. Both muscles contribute to the flexion moment of the shoulder, which decreased during power-assisted propulsion. Previous research comparing muscle activation patterns between regular hand-rim and power-assisted propulsion also showed significantly decreased activity in the pectoralis major.[27, 37, 38] In two studies, activity in the triceps brachii significantly decreased during power-assisted propulsion.[27, 37]

A potential limitation in our experimental design is the use of a treadmill. Wheelchair propulsion on a test track is the most realistic experimental setup. However, performing measurements in this setting is difficult. Motion capturing systems have a limited measurement volume and a constant speed is hard to maintain. For practical considerations we choose a treadmill as the artificial test environment, which is mentioned as the second best option to measure wheelchair propulsion.[53] Although, the absence of air drag reducing validity, propulsion on a treadmill is mechanically comparable to propulsion over ground.[53] However, based on increased propulsion frequency and increased minimum inferior and posterior forces, subjects seemed to have difficulties fine-tuning the right amount of force to stay on the treadmill. For use in the home environment this fine-tuning might be less essential in longer distances but is also necessary for maneuvering in confined spaces. In the prototype wheels, three different settings were programmed regarding the amount of torque. So it is possible to use more power-assist on longer distances and switch to less power-assist in confined spaces.

Another limitation is the higher variability during power-assisted propulsion. This is probably caused by the sensors of the instrumented wheelchair which were replaced to the rigid frame due to the integration of the force sensor, therefore the wheels may react differently than the power-assist wheels they were used to. Also the additional weight, caused by the rigid frame and measurement tools might have contributed to the higher variability, although it was attempted to position the additional mass of the measurement wheel setup as best as possible around the axis in order to diminish the effect of additional weight on the inertia.

In an ideal situation a comparison would have been made between hand-rim propulsion in the subject's own wheelchair and hand-rim propulsion with power-assist wheels mounted on the subject's own wheelchair. Because of the combined use of a force sensor with power-assist wheels, this was not possible, and therefore the power-assist wheels were mounted on a fixed wheelchair frame which was not adjustable for each subject. This might have an impact on different individuals, yet was consistent over the motor on and off condition. In some subjects this may have led to more shoulder abduction than usual. However the influence of configuration, and thus the possible technique consequences, expectedly remained the same between both test conditions and subjects. In addition to diminishing the influence of potential learning or time effects on the results, a random test order was used.

A three-dimensional linked-segment model between hand, forearm, humerus and thorax was constructed to calculate net shoulder joint forces and external joint moments at the shoulder joint.[91] For our research question this approach was satisfactory. If, in future research, more insight in the motor control and contribution of each individual muscle is desirable, a more sophisticated shoulder-arm musculoskeletal model, such as the Delfs elbow-shoulder model,[92] would be more appropriate. As a part of quantifying shoulder load, common sEMG was used focused on superficial shoulder complex muscles involved in hand-rim wheelchair propulsion. For Future research it would be interesting to examine the rotator cuff muscles with fine-wire electromyography or with the above mentioned model. This would be of clinical importance because, particularly overuse injuries to the rotator cuff muscles are a common cause of shoulder pain.[6]

For further research, to affirm the results of this pilot study, it might be interesting to perform a longitudinal study, with a larger research population, to explore if the effects of longer lasting power-assisted propulsion result in a diminished amount of developed shoulder overuse injuries.

Conclusion

According to the guidelines, in order to create a better balance between mechanical loading and the work-capacity of the shoulder complex during propulsion,[8, 43] power-assisted propulsion on a treadmill is effective in reducing the majority of the potential risk factors of shoulder injury. During power assisted propulsion the peak resultant force exerted at the hand-rim decreased and was performed with significantly less abduction and internal rotation at the shoulder. At shoulder level the anterior directed force and internal rotation and flexion moments decreased significantly. In addition, posterior and the minimal inferior directed forces and the external rotation moment significantly increased. The stroke angle decreased significantly as did maximum shoulder flexion, extension, abduction and internal rotation. Stroke-frequency significantly increased. Muscle activation in the anterior deltoid and pectoralis major also decreased significantly. Therefore, the use of power-assisted wheelchairs might be indicated for subjects prone to developing over-use injuries due to hand-rim propulsion or subjects with difficulties driving a hand-rim wheelchair primarily due to lack of upper-extremity power.

Recommendations

- Power-assisted wheelchair propulsion is effective in reducing potential risk factors of shoulder over-use injuries: intensity of shoulder loading, shoulder angles during force generation, shoulder range of motion and intensity of muscle activation.
- The prescription of a power-assisted wheelchair seems indicated for subjects developing over-use injuries due to hand-rim propulsion or subjects with difficulties driving a hand-rim wheelchair primarily due to lack of upper-extremity power.

6

Exploration of shoulder load during hand-rim wheelchair start-up with and without power-assisted propulsion in experienced wheelchair users

Marieke G.M. Kloosterman
Jaap H. Buurke
Leender Schaake
Lucas H.V. van der Woude
Johan S. Rietman

Clinical Biomechanics. 2016;34: 1-6

ABSTRACT

Background: Frequent start movements occurred during the day, yielding high upper extremity stress. The high incidence and the impact of shoulder injury on daily life wheelchair user made it clinically relevant to investigate whether power-assisted propulsion is beneficial during the start.

Methods: Eleven hand-rim wheelchair users performed a start movement in an instrumented wheelchair on a flat surface. Test order was randomly assigned to propulsion with and without power-assist. For each subject, parameters were averaged over 3 repeated starts. For statistical analysis the Wilcoxon signed rank test was used.

Findings: Intensity of mechanical shoulder decreased during power-assisted propulsion for anterior (147.0 (44.8) versus 121.9 (27.4) N; effect size (r) =-.75), posterior (4.8 (14.1) versus 2.7 (11.6) N; r =-.64) and inferior directed forces (82.6 (27.9) versus 68.9 (22.6) N; r =-.78) and abduction (20.2 (14.6) versus 12.9 (7.8) Nm; r =-.88) and extension moments (20.3 (10.7) versus 13.7 (9.1 Nm; r =-.88). Peak resultant force at the rim significantly decreased from 133.5 (38.4) N to 112.2 (25.4) N (r =-.64) and was accompanied by significant decreased shoulder abduction (35.3 (6.7) versus 33.3 (6.8); r =-.67) and significant increased shoulder extension (13.6 (16.3) versus 20.3 (19.1); r =-.78) during power-assisted start-up.

Interpretation: Power-assist hand-rim wheelchairs are effective in reducing external shoulder load and partly effective in reducing force generation in extremes of shoulder motion during start-up. The use of power-assist wheels might reduce the risk of developing shoulder overuse injuries.

INTRODUCTION

The high incidence of shoulder injuries in hand-rim wheelchair users[6, 11, 12] partly originates in wheelchair propulsion itself. The intensity of mechanical loading of the shoulder during the push phase, the highly repetitive nature of the movements and concomitant force generation in extremes of shoulder motion are potential risk-factors related to shoulder overuse injuries.[6, 13-15, 17, 93]

For constant velocity propulsion at 0.9 m/s, it is known that power-assisted wheelchair propulsion is effective in reducing these risk factors compared to purely hand-rim wheelchair propulsion.[27, 94] In healthy subjects it was primarily the shoulder loading which was decreased by power-assisted propulsion.[27] In experienced hand-rim wheelchair users the highest gain was on decreased force generation in extremes of motion, while shoulder load partly decreased during power-assisted propulsion.[94]

In daily life short, slow bouts of active propulsion dominate hand-rim wheelchair usage. During daily hand-rim wheelchair use the number of starts / stops per 1,000 meter is estimated to be 141.8 (60.0)[20]; the daily distance travelled ranged from 1.5 - 2.5 km[18-20] which means 212.7 till 354.5 starts/stops a day. Approximately 63% of the wheelchair propulsion bouts are shorter than 30 seconds, less than 13 meter, and slower than 0.5 m/s.[19] The acceleration during start-up requires more force than maintaining a constant velocity. Stresses on the upper extremity are assumed to be 1.8 - 3.5 times higher during acceleration than during constant velocity propulsion.[21]

Power-assist wheels support regular hand-rim propulsion with electric power. This has a beneficial effect during constant low velocity propulsion over regular hand-rim wheelchair use. Due to the frequent starts during the day, with high stress on the upper extremity and the high impact of shoulder injury in daily life of the hand-rim wheelchair user it is clinically relevant to investigate whether power-assisted propulsion is also beneficial during the start. We hypothesize that the additional power delivered by the motor is already enough during the start to decrease the intensity of shoulder load and to decrease the shoulder angles during peak force.

METHODS

The results presented in this article were part of a larger study focusing on shoulder load during power-assisted propulsion. Therefore, the subjects and part of the methods are similar to those of Kloosterman et al.[94]

Subjects

Eleven hand-rim wheelchair users, six men and five women, with a mean age of 35.6 (5.6) years and a Body Mass Index of 21.5 (3.6), participated in this study. The hand-rim wheelchair was their primary mode of mobility for 12.2 (9.6) years due to incomplete spinal cord injury (n = 4; height T1, T7, T9, T10), Ehlers Danlos (n = 2), hereditary spastic paraplegia (n = 3), cerebral palsy (n = 1), and Friedreich's ataxia (n = 1). All participants were able to propel a hand-rim wheelchair bimanually with sufficient trunk stability to maintain posture. Exclusion criteria were the current use of any type of power-assisted wheelchair, extreme shoulder pain, spasticity, or contractures of the upper extremity which made hand-rim wheelchair propulsion for the duration of the measurements impossible. This study was approved by the local medical ethics committee. All participants gave written informed consent prior to admittance to the study.

Procedure

All subjects practiced at least 1 week and maximal 4 weeks with prototype power-assist wheels (Indes Holding B.V., Enschede, The Netherlands, www.indes.eu; wheels are commercially available as Wheeldrive, Handicare B.V.) on their personal hand-rim wheelchair in their home environment. The weight of the power-assist wheels is 13.3 kg each, and has an additional width of 21.5 mm compared to a normal hand-rim wheelchair wheel. Following this familiarization period with the power-assist system, measurements were conducted in an instrumented power-assisted wheelchair. The measurements were preceded by a short familiarization period (approximately 1 minute) to get used to the experimental wheelchair and measurement set-up. Subjects made a start action from stand still on a flat surface with a length of 2.5 meters. The experimental wheelchair used a prototype power-assist wheels and allowed three dimensional force measurements at the hand-rim. Instruction was to make a start-up action as they would normally do (not as fast as possible). The test order was randomly assigned to propulsion with and without power-assist (respectively motor on / motor off). Only the first push was used for analysis. Kinematic and kinetic data were measured simultaneously. Because kinematics and kinetics of the left and right side highly correlate during straight hand-rim wheelchair propulsion,[74, 89] all data was collected unilaterally at the subject's right side.

The total propulsion cycle (push and recovery) was defined as 100% and the timing of the peak propulsion force was expressed as a percentage of the propulsion cycle. The propulsion cycle was divided into a push phase and a recovery phase. The push phase was defined as the part of the cycle with forward movement of the radial styloid process (velocity < 0m/s) in the saggital plane and the recovery phase by the backward movement of the radial styloid process (velocity > 0m/s). The start-up action was repeated three times for both conditions. Parameters of the initial push phase of the three trials were averaged. Data processing was performed with Matlab (The MathWorks Inc, USA, www.mathworks.com).

Instrumented power-assisted wheelchair

The experimental instrumented wheelchair consisted of prototype power-assist wheels with a six degrees of freedom force and torque sensor(Model FT Delta-SI-660-60, ATI Industrial Automation, Apex, North Carolina, USA, www.ati-ia.com) build in the right wheel. The left wheel was a normal power-assist wheel. The weight of the power-assist wheels is 13.3 kg each, and has an additional width of 21.5 mm each compared to a normal hand-rim wheelchair wheel. Tires were inflated to the by manufacturer recommended tire pressure. The hand-rim was connected to the sensor by a rigid frame (Fig. 1). This arrangement allowed all the forces and moments exerted on the rim to be measured by the sensor. The instrumented wheel was mounted on a standard hand-rim wheelchair (Legend2, Exigo (Handicare, Moss, Norway, www.handicare.com), seat width 0.41 m, total width 0.59 m, diameter hand-rim 0.52 m, diameter tube 0.028 m). This setup was used for all subjects and in both conditions: with and without power-assist (motor turned on / off). Only in the condition with the power-assist turned on the signal caused by deformation of the piezoelectric sensor activated the motor. This resulted in extra power being delivered to the wheel axis, additional to the hand-rim power provided by the wheelchair user. The prototype power-assist wheels had 3 different levels of support, the measurements were performed in mode 2.

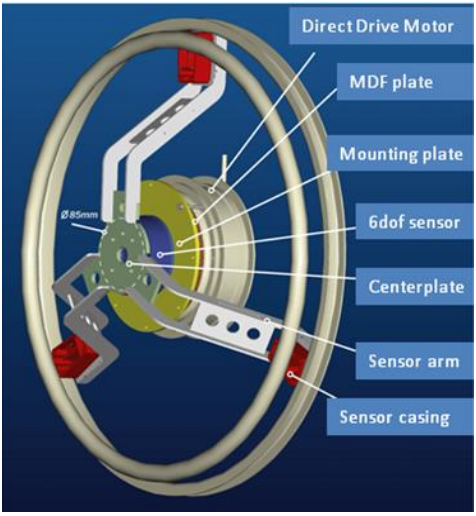

Figure - 1. Schematic of six degrees of freedom force and torque sensor mounted on the wheel and axis of the power-assist wheel. The assisting motor was mounted in the axis itself. A mounting plate and a medium-density fiberboard (MDF plate) were placed between the motor and the sensor. The hand-rim was mounted on the sensor via the sensor casing, sensor arm and center plate.

6

Kinematics
Reflective single markers were placed on the right side of the body at the following bony landmarks: incisura jugularis, xiphoid process, spinous process of the 7th cervical vertebrae, spinous process of the 8th thoracic vertebrae (pointer in static trial), medial and lateral epicondyle, radial and ulnar styloid process,[76] distal point of the second and the fifth metacarpal joint and a marker set of three markers at acromion.[77] . Additionally, four markers were placed at the wheel. Position data was sampled at 100 Hz by means of an infrared three dimensional motion analysis system with six cameras (VICON, MX, Vicon-UK Ltd, Oxford, United Kingdom, www.vicon.com). Kinematic data was low-pass filtered at 6 Hz with a second order, zero phase Butterworth filter.[90] Joint angles were calculated as proposed by the International Society of Biomechanics (ISB).[76] Only for angle calculations between humerus and trunk we used the z–x–y rotation order, instead of the y–x–y order (as proposed by the ISB), to stay close to clinical terminology. The glenohumeral joint rotation center, was calculated from the marker set on the acromion by regression.[77] The anatomical position was taken as the offset position, with all angles set at zero. Next to maximum shoulder angles and shoulder angles during the peak resultant force also push duration, stroke angle (Fig. 2-left), distance travelled, and maximum velocity were reported.

Kinetics
The 3D kinetic data, from the instrumented wheel was sampled at 200 Hz, low-pass filtered at 10 Hz with a second order, zero phase-shift Butterworth filter, and captured using a wireless data acquisition system (Type WLS-9205, National Instruments Corporations, Austin, Texas, USA, www.ni.com). The kinetic data was down-sampled to 100 Hz. The kinetic data was synchronized with the kinematic data, using a reflective marker with a magnet attached. Pulling away this marker just before the measurements starts causes a synchronization pulse on both measurement systems 1) caused by movement of the reflective marker and 2) caused by a signal of a magnetic proximity switch which would detect the absence of the magnet. The forces and moments measured at the axis were calibrated, corrected for baseline values due to gravity, corrected for rotating axes system and converted to forces and moments at the point of force application (PFA) on the rim in a local reference frame. PFA was defined as position of center of mass of the hand[78] on the rim.

A three-dimensional linked-segment model between hand, forearm, humerus and thorax was constructed to calculate net shoulder joint forces and external joint moments at the shoulder joint.[91] The inputs for the model were kinematics of the upper extremity, forces and moments at PFA, segment lengths and estimated segment mass, position center of mass[78] and moments of inertia.[91] Forces and moments were expressed in the local anatomical axis system.[91] Positive forces represent anterior, superior and lateral directed forces (Fig. 2, left and mid panel). Positive moments around the glenohumeral joint represent adduction, internal rotation and flexion moments (Fig. 2 right). For graphical reasons and as a consequence of the chosen model the opposite directions were presented as negative forces and moments. Next to forces and moments at the shoulder, also the exerted forces on the rim, amount and timing of the peak resultant force at the rim ($\sqrt{FX_{rim}^2 + FY_{rim}^2 + FZ_{rim}^2}$), propulsion moment around the axis, effective force, fraction effective force, power output and work were reported.

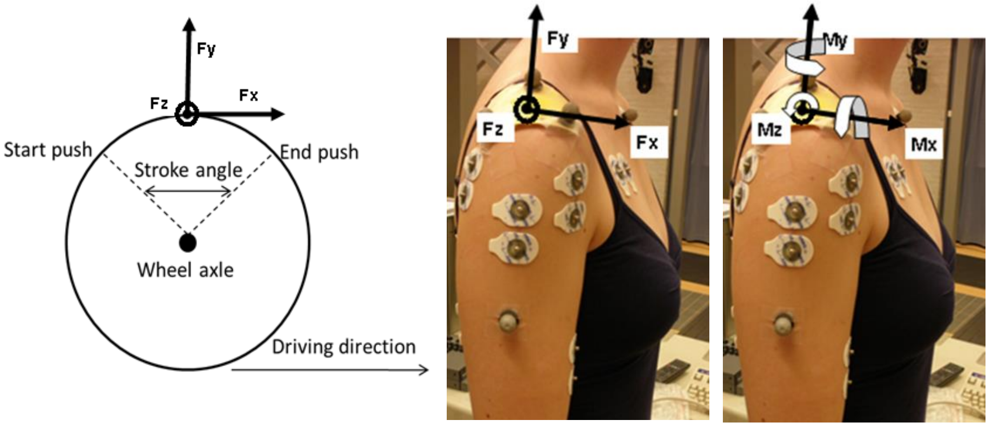

Figure 2 - Clarification of used terminology. **Left and Mid.** The local positive forces FX = anterior, FY = superior and FZ = lateral directed forces at the point of force application on the rim (**Left**) and the glenohumeral joint (**Mid**).**Right.** Positive moments MX = adduction moment, MY = internal rotation and MZ = flexion moment at the glenohumeral joint.

Statistical analysis

For each subject all parameters were average over 3 start movements. These averages were used to calculate a group average with standard deviation. Because of the sample size and the fact that the data were not normally distributed, the differences between start-up with and without power-assist were determined with the Wilcoxon Signed Rank test, reporting the smallest of the two sum of ranks (test statistic T), significance (p), and effect size (r). A p-value less than 0.05 was considered as statistically significant. An effect size of 0.2 indicates a small difference; 0.5 a moderate difference, and 0.8, a large difference. Statistical analysis was done in SPSS 19.

RESULTS

All measurements were performed according to protocol. The mean task load was 24.8 (12.1) J without power-assist and 16.0 (7.3) J with power-assist. For 3 subjects the mean of 2 power-assisted start actions was used (instead of 3), due to an error in data transmission in 1 of their trials.

Kinematics

The start-up was similar for the conditions with and without power-assist on the parameters push duration, stroke angle, and distance travelled (Table 1). The velocity reached during start-up, however, was significantly higher during power-assisted propulsion. Start-up with power-assist was performed with significantly less shoulder internal rotation.

Table 1 - Kinematics: characteristics of the initial start-up push and maximal shoulder angles presented with the results of the Wilcoxon Signed Rank test for the two test conditions.

Kinematic outcome measures- n = 11	Mean (SD) without PA	Mean (SD) with PA	Wilcoxon (T/p/r)
Push Duration (s)	1.3 (0.2)	1.3 (0.2)	5/.965/-.01
Stroke angle (°)	60.9 (13.4)	58.1 (13.6)	5/.534/-.19
Distance travelled (m)	0.6 (0.3)	0.7 (0.2)	3/.424/-.24
Max velocity (m/s)	0.6 (0.2)	0.7 (0.3)	2/.016*/-.72
Maximal flexion (°)	10.7 (10.7)	7.0 (12.0)	2/0.062/.56
Maximal extension (°)	33.4 (12.8)	35.8 (11.3)	5/.213/.38
Maximal abduction (°)	37.3 (6.5)	36.8 (6.0)	5/.859/.05
Minimal abduction (°)	27.6 (4.8)	27.7 (4.9)	5/.929/.03
Minimal internal rotation (°)	6.3 (9.1)	6.0 (10.2)	5/.859/.05
Maximal internal rotation (°)	39.9 (15.4)	35.2 (16.7)	3/.026*/.67

SD = standard deviation; PA = power assist; ° = degrees; *T = test statistic (smallest of the two sum of ranks); p = significance level; r = effect size;* = p < .05; ** = p < .01*

Kinetics at the rim

In Table 2 the kinetic data at the rim is presented. Start-up with power-assist was performed with a lower propulsion moment and less downward force. The peak resultant force decreased significantly during start-up with power-assist and was performed with more extension and less abduction . The power output was significantly lower during start-up with power-assist.

Table 2 - Mean push forces and moments as applied to the rim (local reference frame at point of force application) during the initial start-up push (mean over 11 subjects with 3 start-ups each). The peak resultant force is reported with the associated timing and shoulder angles. All results are presented with the outcomes of the Wilcoxon Signed Rank Test between both test conditions.

Kinetic and kinematic outcome measures	Mean (SD) without PA	Mean (SD) with PA	Wilcoxon (T/p/r)
AT THE RIM			
Forward force (N)	125.5 (30.8)	106.9 (24.5)	2/.050/-.59
Downward force (N)	58.4 (32.5)	34.6 (21.0)	0/.003**/-.88
Inward force (N)	8.1 (9.5)	9.0 (9.0)	2/.182/-.40
Propulsion moment axis (Nm)	15.0 (5.2)	11.8 (3.3)	1/.013*/-.75
Resultant force (N)	90.6 (24.2)	72.7 (17.8)	1/.008**/-.80
Effective force (N)	18.4 (13.3)	19.1 (14.2)	4/.657/-.13
Fraction effective force (%)	27.3 (13.9)	33.0 (16.2)	4/.182/-.40
Power output (W)	20.7 (10.7)	13.8 (7.0)	2/.010*/-.78
Work (J)	24.8 (12.1)	16.0 (7.3)	1/.008**/-.80
OUTCOMES DURING PEAK RESULTANT FORCE AT THE RIM			
Peak resultant force (N)	133.5 (38.4)	112.2 (25.4)	3/.033*/-.64
Timing of peak resultant force (%)	66.3 (10.3)	60.5 (15.8)	4/.062/-.56
Extension angle shoulder (°)	13.6 (16.3)	20.3 (19.1)	2/.010*/-.78
Abduction angle shoulder(°)	35.3 (6.7)	33.3 (6.8)	2/.026*/-.67
Internal rotation angle shoulder(°)	19.9 (14.6)	16.4 (15.1)	2/.062/-.56

*% = percentage of movement cycle; ° = degrees; N = Newton; Nm = Newton Meter; PA = power assist; SD = standard deviation; W = Watt; Wilcoxon T = test statistic (smallest of the two sum of ranks); p = significance level; r = effect size; * = p < .05; ** = p < .01.*

3.3 Kinetics at the shoulder

At shoulder level power-assisted start-up was performed with significantly decreased anterior (147.0 (44.8) and 121.9 (27.4) N), posterior (4.8 (14.1) and 2.7 (11.6) N) and inferior forces (82.6 (27.9) and 68.9 (22.6) N). Abduction and extension moments, decreased respectively from 20.2 (14.6) to 12.9 (7.8) Nm and from 20.3 (10.7) to 13.7 (9.1) Nm (Fig. 3).

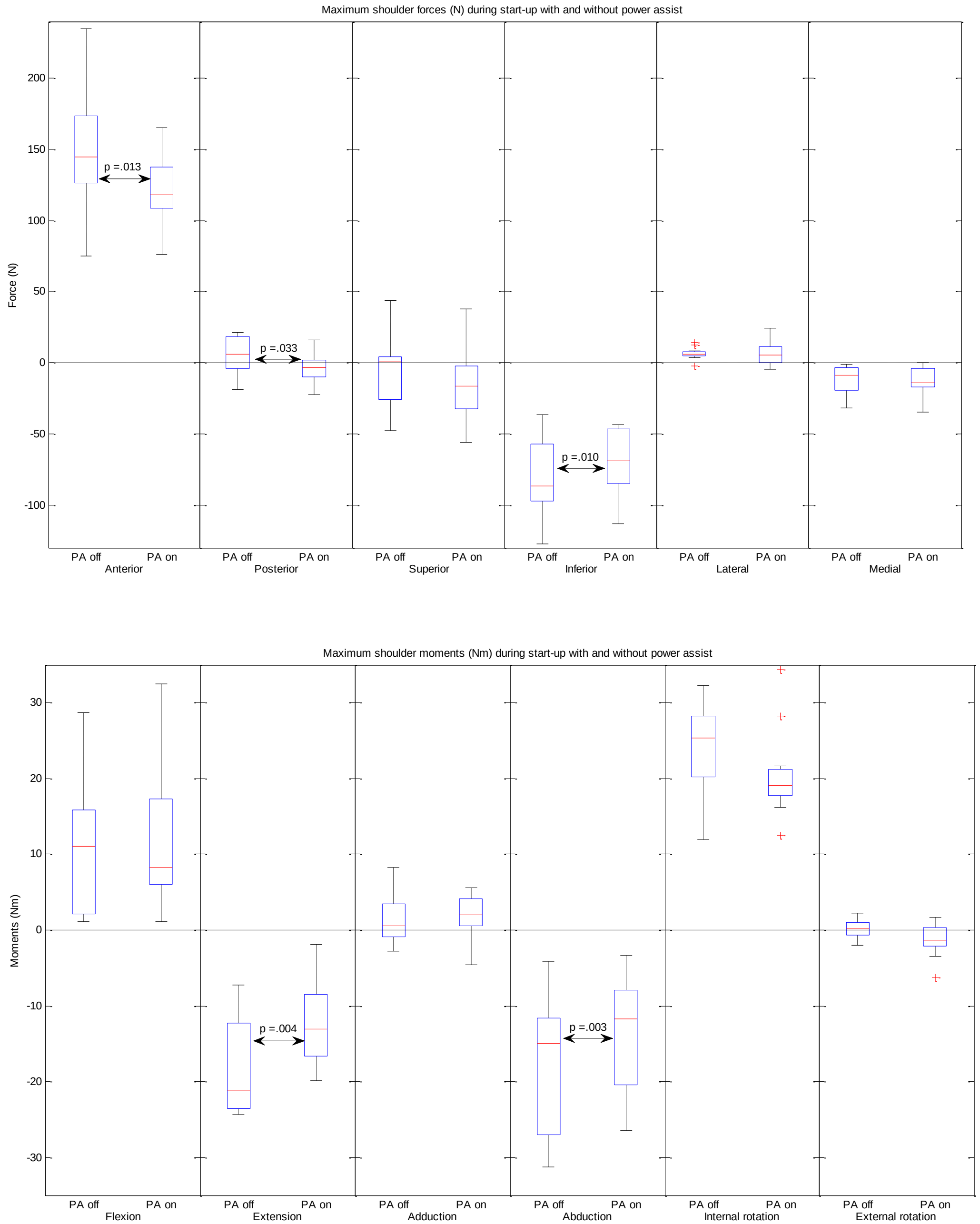

Figure 3 - Top panel - box plot for maximum net shoulder forces (N) and **Bottom panel -** external moments (Nm) during the initial start-up push with and without power-assist (n = 11). In each graph the box plot on the left is start-up without power-assist (PA off) and on the right with power-assist (PA on). All significant differences were presented with the Wilcoxon test statistics (T/*p*/r)**:** T = smallest of the two sum of ranks; p = significance level; r=effect size. + = outlier.

DISCUSSION

Despite the fact that the start movement occurs many times during the day, this is the first study to investigate the influence of power-assisted hand-rim propulsion on shoulder load during the wheelchair start. In this study we compared the start-up with and without power-assist on risk factors of shoulder overuse injuries. These risk factors related to the shoulder overuse injuries are: 1) the intensity of mechanical loading of the shoulder during the push phase, 2) the highly repetitive nature of propulsion motions and 3) force generation in extremes of shoulder motion.

1) The intensity of mechanical loading of the shoulder decreased during power-assisted propulsion for anterior, posterior and inferior directed forces and abduction and extension moments. Since this is the first study investigating shoulder load during the start movement, we compared with data from shoulder load during velocity propulsion. These studies reported decreased peak resultant force, propulsion moments and shoulder load, in healthy as well as in hand-rim wheelchair users,[27, 94] which is comparable with the results during the start. The change in specified directions however, varied between both populations (healthy vs. hand-rim wheelchair users) and both actions (start-up vs. velocity propulsion).[27, 94] The differences between both populations may emerge from certain impairments (e.g. partly innervated upper extremity muscles, hypertonia) as well as the mere extend of hand-rim propulsion experience. Besides, the push of the start-up differs from the push during velocity propulsion. Koontz et al. stated that, in experienced wheelchair users, propulsion kinetics were about 1.8 to 3.5 times higher during start-up than during velocity propulsion, with the largest difference on ramp ascent and grass.[21] For propulsion on flat surface, the results were comparable with our studies. When comparing the results of this study with velocity propulsion we also found peak resultant forces and propulsion moments 1.6 till 2.0 times higher during start-up, independently of propulsion with or without power-assist.[94] The peak resultant force and propulsion moment during the start movement as well as during velocity propulsion on a flat surface were presented in table 3. Because a start movement is performed many times during the day[20] and even with power-assist still remains heavier than constant velocity propulsion, it might be clinically interesting to provide more power-assist during the first pushes.

Table 3 - Differences in peak resultant force and propulsion moment between start and velocity propulsion on a flat surface.

PEAK RESULTANT FORCE (N)	Start	Velocity propulsion	Factor
Koontz[21]	103.2 (24.2)	63.6 (2.9)	1.6
Kloosterman[94] (without PA)	133.5 (38.4)	83.4 (15.9)	1.6
Kloosterman[94] (with PA)	112.2 (25.4)	67.2 (13.5)	1.7
PROPULSION MOMENT (Nm)			
Koontz[21]	25.2 (6.7)	13.3 (0.8)	1.9
Kloosterman[94] (without PA)	15.0 (5.2)	7.3 (2.0)	2.1
Kloosterman[94] (with PA)	11.8 (3.3)	5.8 (1.7)	2.0

PA = power-assist wheelchair use

2) Regarding the repetitive nature, we did not investigate whether the number of starts during a day changed. In further research it might be interesting to investigate if the number of starts and stops during the day differs with the use of power-assisted or usual hand-rim wheelchair wheels. Suppose, the amount of starts during the day remains the same, 212.7 till 354.5 start movements are performed with less shoulder load anyway.

3) Regarding force generation in extremes of shoulder motion the peak resultant force at the rim significantly decreased and was accompanied by a significant decreased shoulder abduction however a significant increased shoulder extension (6.7 degrees) during power-assisted start-up. In contrast, the maximum extension angle during the entire push did not change significantly between both conditions. And the maximum extension angle (mean(SD)) during start-up without and with power-assist was smaller (respectively 13.6 (16.3) and 20.3 (19.1)), when compared to propulsion at 0.9 m/s (respectively 21.5 (12.7) and 26.3 (13.6)) in the same population.[94] The increase in shoulder extension during the peak resultant force, might be caused by the tendency of the timing of this force to occur earlier in the push (60.5 % instead of 66.3%). However, the extension angle is not in the extremes of shoulder motion and occurred during a significant decreased peak resultant force at least.

In an ideal situation a comparison would have been made between hand-rim start-up in the subjects own wheelchair and hand-rim propulsion with power-assist wheels mounted on the subject's own wheelchair. Because of the combined use of a force sensor with power-assist wheels, this was not possible, and we therefore mounted the power-assist wheels on a wheelchair frame which was not adjustable for each single subject, yet was consistent between both conditions. The forced wheelchair fitting, resulting in a different sitting position and upper body orientation than usual, might have contributed to the high standard deviations in kinematics and kinetics. Because in the fixed wheelchair frame, slim subjects are forced to more shoulder abduction and therewith more shoulder internal rotation to reach the hand-rim. The high standard deviations might also be due to differences in propulsion techniques between subjects, differences in upper extremity force and joint mobility. Another disadvantage of a comparison between power-assist on / off instead of propulsion with normal wheels / power-assisted wheels is the difference in weight between both wheels. The power-assisted wheelchair with power-assist wheels is approximately 20 kg heavier than a wheelchair with normal hand-rim wheels,[53] leading to a larger rolling-resistance, and inertia during start-up.[95] However, this remained consistent between both conditions. Consequently, the additional mass of the power-assisted wheelchair, although centered around the rear wheel axis, could be more influential during start-up than during velocity propulsion. Concluding from the results, the additional power delivered by the motor is already enough during start-up to provide an additional biomechanical advantage on shoulder load compared to propulsion without power-assist.

For our research question a relative simple three-dimensional linked-segment model, with net forces and moments as outcome, was adequate. If in future research more insight in for instance, internal loading, motor control and contribution of each single muscle and scapular motion is desirable a more sophisticated shoulder-arm musculoskeletal model (such as the Delft elbow-shoulder model[14, 17, 92, 93]) is anticipated to be more appropriate.

This explorative study was performed with a small research population with varying pathology. To translate to clinical practice, it is interesting to perform a longitudinal study with a larger research population to explore if the effects of power-assisted propulsion found on shoulder load also results in a diminished amount of developed shoulder overuse injuries. To have an advantage in daily life, next to an advantage during start-up and level propulsion, also an advantage in activity and community participation is necessary. For instance the additional weight of the wheels (approximately 13 kg each) can interfere with the ease of use during car transfers and in public transport[31, 35], for example for subjects with upper-limb impairments. The wheels used in this study were prototypes and thus still under development, this study can be used to optimize the power-assist wheels.

The clinical guidelines for reducing shoulder load[8, 43] are only for propulsion not for start-up, it might be valuable to extend the guidelines for hand-rim wheelchair users with recommendations on start-up. Besides, it is interesting to explore the possibilities of providing more power-assist during first pushes than during subsequent propulsion.

In conclusion this study shows that power-assisted hand-rim start-up is effective in reducing the mechanical loading of the shoulder and partly the force generation in extremes of shoulder motion. Specifically, the intensity of mechanical loading of the shoulder decreased during power-assisted propulsion for anterior, posterior and inferior directed forces and abduction and extension moments. The peak resultant force at the rim significantly decreased and was accompanied by a significant decreased shoulder abduction however a significant increased shoulder extension (6.7 degrees) during power-assisted start-up. This could have a positive influence on the risk of the development of shoulder overuse injuries in hand-rim wheelchair users.

HIGHLIGHTS

- Start-up is assumed a straining and frequent element in hand-rim wheelchair use.
- Power-assisted velocity propulsion reduced shoulder load, unknown for start-up.
- Intensity of shoulder loading decreased during power-assisted start-up.
- Also reduced peak resultant force with less shoulder abduction but more extension.
- Use of power-assist might reduce the risk of developing shoulder overuse injuries.

7

Clinical evaluation of hand-rim propulsion with power-assist wheels

Marieke G.M. Kloosterman
Jaap H. Buurke
Lucas H.V. van der Woude
Johan S. Rietman

Based on Conference proceedings of the 5th International State of the Art Congress.
Rehabilitation: Mobility, Exercise & Sports. 2014: 41-3. ISBN: 978-90-75823-87-5

ABSTRACT

Shoulder injuries are common in hand-rim wheelchair users; to reduce upper extremity load during propulsion, power-assist wheels are effective. Whether power-assist propulsion is also beneficial in daily situations is unclear. Therefore wheelchair skills and self-efficacy during hand-rim and power-assist hand-rim propulsion, and the subject's opinion about the power-assist wheels were investigated. Twelve experienced hand-rim wheelchair users tried the power-assist wheels for four weeks in their home environment. The 'Wheelchair Circuit Test' with additionally the 10 seconds and 3 meter wheelie, the 'Self-Efficacy in Wheeled Mobility Scale' and the Dutch version of the 'Quebec User Evaluation of Satisfaction with Assistive Technology' were completed. Between both wheels no significant changes were found on wheelchair skills and self-efficacy. Satisfaction with the device was 3.6 out of 5 points, with the lowest score on weight (2.5) and the highest score on effectiveness (4.0). Although increased ease of propulsion was reported, objective ratings showed no differences in wheelchair skills and self-efficacy. High work-capacity of the upper extremity, use of a hand-bike, and independent car transfers seem to have a negative influence on the usability of power-assist-wheels.

INTRODUCTION

Hand-rim wheelchair users extensively rely on their upper extremities, not only for mobility but also for other activities of daily living like reaching and weight relief lifts.[69] If hand-rim propulsion is compromised for example by upper extremity injury or pain, insufficient arm strength or low cardio-pulmonary reserves, subjects are forced to another way of mobility. Subjects can be pushed by an assistant, shift to a powered wheelchair, use a scooter for outdoors or replace normal wheelchair wheels with power-assist wheels.[1] Each of these options are effective in lowering the mechanical strain. The benefit of a power-assist wheelchair over the other options is that the biomechanical and physiological stress associated with self-propulsion decreases, while preserving the opportunity to exercise wheeling[52] and stay active to some extent.

Within our project group (Active Assistive Devices research line of the MIAS (Major Innovations for an Aging Society) project), we developed power-assist wheels with an additional function: with the small hub it is possible to drive completely powered (see fig 1). With this prototype power-assist wheels shoulder load during propulsion decreased significantly compared to propulsion without power-assist.[27] However, whether these prototypes were also beneficial in daily situations was unclear. Therefore we investigated wheelchair skills and self-efficacy during hand-rim and power-assist wheelchair propulsion in the personal environment and we asked a subject's opinion about the power-assist wheels.

Figure 1 - The used power-assist wheelchair wheels. Large hand-rim for assisted propulsion, small hand-rim for completely powered propulsion.

METHODS

Participants

Twelve hand-rim wheelchair users (six men) with a mean age of 38.6 ± 7.8 years participated in this study. The hand-rim wheelchair is their primary mode of mobility for 13.2 ± 9.1 years due to spinal cord injury (n=5; height T1, T5, T7, T9, T10), Ehlers Danlos (n=2), M. Strümpell (n=2), cerebral palsy (n=1), spastic diplegia (n=1), and Friedreich's ataxia (n=1).

Research protocol

The measurements were part of a larger randomized controlled trial. For the clinical evaluation there were two measurement conditions: own wheelchair frame with (1) normal hand-rim wheels and (2) power-assist wheels. After two weeks using one condition in the home environment, the Wheelchair Circuit Test[96] was performed, additionally with a 10 seconds and 3 meter wheelie. After four weeks the 'Self-Efficacy in Wheeled Mobility Scale'[97] and the Dutch version of the 'Quebec User Evaluation of Satisfaction with Assistive Technology'[98] were completed.

Statistics

The differences between both conditions were determined with the Wilcoxon Signed Rank test, reporting the test statistic T (smallest of the two sum of ranks), significance (p), and effect size (r). The level of significance was set at $p<0.05$.

RESULTS

Between both conditions no significant differences were found in the ability and the performance time scores of the Wheelchair Circuit Test, performance of the 10s and 3m wheelie and in self-efficacy (respectively Wilcoxon Signed Rank test/significance level/effect size:2/.783/−.08, 2/.075/-.54, 0/.180/-.13, 4/.779/-.47 and 3/.609/-.148). Satisfaction with the power-assist wheels was 3.6 out of 5 points, with the lowest score on weight (2.5) and the highest score on effectiveness (4.0) (Table 1). Heavy weight was reported to lead to difficulties with car transfers, replacing wheels, public transport and hand biking. The satisfaction on effectiveness resulted in subjects reporting less strain on the upper extremity, reduced shoulder pain, less energy cost, and no need to be pushed by an assistant.

Table 1 - Results of the D-Quest (n=12). Score ranged from 1 (not satisfied at all) till 5 (completely satisfied).

Items	Mean per item (SD)	Range
Dimensions	3.6 (1.2)	1-5
Weight	2.5 (1.1)	1-5
Adjustability	3.8 (1.1)	2-5
Safety	3.6 (1.0)	2-5
Durability	3.4 (1.0)	2-5
Ease of use	3.6 (1.2)	2-5
Comfort	3.9 (0.9)	3-5
Effectiveness	4.0 (1.0)	2-5
Satisfaction overall	3.6 (1.2)	2-5

CONCLUSION AND DISCUSSION

Although increased ease of propulsion was reported, objective ratings showed no benefits in wheelchair skills and self-efficacy during power-assist hand-rim wheelchair propulsion. In the subjective evaluation high work-capacity of the upper extremity, use of a handbike and independent car transfers which required taking off and putting on the wheels, seem negative influencers for satisfaction with the power-assist-wheels.

8

General discussion

GENERAL DISCUSSION

In this thesis we evaluated, a prototype of newly developed, power-assisted wheelchair wheels, in order to determine the potential value of power-assisted propulsion on shoulder load, daily activities and participation in comparison with hand-rim wheelchair propulsion. In this chapter we will discuss the results found in this thesis, starting with the answers to the research questions.

ANSWERS TO THE RESEARCH QUESTIONS

1. What is the current knowledge of power-assisted wheelchair propulsion?

In chapter 2 an overview of the literature is given till may 2012. In short the systematic search yielded 15 cross-over trials with repeated measurement design and one qualitative interview. Ten studies reported reduced strain on the upper extremity and cardiovascular system during power-assisted propulsion compared to hand-rim propulsion. Twelve studies reported precision tasks easier to perform with a hand-rim wheelchair and tasks which require more torque were easier with a power-assisted wheelchair. Social participation was not altered significantly by the use of a hand-rim, powered, or power-assisted wheelchair. It is possible that daily activities are more related to changes in behavioral and social routines as well as personal factors such as fatigue or physical fitness, rather than to change of wheels.[52]

In combination with the articles presented in this thesis, an additional research paper was published[99] (checked on 3 March 2016). The results of this paper also showed reduced strain on the cardiovascular system and lower car transfer ability with power-assist wheels when compared to hand-rim propulsion .Here, two types of power-assisted wheels were also compared: for outdoor use the Servomatic was preferred over the E.motion.[99]

The results from the articles presented in this thesis are described and discussed in the answers to the remaining research questions.

2. Who might benefit from power-assist wheels?

Most past research was on power-assist wheels performed with hand-rim wheelchair users due to spinal cord injury,[52] which is a small part of the total hand-rim wheelchair population. Also included in (parts of) the studies described in this thesis, beside spinal cord injury, were a few subjects who were wheelchair dependent due to multiple sclerosis, spinal bifida, leg amputation, hereditary spastic paraplegia, polymyositis, sepsis of the knee, avascular necrosis at the hip, stroke, Friedreich's ataxia and cerebral palsy.[52] However, it might be more useful to look at individual and environmental needs instead of diagnosis.

In general, if people have (temporally) difficulty with effectively propelling a hand-rim wheelchair because of pain, low cardiopulmonary reserves, insufficient arm strength, or the inability to maintain a posture effective for propulsion, then transition from a hand-rim wheelchair to another type of mobility device is indicated. Power-assist wheels might be beneficial for above mentioned indications, with the exception of the inability to maintain posture (wheelchair frame / seating remains the same). Subjects who have difficulty propelling a wheelchair in a challenging environment or on longer distances can also benefit from power-assisted wheelchair use. In addition, they can be used for subjects with a progressive disease in order to postpone the transition to a powered wheelchair. Power-assist wheels might be less stigmatizing compared to a powered-wheelchair and easier in transportation. Caution is warranted for the additional width and weight of a power-assisted wheelchair in relation to the usual mode of transportation (independent car transfers, use of public transport, hand-biking) and access to the home environment. Another important issue is that subjects should be able to learn a new mode of ambulation. Finally, the current power-assist wheels cannot be used for one-handed operation, for example in stroke patients.

3. **What are the wheelchair characteristics of the prototype and what are the differences with a hand-rim wheelchair, specifically rolling resistance, propulsion efficiency and energy expenditure?**

Drag forces are significantly higher for the power-assisted wheelchair compared to the hand-rim wheelchair. If the power-assist wheels give adequate support, power-assisted propulsion was more efficient and required less energy input by the user than hand-rim wheelchair propulsion.

During these measurements subjects propelled the wheelchair on a treadmill at a target power output (PO) of 5.5W. Total energy expenditure (P_i = Power input) was calculated based on the average respiratory exchange ratio (*RER* = ratio VCO_2/VO_2) and VO_2 of the last minute of the propulsion: $P_i = (4940\ RER+16040)(VO_2/60)$.[66] Propulsion efficiency (PE) was calculated with: $PE= (PO/P_i)x100\%$.[100] This propulsion efficiency is not the same as the gross mechanical efficiency, because the power output delivered by the motor is included as well, while the energy expenditure from the motor is not. The propulsion efficiency therefore represents the energy expenditure that is needed from the user to overcome a certain task, assisted or not by the motor.

4. **Is the assumption of the effectiveness of power-assisted propulsion in reducing potential risk factors for shoulder overuse injuries correct?**

Guidelines were developed to lower the risk of arm injury during hand-rim wheelchair propulsion in subjects with SCI.[43, 101] These guidelines were recommended to: a) minimize the frequency, b) minimize the force required and c) minimize the extreme or potentially injurious joint positions. Based on chapters 4-6, power assisted propulsion compared to purely hand-rim propulsion is partly effective in reducing these risk-factors:

a) minimize the frequency of repetitive upper limb tasks by decreasing the frequency of the propulsive stroke, the number of transfers, and the frequency of other repetitive vocational and avocational tasks, in which wheelchair propulsion, with a stroke occurring approximately once per second is the most frequent task.[101]

Our results showed that the push frequency did not change significantly with healthy subjects[27], while with hand-rim wheelchair users with power-assist the push-frequency, even increased during propulsion at 0.9 m/s.[102] Plausibly, the subjects could have difficulty fine-tuning the amount of torque they had to produce on the hand-rim in the limited space on the treadmill. More control over the velocity can be reached by making shorter pushes at a higher propulsion frequency. The confined space in front of the wheelchair hampered the possibility of making long smooth strokes.

We did not investigate the influence of power-assisted propulsion on the frequency of other repetitive vocational and avocational tasks. However, it seems unlikely that only with change of wheels, for instance, the number of transfers, weight relief lifts, or reaching over head will decrease.

b) minimize the force required to complete upper limb tasks by minimizing peak forces,[43] maintaining an ideal weight, using a light wheelchair and improving wheelchair propulsion techniques. That is, make long smooth strokes that limit high impacts on the hand-rim (semi-circular pattern), and allow the hand to drift down naturally, keeping it below the hand-rim when not in actual contact with that part of the wheelchair.[101]

Our results showed that the peak resultant force at the rim reduced during propulsion at 0.9 m/s as well as start-up.[27, 102, 103] In this way, the power-assisted wheelchair is beneficial over a hand-rim wheelchair.

In addition to the recommendation to decrease the overall forces, specifically, the posterior and lateral directed forces at the shoulder, superior directed forces combined with internal rotation moments at the shoulder are deemed to be potential risk factors and should therefore be minimized.[11, 15] The results of these specific directions of forces and moments in this thesis were ambiguous. The change in specified directions varied between both populations (healthy vs. hand-rim wheelchair users) and both movements (start-up vs. velocity propulsion).[27, 102] The differences between both populations may emerge from certain impairments (e.g. partly innervated upper extremity muscles, hypertonia) as well as the mere extent of hand-rim propulsion experience. Differences between the tasks may emerge from the intensity of propulsion kinetics. Task intensity was about twice as high during start-up than during steady-state propulsion.[103] In the study with healthy subjects a significant decrease in all of the aforementioned forces (posterior, lateral and superior) and moments (internal rotation) is revealed.[27] In the study with hand-rim wheelchair users only the internal rotation moments decreased significantly during power assisted propulsion, while the posterior directed force even increased.[102] During start-up, of the aforementioned forces and moments, only the posterior directed forces decreased.[103] Although during constant velocity propulsion the increase in posterior directed force in absolute number is small (7.1 N), the reason for the increase is unclear. Possible explanations are that a higher push-frequency with a smaller stroke angle results in a higher acceleration / deceleration of the arm, and slowing down the arm while stabilizing the glenohumeral joint might result in higher posterior forces. Another possibility is that the instrumented wheelchair reacts slightly differently to the prototype used at home. This, in combination with propulsion at a fixed speed on a treadmill, which has a confined space, might result in shorter propulsion strokes to gain more control. This strategy might be comparable to the initial phase of learning hand-rim wheelchair propulsion.[82, 88]

The additional weight of the power-assist wheels (±13 kg per wheel) compared to usual hand-rim wheels, likely leads to higher peak forces during, for instance, car transfers, put on / pull of the wheels. Also hand-biking and being pushed by an attendant is heavier with power-assist wheels. The additional weight is also the cause of the significantly higher rolling-resistance for the wheelchair with power-assist wheels compared to usual hand-rim wheels. Despite this, power-assisted propulsion was more efficient and required less energy input by the user than hand-rim wheelchair propulsion (if motor support is well set).[95]

Based on visual inspection of our results the stroke pattern (arc, semicircular, single loop or double loop) did not change with the change of wheels.

c) minimizing extreme or potentially injurious positions at all joints, especially extreme wrist positions and positions where the shoulder is prone to impingement.[101] The shoulder is most likely to be injured when forces are delivered at the extremes of the range of motion of the glenohumeral joint. Especially when extension is combined with internal rotation[32, 44] or dominance of abduction and internal rotation is apparent.[13, 72]

In the first half of the push phase, there is usually a peak resultant force (which fortunately decreased with power-assist[27, 94, 103]); during this phase, the glenohumeral joint is in extension combined with internal rotation and thus prone to impingement.[32, 44] We found significantly less internal rotation at the shoulder during the peak force at the rim in the power-assisted condition. With regard to extremes of motion, the abduction[102] and internal rotation angles[27, 102] decreased at the time of the peak force during propulsion at 0.9 m/s. At start-up the abduction angle decreased while the extension angle increased.[103]

Overall, the significant changes in shoulder kinematics, during velocity propulsion, are relatively small. However, when the number of pushes during the day is born in mind, these results might be clinically important. Notably, this results in a few degrees less abduction and extension movement, some 1800 bimanual pushes per hour,[4] and, as a result, a reduction in force against gravity. Whether these changes were indeed clinically significant cannot be answered with the cross-sectional pilot study, a longitudinal study with more subjects would be necessary.

It might be argued if during hand-rim wheelchair propulsion, the extremes of shoulder motion are reached. Probably, some of the subjects might reach the full range of motion only for extension (maximum extension ranged approximately from 45 till 60 degrees).

5. **Are power-assist wheels beneficial in daily situations, and what is the user's opinion about the prototype power-assist wheels?**

In chapter 7 we found that although increased ease of propulsion was reported, objective ratings showed no benefits in wheelchair skills and self-efficacy during power-assisted hand-rim wheelchair propulsion. In the subjective evaluation high work-capacity of the upper extremity, use of a hand-bike and independent car transfers which required taking off and putting on the wheels, seemed negative influencers for satisfaction with the power-assist-wheels.

EVALUATION OF THE PROTOTYPE POWER-ASSIST WHEELS

(In)activity

In analogy with the transition from a hand-rim to a powered wheelchair[1], as well as with the transition from purely hand-rim to power-assisted propulsion, there remans the controversy between preservation of upper extremity function and the need to remain physically active. Physical inactivity is contributing to many health related problems such as obesity and diabetes type II and may introduce a cycle of deconditioning and further decline.[18] In the Netherlands, the Dutch Healthy Exercise Norm, NNGB (Nederlandse Norm Gezond Bewegen), is developed to promote a healthy lifestyle in order to prevent chronic diseases due to inactivity. For adults the exercise norm is at least half an hour of moderately intensive physical activity (possibly even in bouts of at least 10 minutes) at least five days a week, but preferably every day. This norm is also relevant for subjects with a chronic condition, with the footnote that, all extra physical exercise is significant, regardless of intensity, duration, frequency and type. To improve cardiovascular fitness, one should meet the fit norm: at least 20 minutes of heavy intensive activity at least three times a week.[104]

When comparing daily wheelchair use to these guidelines, the intensity and duration of daily wheelchair use is not sufficient to maintain or improve cardiovascular fitness or to decrease the risk of secondary health conditions.[20, 105] Therefore, sports or at least additional physical activity integrated into daily life is essential for hand-rim wheelchair users. For inactive subjects any aerobic exercise is, among others, beneficial for cardiovascular fitness, reduction of hypertension, improved glycemic control and improved lipid profiles;[7] the more the better. It is plausible that physical fitness further declines when travelling with less effort. Alternatively, if subjects can independently propel a hand-rim wheelchair (without being pushed by an attendant) or if it might be possible to postpone the transition from a hand-rim to a powered wheelchair with a power-assisted wheelchair, subjects maintain, at least to some extent, the benefits of exercise by hand-rim wheeling.[29, 32, 37]

Physical activity and an active lifestyle in the prevention of long-term health problems and complications should be part of the rehabilitation program, especially in those who are wheelchair dependent.[4] The role of optimal tuning of assistive devices is therefore crucial in the wheelchair user population.

Preservation upper extremity function

It has been shown that an increased level of activity results in reduced pain, fatigue and depression. However, the negative consequences of increased physical activity in hand-rim wheelchair users is the related strain on the upper extremities.[106]

While, there is a need to remain physically active, overload can reinforce further reduction in activity in a vicious circle: overload -> pain often first indication -> functional costs as fatigue and discomfort[51] -> reduced performance in daily activities -> reduced physical capacity -> increased risk of subsequent overloading -> and so on.[107]

Repetitive load on the upper extremities during daily activities as hand-rim wheelchair propulsion, transfers and ischial pressure reliefs as well as reaching from a seated position places a great stress on the upper extremities. This places bones, joints and soft tissues of the shoulder complex at significant risks of overuse injuries.[6] Estimates on the prevalence of shoulder pain, in the spinal cord injury population, ranged from 30% to 73%. The wide variability in these numbers reflects the heterogeneity of study populations in time since injury, age, body mass index, neurologic level and completeness of the injury.[6] All of these factors may influence the development of shoulder pain in the chronic spinal-cord injury population. The most common causes of shoulder pain in this population are musculoskeletal, particularly overuse injuries to the rotator cuff and the impingement syndrome.[13, 70, 108] Repetitive trauma seems to be the most common source of these injuries. Overuse is often defined as repetitive micro-traumata that is sufficient to overwhelm a tissues ability to repair itself. Because the upper extremities of hand-rim wheelchair users are used continuously, adequate muscle recovery and regeneration time may not occur, placing these structures at significant risk for overuse.[6] These injuries have a high impact on quality of life, independence, functional activities, personal care, and ability to work.[101] Our study is instrumental here, where it focused on potential prevention of shoulder overload injuries. The results in this thesis showed partly a decrease in the risk factors related to overuse injuries. However, also with power-assist wheels, hand-rim propulsion remains a highly repetitive strenuous activity. Due to the design, during hand-rim wheelchair propulsion the shoulder is forced in extension and internal rotation. It might be wise to switch between different modes of transportation and use for example a hand-bike outdoors.

Activity and community participation

To have an advantage in daily life, next to an advantage during start-up and level propulsion, also an advantage in activity and community participation is necessary.

Although increased ease of propulsion was reported, objective ratings showed no benefits in wheelchair skills and self-efficacy during power-assist hand-rim wheelchair propulsion among a small (n = 12) group of experienced hand-rim wheelchair users.[109] The measurements in chapter 3, mentioned that the power-assist wheels added enough power to counteract the additional weight but not enough for additional support. During the measurements we unfortunately used this power-assisted wheelchair (and not the extra-power-assisted wheelchair), which might be the reason for no difference on Wheelchair Circuit Test[109] and oxygen uptake during 6 minutes of over-ground propulsion (not published). The next-generation of the used prototype provides more assistance (as the extra-power-assisted wheels in chapter 3), with which the results would probably be better. In the subjective evaluation high work-capacity of the upper extremity, use of a hand-bike, public transport and independent car transfers which required taking off and putting on the wheels, seemed negative influencers for satisfaction with the power-assist wheels.[31, 35, 109]

Social participation and quality of life was not affected by the use of a hand-rim, powered or power-assisted wheelchair.[52, 109] A possible explanation is that daily activities are more related to changes in behavioral and social routines[34] than to change of wheels. Changing habits is not likely to occur within two weeks, especially when the subject is aware of the fact that the wheels must be returned to the investigators.[34] Besides, habit change depends probably more on factors as transportability, social network and personal factors as body strength, fatigue or physical fitness.

During our measurements we noticed that participants had difficulty maintaining a straight course when using power-assist wheels at higher speed, although in their comments they reported that propelling the power-assisted wheelchair was easier compared to regular hand-rim wheelchair propulsion. These observations are in agreement with Best et al (in[33]) who reported ease of performance with power-assisted wheelchairs but better control when using a hand-rim wheelchair. In the case of control, the motor may be accentuating the natural difference in strength between the left and right arm. Another possible explanation could be a delay between the power exerted on the rim and the onset of the support of the motor. Since the information available on the control algorithms of the motors or the details of their design was limited, it would be useful to examine these technical specifications in more detail. With more insight in the technical specifications, it is possible to adjust the power of the motor to the individual propulsion characteristics and check if this will lead to more satisfaction with and control over the power-assisted wheelchair.

When assistive technology for (wheeled) mobility and the biological system do not optimally match and function, a debilitative cycle may start that can lead to an inactive lifestyle, non-use and consequently the risk for secondary complications.[4] To improve the match between wheelchair and user, one can think of personalized maximum velocity and support within the three settings for each rim, compensation for differences in upper extremity force between left and right, customized assistance profiles based on an individual's own propulsion technique. Since, the peak resultant force is still 1.6 times higher during start-up than during velocity propulsion, also more power-assist during start-up might be useful, which requires a smarter control of the wheel technology. In order to further reduce the upper extremity strain, a next step in the development of the power-assist wheels should be decreasing the weight of the wheels. By for instance using a lighter motor or using 1 motor placed at the wheelchair frame instead of one in each wheel. One may potentially benefit here from the e-bike technology revolution.

Wheelchair provision

The provision of assistive devices is country-dependent or for the Netherlands even municipality dependent. In Switzerland a study was performed to determine the differences between the need and the provision of assistive devices in the spinal cord injury population. Findings suggest that despite a low unmet need for basic devices such as hand-rim wheelchairs or crutches, there is considerable unmet need for some supplementary devices such as power-assisted wheelchairs (47.3 %).[110] Part of the cause is that the financial coverage is ensured by a complex network of social and health insurances. Devices are provided according to the principle that the device has to be “appropriate” and “economical”. This often means that part of the costs of devices apart from basic mobility devices, devices that are primarily designed for leisure activities (such as sport wheelchairs) have to be paid by the users.[110] In the USA the Medicare policy determines that an individual receives one wheeled mobility device every five years.[18] Given these costs, for many individuals this makes it financially impossible to use a power-assisted wheelchair as well as a hand-rim or powered wheelchair or mobility scooter. In the Netherlands each municipality has its own regulations and in some municipalities it is not possible to get power-assist wheels if you have a mobility scooter.

Pros and cons

In summary the pros and cons of power-assisted propulsion compared to purely hand-rim propulsion arise:

Pro	Con
Reduced strain on upper extremity	Additional weight (±13 kg per wheel) and width (± 2 cm) can cause problems with transportation (car transfer, public transport, hand-biking) and access to home environment
Reduced strain on cardiovascular system	Difficulty removing and replacing wheels (good hand force and coordination necessary to open quick release handle)
Increase in propulsion efficiency if motor is well set	Higher rolling resistance (effect neutralized by additional power)
Easier access to challenging environments	Difficulty in manoeuvring in confined spaces
Task which requires more force easier to perform, such as carpet, dimple strips, ramp and curb	Difficulty performing tasks which require greater control such as a wheelie (precision tasks)
Fit on most hand-rim wheelchair frames	Velocity is restricted at 6 km/h
Compared to powered wheelchairs:	
Relatively light weight and easy to transport	
Maintaining benefit of exercise	
Appearance less stigmatizing	

THE BIGGEST ROOM IN THE WORLD IS THE ROOM FOR IMPROVEMENT

In an ideal situation a comparison would have been made between propulsion in the subject's own wheelchair and hand-rim propulsion with power-assist wheels mounted on the subject's own wheelchair frame. Because of the construction of the measurement-wheel, without a quick release axle and with a force sensor build on the axis and sensors placed between hub and wheel, it was not possible to change the wheels to the subject's own wheelchair frame. In the current situation, propulsion with the motor turned off was heavier than normal hand-rim wheelchair propulsion (See chapter 3 and table 3, chapter 6 and), and even power-assisted propulsion with the measurement wheels seemed heavier than normal hand-rim propulsion. The fixed wheelchair setup may have led in some subjects to more shoulder abduction than usual. However the influence of configuration, and thus the possible technique consequences, expectedly remained the same between both test conditions and within subjects. The advantage of this measurement set-up was the possibility of measuring kinetic data in both conditions and a standardized test set-up for each participant. For these first explorative studies this set-up worked, however, for future research it would be recommend to think about an alternative way of measuring kinetics at the rim during power-assisted propulsion, such as the SmartWheel (http://smartwheelusa.com/) or Optipush (http://www.max-mobility.com/) for measuring propulsion patterns in hand-rim wheelchair propulsion.

Regarding the experimental set-up, it might be advisable to fix the wheelchair to a rolling system and simulate the power-assist. In this way it might be possible to make long smooth strokes without the limitation of the confined space of the treadmill.

A three-dimensional linked-segment model between hand, forearm, humerus and thorax was constructed to calculate net shoulder joint forces and external joint moments at the shoulder joint [91]. For our research question this approach was satisfactory. If, in future research, more insight in the motor control and contribution of each individual muscle is desirable, a more sophisticated shoulder-arm musculoskeletal model, such as the Delfts elbow-shoulder model [92], would be more appropriate. As a part of quantifying shoulder load, common surface EMG was used focused on superficial shoulder complex muscles involved in hand-rim wheelchair propulsion. For future research it would also be interesting to examine the rotator cuff muscles with fine-wire electromyography or with more accurate estimates of shoulder loading using Delft Shoulder Model. This would be of clinical importance because, particularly overuse injuries to the rotator cuff muscles are a common cause of shoulder pain [6].

With our chosen measurement design, long term effects of power-assisted wheelchairs on upper extremity injuries and physical fitness remained unknown. With power-assisted propulsion, repetitive musculoskeletal injuries can still be present, or have had no time to heal. A longitudinal study can provide information about the long term effects of power-assisted wheelchair use on arm injuries and physical fitness. Future research with actual hand-rim wheelchair users is necessary to explore the short- and long-term effects of power-assisted propulsion on shoulder injuries in this population.

It is a risk to use a prototype for scientific research. Subjects in our study used power-assist wheels for four weeks. In the data we analyzed, no differences were found in 4 weeks activity profile in the power-assist wheels and in their own hand-rim wheelchair (not published). Among others technical problems results in lacking data and subjects not using the power-assist wheels for the complete four weeks. After the measurement of activities and wheelchair skills we found out that the power-assist wheels added enough power to counteract the additional weight but not enough for additional support.[95] It would be useful to repeat the measurements with the final product, which had a higher assistance level.

The power-assist wheels also had a 'joystick function' which provide full support. It might be interesting to investigate how people integrate this function in daily life use. Are people triggered to go for longer distances or travel the same distance with less effort.

CONCLUSION

The aim of this thesis was to evaluate the prototype of newly developed, power-assisted wheelchair wheels, in order to determine the potential value of power-assisted propulsion on shoulder load, daily activities and participation in comparison with hand-rim wheelchair propulsion. In closing, a reflection on the aim of this thesis. Compared to hand-rim propulsion, power-assisted propulsion is effective in reducing part of the potential risk factors of shoulder overuse injuries with the highest gain on lower peak propulsion force on the rim during velocity propulsion as well as the start movement. Power-assisted propulsion might be beneficial for subjects in whom independent hand-rim wheelchair propulsion is endangered by arm injury, insufficient arm strength, or low cardiopulmonary reserves. Additionally, subjects with difficulty propelling a wheelchair in a challenging environment can benefit from power-assisted wheelchair use. Although increased ease of propulsion was reported, objective ratings showed no benefits in wheelchair skills and self-efficacy during power-assisted hand-rim wheelchair propulsion.

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Summary

In **chapter 1** the aim and research questions were introduced. The aim of this thesis was to evaluate, the prototype of newly developed, power-assisted wheelchair wheels, in order to determine the potential value of power-assisted propulsion on shoulder load, daily activities and participation in comparison with hand-rim wheelchair propulsion. Five research questions were answered in this thesis:

1. What is the current knowledge of power-assisted wheelchair propulsion?
2. Who might benefit from power-assist wheels?
3. What are the wheelchair characteristics of the prototype and what are the differences with a hand-rim wheelchair, specifically rolling resistance, propulsion efficiency and energy expenditure?
4. Is the assumption of the effectiveness of power-assisted propulsion in reducing potential risk factors for shoulder overuse injuries correct?
5. Are power-assist wheels beneficial in daily situations, and what is the users opinion about the prototype power-assist wheels?

First, in **chapter 2** an overview is given of the available scientific literature so far. A systematic search yielded 15 cross-over trials with repeated measurement design and one qualitative interview. Methodological quality scored between 9 and 15 points out of the maximum score of 32 (Downs and Black). Ten studies measuring body function and structure reported reduced strain on the arm and cardiovascular system during power-assisted propulsion compared to hand-rim propulsion. Twelve studies measuring activities and social participation reported precision tasks easier to perform with a hand-rim wheelchair and tasks which require more torque were easier with a power-assisted wheelchair. Social participation was not altered significantly by the use of a hand-rim, powered, or power-assisted wheelchair. This review showed that power-assisted propulsion might be beneficial for subjects in whom independent hand-rim wheelchair propulsion is endangered by arm injury, insufficient arm strength, or low cardiopulmonary reserves. Also subjects with difficulty propelling a wheelchair in a challenging environment can benefit from power-assisted wheelchair use. Caution is warranted for the additional width and weight in relation to the usual mode of transportation and access to the home environment.

To explore the characteristics of the wheels used in our research, in **chapter 3** we investigated the differences in rolling resistance, propulsion efficiency and energy expenditure required by the user during power-assisted and regular hand-rim propulsion. Therefore, drag force, energy expenditure and propulsion efficiency were measured in 10 able-bodied individuals with three different wheelchair configurations (purely hand-rim, power-assisted and extra power-assisted propulsions) on a treadmill. Results showed that drag force levels were significantly lower for the hand-rim wheelchair than for the power-assisted ones. The use of the extra-power-assisted

wheelchair appeared to be significantly superior to conventional power-assisted and manual wheelchairs concerning both propulsion efficiency and energy expenditure required by the user. Overall, the results of the study suggest that power-assisted wheelchair propulsion was more efficient and required less energy input by the user, if the motor assistance is well set.

Rolling resistance is one of the main forces resisting wheelchair propulsion in daily life and thus affecting the external load on the upper extremities. Incidences of shoulder overuse injuries among hand-rim wheelchair users are high. It is suggested that part of the risk factors for overuse originate in wheelchair propulsion itself. Although the intensity and frequency of shoulder loading and force generation in extremes of shoulder motion during hand-rim wheelchair propulsion seems one of the causes of shoulder injury, to our knowledge no previous research described the change in upper extremity load between hand-rim and power-assisted propulsion. Therefore, in **chapter 4** a pilot study, with nine healthy subjects, was performed to explore the theoretical framework for the effectiveness of power-assisted propulsion in reducing shoulder overuse injuries. The changes in upper extremity kinematics, kinetics and muscle activation patterns during propulsion with and without power-assist were investigated on a treadmill at 0.9 m/s. Propulsion frequency did not differ significantly between the two conditions. During power-assisted propulsion we found significantly decreased maximum shoulder flexion and internal rotation angles and decreased peak force on the rim. This resulted in decreased shoulder flexion, adduction and internal rotation moments and decreased forces at the shoulder in the posterior, superior and lateral directions. Muscle activation in the pectoralis major, posterior deltoid and triceps brachii was also decreased. So, power-assist wheels influenced the work requirements of hand-rim wheelchair propulsion by healthy subjects. It was primarily the kinetics at rim and shoulder which were influenced by power-assisted propulsion.

To translate this concept to clinical practice, in **chapter 5** this study was repeated with eleven experienced hand-rim wheelchair users. As a result during power-assisted propulsion the peak resultant force exerted at the hand-rim decreased and was performed with significantly less abduction and internal rotation at the shoulder. At shoulder level the anterior directed force and internal rotation and flexion moments decreased significantly. In addition, posterior and the minimal inferior directed forces and the external rotation moment significantly increased. The stroke angle decreased significantly, as did maximum shoulder flexion, extension, abduction and internal rotation. Stroke-frequency significantly increased. Muscle activation in the anterior deltoid and pectoralis major also decreased significantly. In conclusion, compared to hand-rim propulsion, power-assisted propulsion seems effective in reducing potential risk factors of overuse injuries with the highest gain on decreased range of motion of the shoulder joint, lower peak propulsion force on the rim and reduced muscle activity.

The measurements in chapter 4 and 5 were performed at 0.9 m/s. However, short and slow bouts of activity dominate daily wheelchair usage. The acceleration during start-up requires more force than maintaining a constant velocity. Based on previous research, the external stresses on the upper extremity are 2 - 3.5 times higher during acceleration than during constant velocity propulsion. Therefore, we investigated in **chapter 6** whether power-assisted propulsion was also beneficial on shoulder load during start-up. Eleven hand-rim wheelchair users performed a start movement in an instrumented wheelchair on a flat surface. The intensity of mechanical loading of the shoulder decreased during power-assisted propulsion for anterior, posterior and inferior directed forces and abduction and extension moments. The peak resultant force at the rim significantly decreased and was accompanied by a significant decreased shoulder abduction however a significant increased shoulder extension during power-assisted start-up. Thus, power-assisted hand-rim start-up is effective in reducing external shoulder load and partly reducing force generation in extremes of shoulder motion. Which could have a positive influence on the development of shoulder overuse injuries. Because a start movement is performed so often during the day and even with power-assist still remains heavier than velocity propulsion, it might be clinically relevant to provide more power-assist during the first pushes.

To actual benefit from the power-assist wheels also an advantage in daily life should be present. Therefore, in **chapter 7**, we investigated wheelchair skills and self-efficacy during purely hand-rim and power-assisted propulsion in wheelchair users. Besides, we asked subject's opinion about the power-assist wheels. Between hand-rim and power-assisted wheelchair propulsion no significant changes were found on wheelchair skills and self-efficacy. Satisfaction with the power-assist wheels was 3.6 out of 5 points, with the lowest score on weight (2.5) and the highest score on effectiveness (4.0). Although increased ease of propulsion was reported, objective ratings showed no differences in wheelchair skills and self-efficacy. High work-capacity of the upper extremity, use of a hand-bike, and independent car transfers seem to have a negative influence on the usability of power-assist-wheels.

Finally in **chapter 8**, the research questions were answered, the main findings and conclusions of this thesis were discussed, along with suggestions for future research.

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Samenvatting

Samenvatting

Het doel van dit onderzoek is het evalueren van het effect van een prototype rolstoelwiel met hulpmotor op: schouderbelasting, uitvoeren van dagelijkse activiteiten en sociale participatie. Deze wielen geven krachtondersteuning tijdens het rolstoelrijden, vergelijkbaar met een fiets met trapondersteuning. In **hoofdstuk 1** wordt het doel geïntroduceerd met de vijf onderzoeksvragen die zijn beantwoord in dit proefschrift:

1. Wat is de huidige kennis over rolstoelrijden met krachtondersteuning?
2. Wie kunnen profiteren van de wielen met krachtondersteuning?
3. Wat zijn de kenmerken van het prototype en wat zijn de verschillen met een gewone handbewogen rolstoel, in het bijzonder op de rolweerstand, efficiëntie van het rijden en het energieverbruik van de gebruiker?
4. Klopt de aanname dat rolstoelrijden met krachtondersteuning effectief is bij het verminderen van potentiële risicofactoren voor schouderoverbelastingsklachten?
5. Zijn wielen met krachtondersteuning gunstig in dagelijkse situaties, en wat is de mening van gebruikers over het prototype?

Om deze vragen te beantwoorden is als eerste in **hoofdstuk 2** een systematisch review gedaan naar de beschikbare wetenschappelijke literatuur tot nu toe. Dit leverde vijftien cross-sectionele studies met herhaalde metingen design en een kwalitatief interview op. Methodologische kwaliteit van de studies scoorde tussen de 9 en 15 punten van de maximale score van 32. Tien studies keken binnen het domein van lichaamsfunctie en -structuur en vonden verminderde belasting van zowel de bovenste extremiteit als het cardiovasculaire systeem tijdens rijden met krachtondersteuning ten opzichte van volledig handbewogen rolstoelrijden. Twaalf studies rapporteerden binnen de domeinen activiteiten en sociale participatie. Hieruit bleken precisietaken gemakkelijker uit te voeren met een handbewogen rolstoel terwijl taken die meer kracht of vermogen nodig hebben makkelijker uit te voeren waren met een rolstoel met krachtondersteuning. Maatschappelijke participatie veranderde niet significant door het gebruik van een gewone handbewogen rolstoel of een rolstoel met krachtondersteuning. Uit dit review is gebleken dat een rolstoel met krachtondersteuning gunstig kan zijn voor mensen waarbij gewoon rolstoelrijden lastig is door klachten of onvoldoende kracht in de bovenste extremiteit, een lage cardiopulmonale reserve, of voor mensen die moeite hebben met rolstoelrijden in een uitdagende omgeving. Punt van aandacht is het extra gewicht en de breedte van de wielen waardoor bijvoorbeeld een zelfstandige auto transfer, reizen met het openbaar vervoer, het gebruik van een handbike en toegang tot de thuis- en sociale omgeving lastiger kunnen zijn.

De kenmerken van de wielen gebruikt in ons onderzoek, zijn in **hoofdstuk 3** onderzocht op rolweerstand, efficiëntie en energieverbruik van de gebruiker. Daarvoor werd op een loopband een weerstandstest gedaan, het energieverbruik en de efficiëntie gemeten bij tien gezonde proefpersonen en met drie verschillende rolstoelconfiguraties (gewone rolstoelwielen, handbewogen met krachtondersteuning en met extra krachtondersteuning). De resultaten toonden aan dat de rolweerstand significant lager was voor de gewone rolstoelwielen in vergelijking met de wielen met krachtondersteuning. Het gebruik van extra krachtondersteuning bleek significant beter dan de andere twee configuraties voor zowel efficiëntie als energieverbruik van de gebruiker. Kortom, de resultaten van de studie suggereren dat rolstoelrijden met krachtondersteuning efficiënter is en minder energie kost (voor de gebruiker), indien de motorondersteuning goed is ingesteld.

Rolweerstand is een van de belangrijkste krachten die overwonnen moet worden tijdens rolstoelrijden in het dagelijkse leven en heeft dus een grote invloed op de externe belasting van de bovenste extremiteiten. Overbelasting van de schouder komt veel voor bij rolstoelgebruikers. Er wordt gesuggereerd dat een deel van de risicofactoren voor overbelasting het rolstoelrijden op zich is. De intensiteit en frequentie van de belasting op de schouder en het krachtzetten in de eindgrenzen van het schoudergewricht tijdens handbewogen rolstoelrijden worden gezien als risicofactoren. Mogelijk dat rolstoelrijden met krachtondersteuning hierop kan aangrijpen. Toch is er geen eerder onderzoek beschreven dat de verandering bekijkt in de belasting van de bovenste extremiteit tussen handbewogen rolstoelrijden met en zonder krachtondersteuning. Daarom is in **hoofdstuk 4** een pilotstudie met negen gezonde proefpersonen uitgevoerd om het theoretisch kader voor de effectiviteit van rolstoelrijden met krachtondersteuning op risicofactoren van schouderoverbelasting te verkennen. De veranderingen in de kinematica, kinetica en spieractivatiepatronen van de bovenste extremiteit tijdens rolstoelrijden met en zonder krachtondersteuning werden onderzocht op een loopband op 0,9 m/s. Slagfrequentie verschilde niet significant tussen de twee condities. Tijdens rolstoelrijden met krachtondersteuning was er een significant verminderde maximale schouderflexie en endorotatie en verminderde piek resultante kracht uitgeoefend op de hoepel. Dit resulteerde in een vermindering van de schoudermomenten in flexie-, adductie- en endorotatierichting en afgenomen krachten op de schouder in posterior, superior en laterale richtingen. Spieractivatie in de pectoralis major, deltoideus pars posterior en triceps brachii waren eveneens verlaagd. Dus rolstoelrijden met krachtondersteuning beïnvloedt de risicofactoren voor schouderoverbelasting bij gezonde proefpersonen. Met name de krachten en momenten uitgeoefend op de hoepel en de schouder werden positief beïnvloed door rolstoelrijden met krachtondersteuning.

Om dit concept te vertalen naar de klinische praktijk, is in **hoofdstuk 5** deze studie herhaald met elf ervaren rolstoelgebruikers. Uit deze studie kwam naar voren dat dat tijdens rolstoelrijden met krachtondersteuning de piek resultante kracht op de hoepel significant lager is en wordt uitgevoerd met significant minder abductie en endorotatie in de schouder. Op schouderniveau leidde dit tot significant verminderde anterior gerichte kracht en endorotatie- en flexiemomenten. Aan de andere kant namen de posterior gerichte krachten en de exorotatiemomenten significant toe net als de slagfrequentie. De hoek van contact van de hand op de hoepel nam significant af, net als de maximale schouderflexie, -extensie, -abductie en -endorotatie. Spieractivatie in de deltoideus pars anterior en pectoralis major namen ook significant af. Concluderend, rolstoelrijden met krachtondersteuning lijkt effectief in het verminderen van potentiële risicofactoren op overbelastingsklachten, met name ten aanzien van de schouderkinematica, lagere piek resultante kracht op de hoepel en verminderde spieractiviteit.

De metingen in hoofdstuk 4 en 5 werden uitgevoerd bij 0,9 m/s. Echter, korte en langzame periodes van activiteit domineren dagelijks rolstoelgebruik. De versnelling tijdens het starten vereist meer kracht dan het handhaven van een constante snelheid. Op basis van eerder onderzoek, is de externe belasting op de bovenste extremiteit 2 tot 3,5 keer hoger tijdens acceleratie dan tijdens rolstoelrijden bij een constante snelheid. Daarom hebben we in **hoofdstuk 6** onderzocht of rolstoelrijden met krachtondersteuning ook positief werkt op de schouderbelasting tijdens de start. Elf rolstoelgebruikers voerden een startbeweging uit in een geïnstrumenteerde rolstoel op een vlakke ondergrond. De intensiteit van de abductie- en extensiemomenten en krachten uitgeoefend op schouder richting anterior, posterior en inferior daalden significant. De piek resultante kracht op de hoepel verminderde significant en ging gepaard met een significant afgenomen schouderabductie maar wel met een significant verhoogde schouderextensie tijdens starten met krachtondersteuning. Dus rijden met krachtondersteuning is effectief in het verminderen van de externe schouderbelasting en deels in het verminderen van het krachtzetten in de eindgrenzen van het schoudergewricht. Dit zou een positieve invloed kunnen hebben op risicofactoren van schouderoverbelastingsklachten. Omdat een startbeweging zo vaak wordt uitgevoerd tijdens de dag en zelfs met krachtondersteuning nog steeds zwaarder is dan op constante snelheid rolstoelrijden zonder krachtondersteuning, kan het klinisch relevant zijn om te zorgen voor meer ondersteuning tijdens de eerste slag.

Om daadwerkelijk te profiteren van de wielen met krachtondersteuning moet er ook een voordeel in het dagelijks leven zijn. Daarom is in **hoofdstuk 7** onderzocht of de rolstoelvaardigheden en eigen effectiviteit verschillen tussen handbewogen rolstoelrijden en rijden met krachtondersteuning. Daarnaast vroegen we de mening over de wielen met krachtondersteuning. Ondanks dat rijden met krachtondersteuning als lichter wordt ervaren dan gewoon rolstoelrijden, werden geen significante veranderingen gevonden op rolstoelvaardigheden en eigen effectiviteit. Tevredenheid over de wielen met krachtondersteuning was 3,6 op een schaal van 5, met de laagste score op gewicht (2,5) en de hoogste score op effectiviteit (4,0). Hoog spiervermogen van de bovenste extremiteit, het gebruik van een handbike en onafhankelijke autotransfers lijken een negatieve invloed te hebben op de bruikbaarheid van de wielen met krachtondersteuning.

Tot slot zijn in **hoofdstuk 8** de onderzoeksvragen beantwoord, de belangrijkste bevindingen en conclusies van dit proefschrift besproken, samen met suggesties voor toekomstig onderzoek. Goede rolstoelvoorzieningen zijn in ieder geval cruciaal in de controverse tussen enerzijds de noodzaak van een fysiek actieve leefstijl en anderzijds het behoud van functie van de bovenste extremiteit, juist ook op langere termijn.

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Bedankt!

Bedankt!

Klaar! Mijn proefschrift is na 3 jaar "bijna klaar" dan nu echt af! Mijn naam mag dan voorop dit boekje staan, maar zonder een aantal mensen was dit promotietraject nu niet succesvol afgerond of was in elk geval de weg ernaartoe een stuk minder leuk geweest.

Allereerst, iedereen die het heeft aangedurfd om zijn eigen vertrouwde rolstoelwielen tijdelijk te verruilen voor een prototype rolstoelwiel met krachtondersteuning; bedankt voor jullie deelname en feedback op het product. Dit is toch echt de basis van dit proefschrift geweest. En Julian, bedankt voor het rijdend krijgen en houden van alle deelnemers aan dit onderzoek.

En dan mijn promotieteam. Beste Hans en Jaap, bedankt voor jullie begeleiding bij RRD. Jullie hebben met jullie klinische blik, humor en nuchterheid de werkoverleggen prettig gemaakt en heel wat obstakels gerelativeerd. De ondersteuning op momenten dat het extra nodig was, heb ik erg gewaardeerd. En Hans, het congres in Puerto Rico met jou, Gerdienke en Marc blijft er eentje om met een grote glimlach aan terug te denken.
Beste Luc, jij kwam later het team versterken. Jouw enorme kennis op rolstoelgebied is zeer waardevol geweest. De gouden tip om een dag minder als fysiotherapeut te gaan werken en deze dag aan mijn promotie te besteden, klinkt achteraf heel logisch maar heeft tegelijkertijd wel voor meer rust en een eindsprint gezorgd. Bedankt voor de prettige samenwerking.

Graag wil ik de leden van mijn promotiecommissie bedanken voor de genomen moeite om mijn proefschrift te beoordelen en naar Enschede te komen voor mijn verdediging.

Collega's van RRD, bedankt voor de ontzettend leuke tijd die ik hier heb gehad. Op de eerste plaats natuurlijk dank voor de vele (praktische) hulp bij werkgerelateerde zaken, zoals het bedenken van een onderzoeksopstelling, hulp bij Matlab, het verplaatsen van loopbanden en het oplossen van alles waarvan werd gedacht “dat moet niet kunnen” maar toch bleek te kunnen (op kamer 15..). Maar misschien zijn de beste ideeën wel ontstaan bij de koffie-automaat, tijdens het lunchwandelen, de hardlooprondjes, partijtjes rolstoelbasketbal of de-laatste-donderdag-van-de-maand-borrels. Ontzettend fijn om bij collega's binnen te kunnen lopen om lief en leed te delen en voor de broodnodige dosis humor.

Thijs, Erik en Corien, jullie kunnen onmogelijk in mijn dankwoord ontbreken. Jullie hebben mijn hele RRD-periode alle grote en kleine frustraties die bij een promotie komen kijken voorbij horen komen en de successen (als geaccepteerde artikelen en congresbijdragen) gevierd. Maar eigenlijk ging het vooral over dingen die weinig met werk te maken hadden. Heel wat goede (en minder goede) muziek kwam voorbij. De

RRD-danceplaat is ondertussen grijs gedraaid en heeft heel wat werkuren en fietsrondjes van een mooie soundtrack voorzien. Bananen- en andere humor gingen over en weer, er is heel veel gelachen en er zijn ook mindere momenten gedeeld. Ik ben er vaak aan herinnerd dat jullie wel een bladzijde in mijn dankwoord zouden verdienen. En dat is ook zo! Alleen ben ik niet zo lang van stof… Misschien een goed alternatief om op een mooie zomeravond de barbecue voor jullie aan te steken om te vieren dat mijn promotietraject er nu echt op zit en er nog 3 mooie promoties gaan volgen! Thijs, vanaf de studentenkamer samen opgetrokken in onderzoeksland. Ik ben erg blij dat je mijn paranimf wilt zijn om mij, met jouw humor, ook door de laatste loodjes heen te slepen.

Sietske, fijn dat ook jij mijn paranimf wilt zijn. Je hebt me ontzettend hard ingehaald met jouw promotie (echt knap gedaan!) en ik heb de finish nu ook bereikt! Tijdens bewegingswetenschappen (en daarna) hebben we heel wat gezellige koppen koffie en biertjes gedronken. Ik hoop dat er nog vele zullen volgen! En wat betreft die flamingo's.. misschien maar eens een dagje diertuin plannen ;-)

Lieve vrienden en familie, bedankt voor jullie interesse in mijn onderzoek en gelukkig ook in heel veel andere dingen. Want ook promotie-onderzoek blijft maar gewoon werk. Fijn dat ik altijd bij jullie terecht kan.

Lieve Mark, we zijn een goed team. Het is fijn om samen te kunnen genieten van een glas wijn en lekker eten bij de kachel of een zomeravond in de tuin en het meest natuurlijk van onze lieve Lauren. Dan heeft het afronden van dit proefschrift maar wat langer geduurd!

Tijd voor de cooling down! Uiteraard met de RRD-danceplaat. Wat zou het mooi zijn als de Wheeldrive de gebruikers hetzelfde gevoel geeft, als ik heb bij het horen van dit nummer na een lekker rondje fietsen:

"wie döt mij wat, wie döt mij wat
wie döt mij wat vandage
'k heb de banden vol met wind
nee ik heb ja niks te klagen
wie döt mij wat, wie döt mij wat
wie döt mij wat vandage
'k zol haost zeggen, jao het mag wel zo!"

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Over de auteur

Over de auteur

Marieke Kloosterman werd geboren op 19 juli 1983 in Oldenzaal. In 2001 is zij gestart met de studie Fysioherapie aan Saxion Hogeschool Enschede. Aansluitend is zij in 2005 gestart met de opleiding Bewegingswetenschappen aan de Rijksuniversiteit Groningen. Deze heeft zij in 2009 afgerond met een stage bij Roessingh Research and Development (RRD), waarbij het onderwerp het effect van de Freebal (armondersteuning) bij het trainen van de bovenste extremiteit van dwarslaesiepatiënten was. Aansluitend is zij bij RRD aan haar promotieonderzoek begonnen waarvan dit proefschrift het resultaat is. Naast het afronden van het proefschrift heeft zij als fysiotherapeut gewerkt in de eerstelijn en wordt binnenkort de overstap gemaakt naar de tweedelijn.

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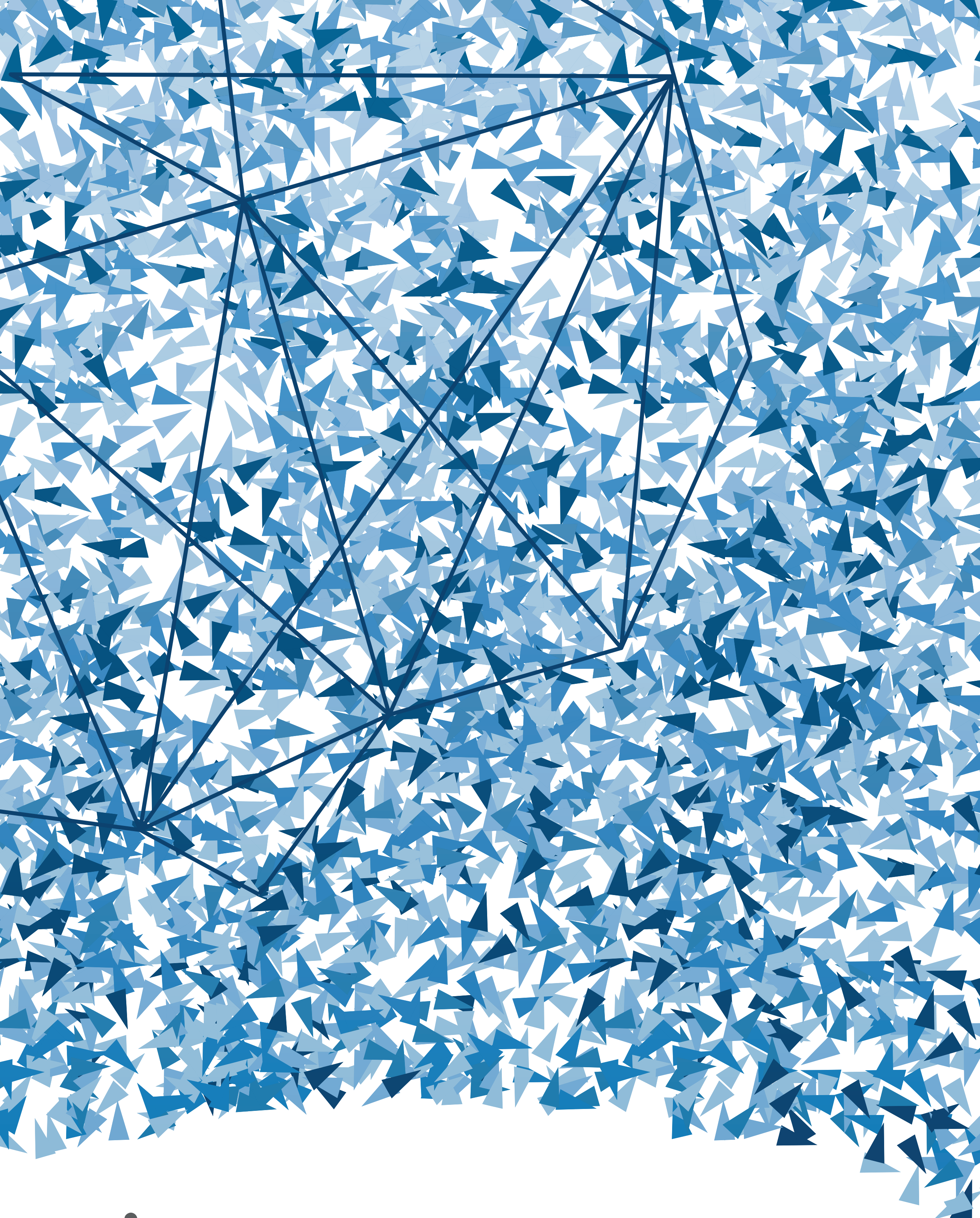

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37

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ISBN 978-90-365-4120-6