Final Paper

USING THE REVISED STRAIN INDEX TO QUANTIFY DISTAL UPPER LIMB PHYSICAL EXPOSURE FROM WHEELCHAIR PROPULSION

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DECLARATION

I hereby declare and confirm that this thesis is entirely the result of my own original work. Where other sources of information have been used, they have been indicated as such and properly acknowledged. I further declare that this or similar work has not been submitted for credit elsewhere.

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ABSTRACT

Background: According to the U.S. Census Bureau approximately 3.6 million people aged 15 or older depend on a wheelchair for mobility. That means that their upper limb is used not only for the motions it is designed for but also for mobility in daily life. To evaluate upper limb physical demands a laboratory is required which cannot directly measure daily life. Therefore, it would be helpful to find an analysis method which works outside a laboratory.

Objective: To evaluate if the Revised Strain Index (RSI) distal upper limb physical exposure quantification method can be used to analyze manual wheelchair propulsion and thus estimate risk of upper extremity disorders.

Methods: One subject who had no experience in using a wheelchair propelled it in four different conditions in a laboratory environment. An instrumented SmartWheel was used to obtain forces and moments and a video camera recorded data for RSI analysis. The videos for each trial were analyzed in two ways, the RSI method and by using the data from the instrumented wheel. These data were compared and then used with data from published literature to estimate the range of RSI scores that would apply to wheelchair propulsion on flat, level ground.

Results: RSI scores ranged from “safe” to “hazardous”. Individual exertions resulted in low RSI scores. However, wheelchair propulsion typically requires many exertions per minute. The high frequency of exertion can lead to high risk physical exposures, particularly if propulsion occurs for several consecutive minutes.

Conclusion: The RSI appear to be applicable to quantifying physical exposure from wheelchair propulsion. Additional analyses are needed to determine if the RSI scores correlate with laboratory-based measurements and the perceived stresses of wheelchair users.

CONTENTS

1. INTRODUCTION

1.1. BIOMECHANICAL MEASUREMENTS

The quantitative engineering tools most commonly used for quantitative assessment of manual wheelchair mobility are a SmartWheel to measure kinetics and a motion analysis system to get kinematic data. The Vicon Motion Capture System is one type of a motion analysis system.

1.1.1. KINETICS

"*Kinetics is the branch of the study of mechanics that describes the effect of forces on the body*." [1] According to Newton the quantity of force (F) is the product of mass (m) and acceleration (a). Looking at the kinesiologic perspective, a force is either a push or a pull which produces, arrests or modifies movement and is often referred to as a load. Examples of loads are tension and compression as well as bending and torsion. These can also occur as combined loading. In a kinetic movement analysis, which examines the forces causing the movement, only the effects of forces can be observed because they cannot be seen. Forces can be distinguished into internal and external forces. Structures located within the body are producing internal forces whereas external forces emerge from outside of the body. Similarly, internal and external torques exist. A torque is defined as the "product of the perpendicular distance between the axis of rotation of the joint and the force" and is generally described as a rotatory equivalent to a force [1], [2].

1.1.2. SMARTWHEEL

The SmartWheel (Out-Front, Mesa, AZ, USA) is an instrumented wheel that measures angular position and velocity of the wheel, and the 3-dimensional forces and moments applied to the pushrim during propulsion. For each stroke all forces and moments are provided in three global reference planes [3]. This is executed by using 12 calibration constants to convert the raw voltage provided by 6 strain gages into forces and moments. The units of the resulting moments and forces are Newton Meters [Nm] and Newtons [N] respectively.

The important parameters for this pilot study are Fx which is applied laterally, Fy, the force applied up and down on the pushrim and Mz, the moment about the axis of rotation [4]. By analyzing each push on the handrim, the SmartWheel quantifies factors like forces, frequency and push length, and also creates reports which can be used by therapists to help wheelchair users optimize manual propulsion [5].

1.1.3. KINEMATICS

"*Kinematics is a branch of mechanics that describes a motion of a body, [or of any of its parts or segments,] without regard to the forces or torques that may produce the motion*." [1] Involved in the description of the motion are position, velocity, and acceleration of a body. The general two types of motions which occur are translation and rotation. Translation describes a linear movement where all observed body parts move in the same direction and parallel to all other parts of one body. The motion in a circular path from one rigid body around a pivot point or axis is called rotation. When considering the human body, the pivot point for angular motion of body parts is called axis of rotation. A specific field of kinematics where the motion of bones relative to the three cardinal planes, sagittal, frontal and horizontal, is described is called osteokinematics. For example, flexion and extension are movements in the sagittal plane whereas abduction and adduction take place in the frontal plane, and axial rotation occurs in the horizontal plane. The primary emphasis, considering the field of biomechanics, is on the quantitative analysis. Here data is collected during the performance of a movement and those measurements are in further consequence numerically analyzed [1], [2].

1.1.4. VICON MOTION CAPTURE SYSTEM

Motion Capture is the process of recording the movement of people or objects. The Vicon systems can be used to measure or provide real-time feedback on the movements of either the whole body or just one part of it. It is often used in gait or posture analysis but also in the entertainment industry.

The system utilizes a camera array to track reflective markers through three-dimensional space. These markers are placed on anatomical landmarks which vary with the biomechanical models used for analysis with the corresponding software. The software depends on the use of the Vicon system. In clinical science and biomechanics and sports science the software Nexus is used.

With calibration at the beginning the room where data collection will take place is used to set a global origin. This is extremely important because all the outputting 3D marker position data is described relative to a global origin [6].

1.2. MANUAL WHEELCHAIR PROPULSION

According to the U.S. Census Bureau about 30.6 million people aged 15 years and older suffer from lower body limitations associated with ambulatory activities in 2010. In other words, 12.6 percent of the population of the United States needs an assistive device. About 3.6 million individuals in this age group depend on a wheelchair (WC) to manage the activities of daily living [7]. To maintain this ability correct functionality of the upper limbs is an essential requirement to provide individuals relying on a manual wheelchair as much autonomy as possible [8].

1.2.1. UPPER LIMB DEMANDS

Manual Wheelchair Users (MWUs) must rely on their upper extremity (UE) for almost all activities in everyday life and moreover they completely depend on their UE for mobility during wheelchair propulsion [9]. Propulsion is defined in the Macmillan dictionary as the force that moves or pushes something forward. In the context of wheelchair propulsion its meaning describes pushing a wheelchair forward [10]. The high demands from propelling a wheelchair and daily life exercises can lead to excessive stresses in the upper limb. This mainly happens since the UE is not originally structured for mobility but for stability. Thus, MWUs often suffer from pain in their bones, joints and soft tissues of the upper limb [9]. Additional to the pain many MWUs also report instability which can occur because, as already mentioned above, the purpose of the UE should normally be to guarantee stability whereas for manual wheelchair users it needs to guarantee mobility as well [11]. Since manual wheelchair propulsion is also a highly repetitive motion with a very short cycle time, MWUs are moreover at high risk of overuse pain and injury. More than half of all manual wheelchair users will develop overuse injuries or pain in the upper extremity in their life [11], [12].

The three biomechanical factors high force requirements, repetitive motion and extreme joint motion have been shown to infect the upper arm pathology at most concerning distal upper extremity (DUE) musculoskeletal disorders (MSD) [13]. To propel a wheelchair, high forces need to be generated by muscles and applied to the push rim of the chair. Thereby not only high intersegmental forces are created but also joint moments higher than 50% of the maximum accessible values [14]. Shimada et al as well as Veeger et al showed that during wheelchair propulsion the shoulder, elbow and wrist joints have to create substantial forces at joint angles which are almost the physiological limit. Considering the already mentioned strain on the upper extremity it must be considered that those activities are performed all day long for a lifetime [8], [15].

Sie et al found that 59% of all MWUs with tetraplegia and 41% of all MWUs with paraplegia suffer from significant upper limb pain. The most commonly affected areas are the wrists, elbows and shoulders. The shoulder is the most reported site of musculoskeletal injury whereas the most common neurologic cause of UE pain in MWUs is carpal tunnel syndrome (CTS) [9]. Prevalence rates for CTS for people with spinal cord injury may be as high as 50 to 60 % and increase with the duration of injury [16]. CTS is furthermore next to shoulder impingement/rotator cuff tendinitis one of the most often occurring overuse injuries in the MWU population [17]. Concerning shoulder pain, shoulder impingement is with a prevalence of 73% the most common diagnosis [18]. The activities most associated with shoulder pain in the population of MWUs are reaching overhead, transfers and propelling a wheelchair [19]. Shoulder pain was most related to the functional activities associated with wheelchair mobility, transfers, pressure relief and upper body dressing. Thus, upper extremity pain leads to severe limitations in everyday life activities for manual wheelchair users [20].

To reduce upper extremity demands and injuries for MWUs Paralyzed Veterans of America established propulsion technique guidelines. In their recommendations they provide information about the initial assessment process, ergonomics as well as equipment selection and training environmental adaption. Information about treatment of chronic musculoskeletal pain to maintain function and exercise recommendations is also given along with an explanation about the management of acute and subacute upper limb injuries and pain. The authors state that, to minimize the injury potential for MWUs, cadence should be reduced and peak handrim forces should be minimized. Furthermore, the contact angles should be as large as possible so that long, smooth push strokes are possible [21]. The application of the guidelines is not as easy as it sounds because even though minimizing cadence reduces the muscle demand and fatigue – which could decrease UE injuries and pain – it increases average muscle stress. Likewise, minimizing peak force leads to increased cadence and recovery power. Moderate changes considering those variables may definitely reduce overall muscle demand but bringing the change to extreme levels may harm MWUs [22].

To help prevent UE injuries and pain and investigate biomechanical loads which affects MWUs a general description of wheelchair propulsion was created and further investigated so that the least demanding way of propelling a wheelchair can be recommended and trained.

1.2.2. STROKE CYCLE

To describe wheelchair propulsion in a better way, a comprehensive definition of a stroke cycle should be provided not only to standardize analysis but also to improve clinical value [23].

Analogous to the gait cycle the stroke cycle in wheelchair propulsion was developed which consists of two different phases. These phases are called push and recovery phase and work after the same principle like swing and stance phase of gait [24], [25]. To create a definition which meets those requirements and moreover to show the clinical usefulness of it the study focused on the phase of pushrim contact. To show the difference between propulsive and non-propulsive contact measurements of axle moment and total force were used [23]. The hand is in contact with the push rim of the wheelchair and applies force to it in the push phase to preserve or increase wheelchair velocity. The recovery phase describes the period when the hands are not in contact with the push rim and are pulled back in preparation for the next push. Comparing the stroke cycle again to the gait cycle both define a repeating structure of loading and unloading of distal segments to enable mobility [24], [25].

To give an example for the usage of the theoretical description above, a study by Callinger et al in 2008 is mentioned. Here the push phase description was used by defining it as a deviation of push rim force and moment data from baseline (0) which correctly represents the period where the hand is contacting the push rim. This way of implementation is consistent with the explanation above and was used for visualization of the process described theoretically [26].

1.2.3. STROKE PATTERNS

After the stroke cycle was described further research was carried out in the field of manual wheelchair propulsion to learn more about the effect of daily wheelchair use on the human body. Special focus was laid again on the hand movement during propulsion especially during the recovery phase. By that stroke patterns where discovered. Those patterns describe the hand movement during the recovery phase and are usually measured by tracking the motion of the hand during a propulsive stroke [23], [27].

The first to investigate stroke patterns were Sanderson and Sommer. With circular and pumping they recognized two different patterns when focusing on the hand movement. In the circular propulsion technique the hand follows the push rim whereas during pumping, a more abrupt style, the hand follows the handrim only for a small arc [24]. In a later study with five male MWU athletes Veeger et al discovered the same two stroke patterns by focusing on the third metacarpophalangeal joint (MCP) [28].

Shimada et al investigated wheelchair propulsion biomechanics in order to reduce or better prevent musculoskeletal injuries. Therefore, the study focuses on joint kinematics and push rim kinetics because both were considered important biomechanical components which should be explored to describe different stroke patterns. To characterize the patterns which might occur joint accelerations, joint range of motion (ROM), stroke efficiency and wheelchair propulsion phases were investigated. Measurements were performed using a camera-based motion analysis system to measure kinematic data and a SmartWheel (see **Fehler! Verweisquelle konnte nicht gefunden werden.**) to obtain kinetic data.

Three stroke patterns could be identified by using the kinematic data from the second MCP:

a) Semicircular (SC)
   Here the hands are dropping below the propulsion path during the recovery phase. The way of the hand applying this pattern can be seen in Figure 1.
b) Single looping over propulsion (SLOP)
   The SLOP pattern is shown in Figure 2. Characteristic for this propulsion is that the hands rise above the push rim during the recovery phase.

The motion of the hand was the feature of SC and SLOP patterns that distinguished them from each other.

c) Double looping over propulsion (DLOP)
   In the DLOP pattern, presented in Figure 3, the hands rise at the beginning above the push rim, then cross over and finally drop under the push rim during the recovery phase.

The difference between SLOP and DLOP was the cross over point in the DLOP pattern, while the subjects using SLOP did not share a common coordinate.

When investigating the patterns regarding efficiency, the study concluded that SC is the most efficient one [8]. Due to the fact that only seven subjects participated in this study, Boninger et al implemented a study with the purpose to classify stroke patterns with a larger sample of MWUs. Boninger et al explored the same three patterns as Shimada et al but during classification another stroke pattern was identified: arcing.

d) Arcing
   In this pattern, which can be seen in Figure 4, the third MCP joint follows an arc along the path of the push rim during the recovery phase, similar to the push phase.

In the following pictures the y-axis shows the displacement of the marker on the hand in mm in the vertical way ranging from 400 to 750 and the x-axis shows the displacement in mm ranging from -300 to 400 in the horizontal way.

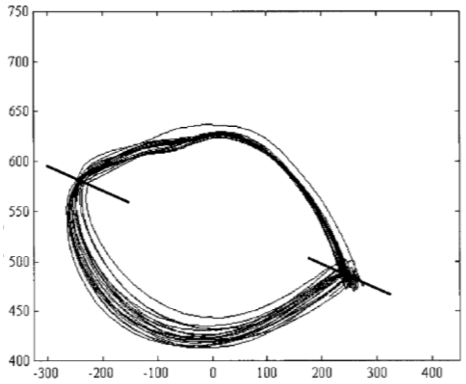

FIGURE 1: SC PATTERN [27]

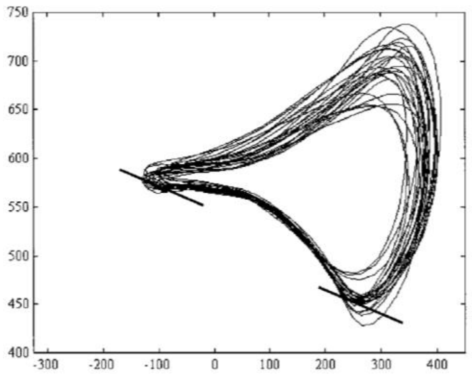

FIGURE 2: SLOP PATTERN [27]

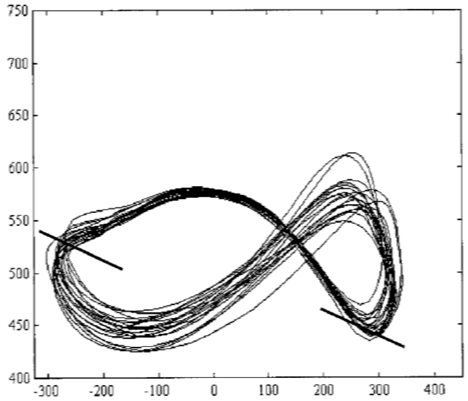

FIGURE 3: DLOP PATTERN [27]

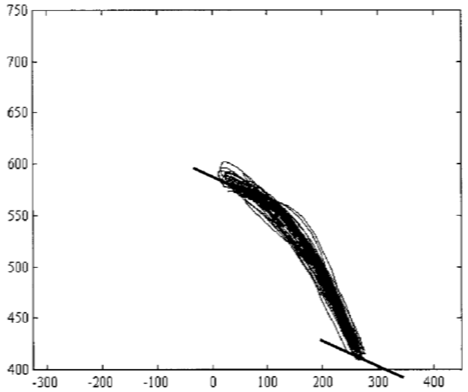

FIGURE 4: ARCING [27]

In the four pictures (Figure 1, Figure 2, Figure 3 and Figure 4) shown above, the black bar on the right side represents the beginning of a propulsive stroke and the left bar shows the end of the stroke and the beginning of the recovery phase.

The study from Boninger et al showed that the most used pattern was SLOP followed by DLOP and SC. The least used pattern was arcing. Like Shimada et al, this study also reports that SC is the most efficient way to propel a wheelchair. This was explored by the fact that this pattern showed the lowest cadence and the highest ratio of push time to recovery time [27]. Other studies, which were carried out similarly, came to the exact same conclusion [29], [30], [31] .

1.3.THE REVISED STRAIN INDEX

The Revised Strain Index is a distal upper extremity physical exposure assessment model developed in 2017 as an improvement to the Strain Index which was first proposed from Moore & Garg in 1995. It examines single task jobs focusing on the risk of those for DUE MSDs [32].

In general, it serves as an observational assessment method without any gear of a lab which can be executed outside of a clinical area only needing a trained ergonomist.

1.3.1. ERGONOMIC DEVELOPMENT

The National Institute of Occupational Safety and Health (NIOSH) defines ergonomics as the science focusing on the fit of workplace conditions and job demands to the capabilities of the working population. An ergonomics program is described by NIOSH as a systematic process where risk factors are identified, analyzed and controlled, often to reduce MSDs. By understanding ergonomics, programs to prevent or at least minimize work-related musculoskeletal disorders (WSMDs) can be developed [33].

MSDs are described as disorders of the nerves, muscles, blood vessels as well as ligaments and tendons. If an injury or illness is work-related it is an event or exposure in the work environment which either caused or contributed to the resulting condition or significantly intensified a preexisting injury or illness. The U. S. Department of Labor states that work-related MSDs are one of the most frequently reported causes of days away from work or days of restricted work activity [34]. The Bureau of Labor Statistics reported that 356,910 cases of nonfatal occupation injuries and illnesses in 2015 (31%) were related to MSDs. Moreover, the median days away from work is 12 days for workers suffering from WMSDs. The median is four days higher than the median for other work-related injuries, which is eight days off [35]. Manual workers in different industries can be exposed to risk factors at work, such as bending, reaching overhead, lifting heavy items, working in awkward body postures and performing the same task over and over again [33]. Common examples for MSDs are carpal tunnel syndrome (CTS), rotator cuff syndrome, epicondylitis, and many more [34]. Ergonomics Programs have now aimed to enable employers to detect WSMD problems and come up with solutions. Furthermore, with this approach further losses in productivity, quality, and lost time from injury can possibly be prevented [33]. The Strain Index and the Revised Strain Index are examples for assessment methodologies to detect WSMD [32].

1.3.2. THE STRAIN INDEX

The Strain Index is a job analyzing method to determine if workers are at risk of DUE disorders. Moore and Garg proposed this methodology in 1995 to investigate jobs and workplaces for the threat of DUE MSDs. Their model is based on multiplicative interactions between six task variables. The variables are (1) intensity of exertion, (2) duration of exertion (as a percentage of cycle time), (3) efforts per minute, (4) hand/wrist posture, (5) speed of work, and (6) duration of task per day. Each variable is assigned a rating from one to five and with that scores the multipliers are determined by using the table provided by the User's Guide for the Strain Index from Moore and Garg. The variables and their multipliers were selected considering biomechanical, physiological, and epidemiological principles. Even though there is no proof for an exact multiplicative relationship between the risk of upper extremity disorders and the chosen variables, Moore and Garg considered it a reasonable assumption based on current knowledge. The most important (highest weighted) variable is intensity of exertion which estimates the strength (muscular effort) which is required for a one-time performance of the task. Percentage duration of exertion reflects the biomechanical and physiological strain on the DUE by measuring the time an exertion is maintained during a duty cycle. In the SI methodology a duty cycle refers to the exertional cycle. The efforts per minute variable resembles the frequency of exertion as being the number of exertions per minute. Hand/wrist posture is an estimate of the position of the hand or wrist in comparison to the neutral position. Speed of work refers to how fast the worker is working and shows if there is enough recovery time during consecutive exertions. Duration of task per day is the number of hours the worker spent on doing the task in one day. The Strain Index score (SI score) is the product of all six multipliers as shown by Equation 1:

EQUATION 1: SI SCORE

$$\begin{aligned}\mathrm{SI} = {} & (\text{Intensitiy of Exertion Multiplier}) * (\text{Duration of Exertion Multiplier}) \\ & * (\text{Exertions per Minute Multiplier}) * (\text{Posture Multiplier}) \\ & * (\text{Speed of Work Multiplier}) * (\text{Duration per Day Multiplier})\end{aligned}$$

To test the method, they used collected data from a previously performed study. The SI was calculated for every subject and a threshold SI score of 5 was selected to distinguish safe from hazardous jobs. All but one were classified right whether they lead to DUE MSDs or not [36]. More validity was shown through other studies, for example Knox and Moore used the Strain Index and the cutoff point of 5.0 to analyze jobs in a turkey processing plant and found that it was reliable [37]. Rucker and Moore suggested a cutoff point of 9.0 would be more relatable for manufacturing jobs because these workers are exposed to a higher duration of exertion and more efforts per minute but on the contrary to lower force requirements than the ones studied previously in a turkey or in a pork processing plant [38]. Those results provide additional evidence of the external validity and predictive validity of the Strain Index. Moore, Vos, Stephens, Stevens and Garg compared the three previously mentioned studies and decided on a SI score ≥ 6.1 to describe jobs as hazardous which might lead to DUE MSDs [39].

1.3.3. IMPROVEMENT OF THE SI – THE RSI

According to Moore and Garg [36], their proposed methodology of the Strain Index in 1995 has certain limitations. It is for example difficult to discriminate between a light and a somewhat hard exertion. It would be better to have a more objective assessment method which can be used to analyze different tasks [9], [36], [42]. Garg, Moore and Kapellusch [32] proposed with the Revised Strain Index a model which should not only help to correct the problem mentioned but also three other limitations which occur when using the Strain Index from 1995 job analysis method. One is the use of categorical variables and their corresponding multipliers. With that, an only one unit change leads to a completely different SI score [32]. Another problem in the application of the SI is that the efforts per minute multiplier ends at 20 exertions per minute which is the reason that tasks with more than 20 exertions per minute cannot be properly evaluated [42]. The last limitation Moore and Garg [32] are addressing is the use of duty cycle. Even though two tasks may have the same duty cycle one cannot say if there is a higher frequency and lower duration of exertion or lower frequency and higher duration of exertion. This is a problem because the collocation mentioned last may be a lot more fatiguing [43], [44].

The model of the RSI works similar to the SI from 1995 except that the speed of work variable is not used anymore, it is based on duration per exertion rather than duty cycle and instead of categorical variables and multipliers, continuous variables and multipliers are applied [32].

The Revised Strain Index is a five-variable model which consists of (1) intensity of exertion, (2) efforts per minute, (3) duration per exertion, (4) hand/wrist posture and (5) duration of task per day. The intensity of force variable resembles the force required to complete a task and can be estimated using the BORG CR-10 rating. Efforts per minute is synonymous with frequency of exertion and the variable is a measure of repetitiveness which is in this case defined as the number of exertions per minute. The duration per exertion variable stands for the average time that an exertion is applied. Hand/wrist posture refers to the anatomical position of the hand/wrist relative to anatomical neutral with a distinction in the measure whether the wrist is in neutral position, flexion or extension. Analysts must observe with attention to two things: (i) if the wrist is in flexion or extension when force is applied and (ii) what the amount of flexion/extension is when applying force. The last variable, duration of task per day, is the total time a task is performed per workday and is measured in hours. As can be seen from the variable explanation above, the variables (1), (2) and (5) are defined the same way they were in the 1995 SI method. For the posture variable the distinction between applying force either in wrist flexion or extension is new and instead of duty cycle duration of exertion is being used.

The multipliers for the RSI are based on the principle that increasing values for any of the variables lead to an increased strain on the body. Similar to the 1995 SI model professional judgement was used to define the equations used to calculate the multipliers which are consistent with psychophysical, physiological, biomechanical, and epidemiological considerations. The equations for every multiplier can be discerned from Garg, Moore and Kapellusch [32].

The RSI score is the product of the five multipliers:

EQUATION 2: RSI SCORE

$$\mathrm{RSI} = \mathrm{IM} * \mathrm{EM} * \mathrm{DM} * \mathrm{PM} * \mathrm{HM}$$

IM = intensity of exertion (force) multiplier
EM = exertions per minute (frequency) multiplier
DM = duration per exertion multiplier
PM = hand/wrist posture multiplier
HM = duration of task per day multiplier.

A score up to ten is considered ‘safe’, everything above is considered ‘hazardous’ [32].

1.4. RELATION OF THE RSI AND WC PROPULSION

As stated in chapter 1.2.1 upper limb demands are a big problem for MWUs. Not only the normal tasks of the upper extremity in daily living are needed, also their mobility depends exclusively on their upper limb. Likewise, workers, mainly in factories doing single task jobs, who have a strain on the upper extremity for at least eight hours on a normal work day rely a lot more on the upper limb than people in other jobs. Boninger et al also mentioned a connection between those two different exposure factors concerning the prevention of upper-limb pain [29]. Task performance modification based on ergonomic analysis is mentioned as a beneficial factor. It has been proven that this treatment reduces the incidence of pain of the upper limb in different work settings [45], [46] .

To examine the upper extremity demand through wheelchair propulsion with the RSI method would be a great benefit in the ergonomic field. By now detailed analysis of kinetic data like forces can only be carried out in a clinical laboratory environment. Thus, a huge drawback is that it is almost impossible to represent the conditions of daily living. With the RSI method a video is all what is needed along with a trained ergonomist who can make assumptions and ratings on how a specific sequence of motions affect the upper extremity of wheelchair users and furthermore come up with improvements on those movements.

Special focus is laid on the force laterally applied to the wheel which is mostly responsible to get the wheelchair moving.

The data provided by a study which measured pushrim forces and joint kinetics during wheelchair propulsion is also considered to compare the data from this pilot study to get a more comprehensive view on the subject.

2. METHODS

2.1.SUBJECT

The subject in this pilot study was a 20 years old female with no experience in using a wheelchair. No medical conditions which would interfere with data collection were reported.

2.2.DATA COLLECTION

The wheelchair used for data collection was the model ACTIONPRO from the company Action Technology, a division of Invacare Corporation. To collect kinetic data the wheel on the dominant side of the subject was replaced by a SmartWheel. The use of the instrumented wheel did not lead to any changes concerning the camber, axle position or diameter of the subjects normal pushrim. A wheel which shares the exact same sizes and parameters with the SmartWheel was used on the non-dominant side. Both wheels had air tires and no gloves or plastic-coated handrim was needed to assist the propulsion.

Kinematic data was collected with a Vicon motion capture system. Twenty-seven reflective markers were fixed to bony landmarks on the trunk and upper limbs. Another two markers were placed on the SmartWheel and four on the back of the wheelchair for orientation. Marker trajectories were recorded with 12 cameras of the Vicon system. All trials were collected at 100Hz.

The subject propelled the wheelchair at a self-selected speed and for three to five stroke cycles per trial. Two different hand-wheel grasps were measured: (1) open handed (i.e., palmer push on wheel), and (2) closed handed (i.e., oblique grasp on hand-rim). Trials were performed both on: (1) a wooden floor, and (2) a treadmill. Wheelchair velocity was not directly measured but was approximately constant across trials. Adequate rest was provided to the subject as needed. All trials were performed in the UWM Mobility Lab.

The SmartWheel data was recorded at 240 Hz and synchronized with the Vicon motion capture system which collected data at 100Hz. Video cameras recorded every trial which was necessary to analyze all trials with the RSI method.

2.3.DATA ANALYSIS

Each of the anatomical landmarks was digitized by the motion analysis system for the kinematic data analysis. The data was processed with Nexus software. An upper extremity biomechanical model [47] was used to calculate joint kinetics and angles.

Kinematic data were collected but not used in this pilot study.

For the kinetic data analysis, the Fx, Fy and Mz output from the SmartWheel were used. The forces Fx and Fy were directed in the anterior/posterior and superior/inferior direction, while Fz was directed in the medial/lateral direction. Mz is the moment which is created around the wheelchair hub.

The videos of each trial were analyzed frame by frame to determine analyst's observed length of exertion and hand/wrist posture. Both hands were treated equally because they moved in the exact same way on both sides. The analysis was executed independently by two different persons to provide a more general analysis. To see how long force is applied to the handrim, which is the current definition of length of exertion, the analysis focused on the interaction of the hand with the pushrim of the wheelchair. This was also true for the analysis of posture. Here, every change of the hand or wrist when attached to the handrim was noted.

MATLAB (The MathWorks, Inc., Natick, MA, USA) was used to calculate RSI scores by using data from the kinematic analysis through the SmartWheel combined with data from the video analysis.

The duration per exertion was determined from the SmartWheel data for each trial for Fx, Fy and Mz. Therefore, the data was read into the program and the length was calculated by using the function *ginput*. Every length of exertion for each trial was registered in a file where the trials were distinguished between their four conditions (i.e., flat ground vs. treadmill, and open-handed vs. closed handed).

For the intensity of exertion variable in the RSI methodology only one value for the applied force can be used; however, applied force changes during each propulsion exertion. To examine different estimations of exertion intensity, the mean force, peak force and 90th percentile force was calculated for each trial. A file similarly to the length of exertion was created where the trials were also split into their four different conditions.

Out of the values the corresponding RSI multipliers IM (intensity of exertion multiplier) and DM (duration of exertion multiplier) were computed using the formulas created by Garg, Moore and Kapellusch [32] which were implemented in a MATLAB function.

EQUATION 3: INTENSITY OF EXERTION MULTIPLIER

$$\mathrm{IM} = \begin{cases} 30.00 * \mathrm{I}^3 - 15.60 * \mathrm{I}^2 + 13.00 * \mathrm{I} + 0.40, 0.0 < \mathrm{I} \leq 0.4 \\ 36.00 * \mathrm{I}^3 - 33.30 * \mathrm{I}^2 + 24.77 * \mathrm{I} - 1.86, 0.4 < \mathrm{I} \leq 1.0 \end{cases}$$

EQUATION 4: DURATION OF EXERTION MULTIPLIER

$$\mathrm{DM} = \begin{cases} 0.45 + 0.31 * \mathrm{D}, \mathrm{D} \leq 60\mathrm{s} \\ 19.17 * \log_e \mathrm{D}, \mathrm{D} > 60\mathrm{s} \end{cases}$$

EQUATION 5: RSI$_1$ MATRIX

$$\mathrm{RSI_1 matrix} = \mathrm{IM} * \mathrm{DM}'$$

To get an idea about the range of RSI$_1$ scores, where only intensity of exertion and duration of exertion are considered, and all the other components are 1 a matrix was created. Here, the DM (Equation 4) vector was multiplied with the EM (Equation 3) vector (Equation 5). The duration of exertion in seconds, a column vector sorted from low to high, was plotted over the intensity of exertion as percent of the maximum strength (MVC) row vector which was also sorted from low to high.

EQUATION 6: %MVC

$$\%\mathrm{MVC} = \frac{\mathrm{distance} * \mathrm{force\ value}}{\mathrm{MVC}}$$

The parameter distance in Equation 6 is measured from the joint center to where the force is applied to the pushrim. The intensity of exertion vector was created by using the minimum value of the mean force vector and take equal steps to the maximum value from the peak force vector. With the MATLAB function *interp1* a complementary vector for the duration which starts with the minimum value of the length of exertion vector and ends with the maximum value from the same vector. The RSI_1 matrix was calculated several times where the intensity of exertion vector and the length of exertion vectors change but the way of computing the matrix always stays the same.

Later, the frequency multiplier was added to the RSI calculation. The efforts per minute variable was calculated by computing the frequency in Hz with MATLAB and convert it into the required unit efforts/min. For the outcomes the complementary multiplier EM (Equation 7) was calculated, and a matrix was generated with the RSI_1 values over frequency, shown in Equation 8.

EQUATION 7: EFFORTS PER MINUTE MULTIPLIER

$$\mathrm{EM} = \begin{cases} 0.10 + 0.25 * \mathrm{E}, \mathrm{E} \leq 90/\mathrm{m} \\ 0.00334 * \mathrm{E}^{1.96}, \mathrm{E} > 90/\mathrm{m} \end{cases}$$

EQUATION 8: RSI_2 MATRIX

$$\mathrm{RSI_2 matrix} = \mathrm{EM} * \mathrm{RSI_1}$$

Another matrix was created where the frequency values were taken out of literature [48], [49], [50] to compare the scores to the ones computed using collected data. Those matrices were then combined into one which shows frequencies from the literature and from collected trials.

Until now the hours per day multiplier (HM) and the posture multiplier are still considered to be 1 and only the variables intensity of exertion, duration of exertion and efforts per minute variables contribute to the current RSI score. The posture still stays 1 but now the HM (Equation 9) is also taken into account. Again, the scores of the recent RSI which is the column vector RSI_2 are multiplied with the HM row vector and a matrix is created as can be seen in Equation 10.

EQUATION 9: HOURS PER DAY MULTIPLIER

$$\mathrm{HM} = \begin{cases} 0.2, \mathrm{H} \leq 0.05\mathrm{h} \\ 0.042 * \mathrm{H} + 0.09 * \log_e(\mathrm{H}) + 0.477, \mathrm{H} > 0.05\mathrm{h} \end{cases}$$

EQUATION 10: RSI_3 MATRIX

$$\mathrm{RSI_3 matrix} = \mathrm{HM} * \mathrm{RSI_2}$$

All those matrices were calculated for the wrist and the shoulder. The maximum strength was assumed to be 23 N-m for the wrist and two values, 30 N-m and 60 N-m were used for the maximum strength of the shoulder. For shoulder, the first value represents a truly general population whereas the second value represents a general industrial population which does shoulder work. Both values were derived from laboratory data collected by Dr. Kapellusch.

3. RESULTS

3.1. DURATION OF EXERTION

To get the exact duration of one exertion the first thing done was a video analysis. Later, the received values were compared with those from a MATLAB program. Important for the comparison is that two different sample rates are used by the two different systems. For the visual analysis the videos were analyzed using the Vicon System which has a sample rate of 100Hz. The forces measured by the SmartWheel on the other hand are sampled with 240Hz.

The following table shows the difference between the video analysis and the calculated values for duration of exertion of Fx in the first trial collected on the floor:

TABLE 1: COMPARISON OF VISUAL ESTIMATED AND CALCULATED DURATION OF EXERTION VALUES

Exertion	Calculations using Fx	Visual analysis
1	1.56 secs	0.79 secs
2	0.65 secs	0.41 secs
3	0.58 secs	0.39 secs

As can be seen in Table 1 the values vary whether they are calculated with the MATLAB program or estimated with visual analysis. In both ways the gap between the first two values is a lot bigger than those between the last two values.

3.2. INTENSITY OF EXERTION

The RSI model implies that the force applied in one exertion does not change over time. This is not possible considering wheelchair propulsion. Furthermore, several estimations must be tested to show what would work best to substitute for the whole force. Here the force Fx was examined by calculating the mean, the peak and the 90th percentile for each exertion for the trials under the same conditions.

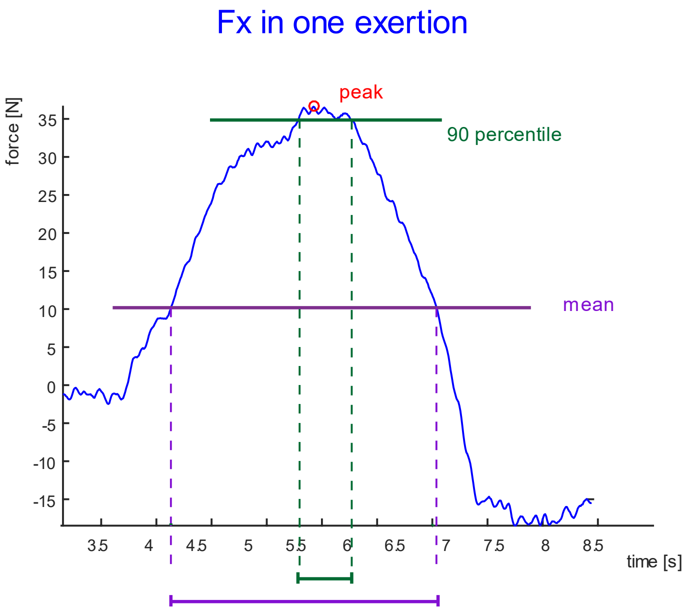

FIGURE 5: ONE EXERTION IN FX

In Figure 5 the force history is shown over one sample exertion. The peak, 90th percentile and mean force values are highlighted in this graph. Furthermore, the impact of duration can be obtained from the figure. As can be clearly seen the peak force occurs only once over the exertion period. To estimate it for the whole time would be an overestimation. The opposite problem occurs when looking at the mean. Here the duration is reasonable with the force. Unfortunately, the mean force is too small to cover the whole duration because none of the higher values are considered. The value of the 90th percentile does not differ too much from the peak force which confirms with assumptions. Therefore the 90th percentile force over the whole duration could also be an overestimation because those high values only occur for a very short period as shown in the figure.

3.3. RSI_1 = IM*DM

By estimating all other values needed for the RSI calculation as 1 a first multiplication was implemented by only using the intensity of exertion multiplier and duration of exertion multiplier. Therefore, the durations of applied force in the forward direction, Fx, were sorted and the largest and smallest duration was identified. Between those two values the distances were made even to get 14 values. The complementary 14 values for the percentage of maximal strength required in that particular part of the upper extremity to propel a wheelchair were calculated in MATLAB.

3.3.1. WRIST

As stated before, the assumed value for maximum strength (MVC) is 23Nm. By using this and the distance between joint center and the section of the handrim where force is applied the %MVC could be calculated out of the force values.

TABLE 2: RSI$_1$ MATRIX WRIST - MEASURED DATA

		duration per exertion (sec)												
		0.43	0.52	0.61	0.7	0.79	0.88	0.97	1.06	1	1.24	1.33	1.42	1.51
%MVC wrist force (%)	1.75	0.36	0.38	0.4	0.42	0.43	0.45	0.47	0.49	0.5	0.52	0.54	0.55	0.57
	2.72	0.43	0.45	0.48	0.5	0.52	0.54	0.56	0.58	0.6	0.62	0.64	0.66	0.68
	3.69	0.5	0.53	0.55	0.57	0.6	0.62	0.65	0.67	0.69	0.72	0.74	0.77	0.79
	4.66	0.57	0.6	0.62	0.65	0.68	0.71	0.73	0.76	0.79	0.81	0.84	0.87	0.9
	5.63	0.64	0.67	0.7	0.73	0.76	0.79	0.82	0.85	0.88	0.91	0.94	0.97	1
	6.60	0.7	0.73	0.77	0.8	0.83	0.87	0.9	0.93	0.97	1	1.03	1.07	1.1
	7.57	0.76	0.8	0.84	0.87	0.91	0.95	0.98	1.02	1.06	1.09	1.13	1.17	1.2
	8.54	0.83	0.87	0.91	0.95	0.99	1.02	1.06	1.1	1.14	1.18	1.22	1.26	1.3
	9.51	0.89	0.93	0.97	1.02	1	1.1	1.14	1.19	1.23	1.27	1.31	1.36	1.4
	10.49	0.95	1	1.04	1.09	1.13	1.18	1.22	1.27	1.31	1.36	1.4	1.45	1.49
	11.46	1.01	1.06	1.11	1.16	1.2	1.25	1.3	1.35	1.4	1.45	1.49	1.54	1.59
	12.43	1.07	1.12	1.17	1.22	1.28	1.33	1.38	1.43	1.48	1.53	1.58	1.63	1.68
	13.40	1.13	1.18	1.24	1.29	1.35	1.4	1.45	1.51	1.56	1.62	1.67	1.72	1.78

Based on duration and forces the RSI$_1$ scores shown in Table 2 range from 0.36 to 1.78. All those outcomes display that the exposure of the wrist is not hazardous for a single exertion. The red square in the middle shows most-likely, representative values which range from the score 0.65 to the score 1.36. All other combinations, while feasible, are likely to be either too high or too low to represent the typical RSI score associated with a single exertion.

It is shown that the differences between the values are quite small in practical terms. The only way to get a score which shows that wheelchair propulsion is hazardous could show up when the frequency of exertion is very high.

3.4. DATA FROM LITERATURE

To get a more general idea if the RSI would work as an analysis method to depict DUE MSDs it was also applied to the data out of the paper 'Pushrim Forces and Joint Kinetics During Wheelchair Propulsion' by Robertson and his coworkers. Robertson's objective was to investigate pushrim forces and joint kinetics during wheelchair propulsion. Focus was furthermore laid on the differences between experienced wheelchair users and non-experienced wheelchair users. Like the methods in this pilot study, a force-sensing pushrim was used to get forces and moments. Those were later analyzed and compared for both groups. Their major outcome was that experienced MWUs tended to push longer, used forces with lower peaks and it took them longer time to reach peak values [14].

The values for duration of exertion were taken out of a figure showing one stroke cycle of wheelchair users and non-wheelchair users. Distance is not required anymore because data used to calculate %MVC is already given in Nm as we are now talking of moments. The %MVC was computed by taking the mean of shoulder moments minus standard deviation as a minimum and maximum plus standard deviation as peak value.

3.4.1. WRIST – DATA FROM LITERATURE

Using data from the Robertson et al paper results in the matrix in Table 3. The range of the values for the joint moments was defined from Robertson with calculated mean and maximum values for moments in the wrist.

TABLE 3: RSI$_1$ MATRIX WRIST – LITERATURE DATA

%MVC wrist force (%)	duration per exertion (sec)												
	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80
2.17	0.35	0.36	0.37	0.38	0.39	0.40	0.41	0.42	0.43	0.44	0.45	0.46	0.47
6.52	0.61	0.63	0.65	0.66	0.68	0.70	0.72	0.74	0.76	0.78	0.79	0.81	0.83
10.87	0.85	0.88	0.91	0.93	0.96	0.98	1.01	1.03	1.00	1.09	1.11	1.14	1.16
15.22	1.09	1.12	1.15	1.19	1.22	1.25	1.28	1.32	1.35	1.38	1.42	1.15	1.48
19.57	1.32	1.36	1.40	1.44	1.48	1.52	1.56	1.60	1.64	1.68	1.71	1.75	1.79
23.91	1.55	1.60	1.64	1.69	1.74	1.78	1.83	1.88	1.93	1.97	2.02	2.07	2.11
28.26	1.79	1.85	1.90	1.96	2.01	2.07	2.12	2.17	2.23	2.28	2.34	2.39	2.45
32.61	2.06	2.12	2.18	2.25	2.31	2.37	2.43	2.49	2.56	2.62	2.68	2.74	2.81
36.96	2.35	2.42	2.49	2.56	2.63	2.70	2.78	2.85	2.92	2.99	3.06	3.13	3.20
41.30	2.68	2.76	2.84	2.92	3.00	3.08	3.16	3.24	3.32	3.41	3.49	3.57	3.65
45.65	3.04	3.13	3.22	3.31	3.41	3.50	3.59	3.68	3.77	3.87	3.96	4.05	4.14
50.00	3.43	3.53	3.64	3.74	3.85	3.95	4.05	4.16	4.26	4.37	4.47	4.57	4.68
54.35	3.86	3.98	4.10	4.21	4.33	4.45	4.56	4.68	4.80	4.92	5.03	5.15	5.27

In comparison to the RSI$_1$ score, calculated using the data from our trials, the range in this matrix (Table 3) is shown to be a lot bigger than in Table 2 with the scores ranging from 0.35 to 5.27 and the scores in the red square representing the average RSI scores range from 1.19 to 3.41.

This mainly comes from the %MVC values which are quite higher with a difference in the maximum values compared to measured data from approximately 40.

3.4.2. SHOULDER – DATA FROM LITERATURE

To calculate the RSI$_1$ matrix for the shoulder the values for duration per exertion were taken out of the same figure as explained in 3.4.1. The %MVC was calculated also exactly the same way but two times. That was because of the two different MVCs given from Dr. Kapellusch as explained in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

TABLE 4: RSI$_1$ MATRIX SHOULDER MVC = 30

		duration per exertion (sec)												
		0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.60	0.65	0.7	0.75	0.8
%MVC shoulder force (%)	15.00	1.08	1.11	1.14	1.17	1.21	1.24	1.27	1.30	1.34	1.00	1.40	1.43	1.47
	20.67	1.37	1.42	1.46	1.50	1.54	1.58	1.62	1.67	1.71	1.37	1.79	1.83	1.87
	26.33	1.68	1.74	1.79	1.84	1.89	1.94	1.99	2.04	2.09	2.14	2.19	2.25	2.30
	32.00	2.02	2.08	2.14	2.20	2.26	2.33	2.39	2.45	2.51	2.57	2.63	2.69	2.75
	37.67	2.40	2.47	2.54	2.62	2.69	2.76	2.84	2.91	2.98	3.05	3.13	3.20	3.27
	43.33	2.84	2.93	3.01	3.10	3.19	3.27	3.36	3.44	3.53	3.62	3.70	3.79	3.87
	49.00	3.34	3.44	3.54	3.61	3.74	3.84	3.94	4.04	4.15	4.25	4.35	4.45	4.55
	54.67	3.90	4.01	4.13	4.25	4.37	4.49	4.60	4.72	4.84	4.96	5.08	5.19	5.31
	60.33	4.54	4.68	4.82	4.95	5.09	5.23	5.37	5.50	5.64	5.78	5.92	6.05	6.19
	66.00	5.29	5.45	5.61	5.77	5.93	6.09	6.25	6.41	6.57	6.73	6.89	7.05	7.21
	71.66	6.16	6.35	6.54	6.72	6.91	7.10	7.28	7.47	7.66	7.84	8.03	8.22	8.40
	77.33	7.18	7.40	7.62	7.84	8.05	8.27	8.49	8.71	8.92	9.14	9.36	9.58	9.79
	83.00	8.37	8.62	8.87	9.13	9.38	9.63	9.89	10.14	10.39	10.65	10.90	11.15	11.41

Shown in Table 4 are the values calculated with MVC = 30Nm. The range is very big, with scores starting at 1.08 going up to 11.41. It is shown that there are already scores in the matrix which are higher than 10 and furthermore considered hazardous. Especially with the maximum of %MVC the scores start almost at the threshold and pass it with a duration of exertion of 0.55 seconds.

TABLE 5: RSI$_1$ MATRIX SHOULDER MVC = 60

	duration per exertion (sec)												
%MVC shoulder force (%)	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.60	0.65	0.7	0.75	0.8
7.50	0.67	0.69	0.71	0.73	0.75	0.77	0.79	0.81	0.83	0.85	0.87	0.89	0.91
10.33	0.82	0.85	0.87	0.90	0.92	0.95	0.97	1.00	1.02	1.05	1.07	1.10	1.12
13.17	0.98	1.01	1.04	1.07	1.10	1.13	1.16	1.18	1.21	1.24	1.27	1.30	1.33
16.00	1.13	1.16	1.20	1.23	1.26	1.30	1.33	1.37	1.40	1.44	1.47	1.50	1.54
18.83	1.28	1.32	1.36	1.39	1.43	1.47	1.51	1.55	1.59	1.63	1.66	1.70	1.74
21.7	1.43	1.47	1.51	1.56	1.60	1.64	1.69	1.73	1.77	1.82	1.86	1.90	1.95
24.50	1.58	1.63	1.68	1.73	1.77	1.82	1.87	1.92	1.97	2.01	2.06	2.11	2.16
27.33	1.74	1.79	1.85	1.90	1.95	2.00	2.06	2.11	2.61	2.22	2.27	2.32	2.37
30.17	1.91	1.97	2.02	2.08	2.14	2.20	2.25	2.31	2.37	2.43	2.48	2.54	2.60
33.00	2.08	2.15	2.21	2.27	2.34	2.40	2.46	2.52	2.59	2.65	2.71	2.78	2.84
35.83	2.27	2.34	2.41	2.48	2.55	2.61	2.68	2.75	2.82	2.89	2.96	3.03	3.10
38.67	2.47	2.55	2.62	2.70	2.77	2.85	2.92	3.00	3.07	3.15	3.22	3.30	3.37
41.50	2.69	2.77	2.85	2.94	3.02	3.10	3.18	3.26	3.34	3.43	3.51	3.59	3.67

Scores calculated with the maximum strength = 60Nm are shown in Table 5. Compared to the %MVC values when calculating with MVC = 30Nm the scores are quite smaller with a range from 0.67 to 3.67. Those are even smaller than those computed for the wrist, especially in the lower right corner, when using the maximum values of both variables.

From this point on only data out of the matrices which were created with data out of literature is used in the calculations. Whereas in our pilot study only one subject propelled the wheelchair, four wheelchair users and four not-wheelchair users completed the trials in the study from Robertson et al [14]. Thus, their results are more general and provide a better and broader range.

3.5. EFFORTS PER MINUTE

Repetitive exertions and in particular forceful exertions can increase risk of injury. The RSI frequency variable represents the risk of repetitive exertions. Only six scores in the matrix created out of Robertson's shoulder moments with a maximal strength of 30 Nm are considered hazardous when only taking duration and force into account but the question appearing here is what will happen when many exertions are following each other. Having an extremely high value for the frequency could change the beforehand calculated RSI out of duration and force, as mentioned above. The frequency was calculated as necessary for the RSI multiplier in efforts per minute.

For the RSI_2 score calculations, the posture and hours per day values are still assumed as 1. The frequencies which occur during the trials on flat ground with the open-handed propulsion technique range from 36,47 efforts/min to 40,06 efforts/min. In the papers and out of the video [51] the stroke cycles per minute are with a range from 45 to 70 higher than measured from our trials [48]–[50]. Our frequencies are not so far away from the minimum frequencies in the literature and to create matrices with $RSI_2 = EM*RSI_1$ the frequencies will be combined into a range from 35 to 70 evenly segmented to get 8 values. The RSI_1 scores are out of the red square of each of the matrices above. The upper left value serves as the minimum and the lower right value as the maximum. This vector is also evenly segmented into 8 values to calculate the RSI_2 matrix.

3.5.1. WRIST

By adding the frequency parameter into the RSI calculations, we get $RSI_2 = DM*IM*EM$.

TABLE 6: RSI_2 MATRIX WRIST

		RSI$_1$							
		1.30	1.60	1.90	2.20	2.50	2.80	3.10	3.40
frequency (efforts/min)	35.0	11.51	14.16	16.81	19.47	22.13	24.78	27.44	30.09
	40.0	13.13	16.16	19.19	22.22	25.25	28.28	31.31	34.34
	45.0	14.76	18.16	21.56	24.97	28.38	31.78	35.19	38.59
	50.0	16.38	20.16	23.94	27.72	31.50	35.28	39.06	42.84
	55.0	18.01	22.16	26.31	30.47	34.63	38.78	42.94	47.09
	60.0	19.63	24.16	28.69	33.22	37.75	42.28	46.81	51.34
	65.0	21.26	26.16	31.07	35.97	40.88	45.78	50.69	55.59
	70.0	22.88	28.16	33.44	38.72	44.00	49.28	54.56	59.84

As can be seen in Table 6 the scores are all higher than 10 and therefore considered hazardous to the hand/wrist. The range goes from 11.51(nominally hazardous) to 59.84 (very hazardous) and even though the minimum and maximum values are very unlikely to be found when analyzing wheelchair propulsion, the red square in the middle which represents the probably actual range start at 21.56 and go up to 42.28 (hazardous).

3.5.2. SHOULDER

TABLE 7: RSI$_2$ MATRIX SHOULDER MVC = 30

		RSI$_1$							
		2.45	3.05	3.65	4.25	4.85	5.45	6.05	6.65
frequency (efforts/min)	35.0	26.68	26.99	32.30	37.61	42.92	48.23	53.54	58.85
	40.0	24.75	30.81	36.87	42.93	48.99	55.05	61.11	67.71
	45.0	27.81	34.62	41.43	48.24	55.05	61.86	68.67	75.48
	50.0	30.87	38.42	45.99	53.55	61.11	68.67	76.23	83.79
	55.0	33.93	42.24	50.55	58.86	67.17	75.48	83.76	92.10
	60.0	37.00	46.06	55.12	64.18	73.24	82.30	91.36	100.42
	65.0	40.06	49.87	59.68	69.49	79.30	89.11	98.92	108.73
	70.0	43.12	53.68	64.24	74.80	85.36	95.92	106.48	117.04

Table 7 shows the RSI$_2$ score with estimating the maximal strength = 30. The values are very high with the maximum in the lower right corner being ten times higher than the threshold from safe to hazard which is 10.0. The range is twice as much as that for the wrist from 26.68 to 117.04. Also, the range in the red square which goes from 41.43 to 82.30 is with a difference greater than 40 almost as big as the one in the whole matrix for the wrist.

TABLE 8: RSI$_2$ MATRIX SHOULDER MVC = 60

	RSI$_1$							
frequency (efforts/min)	1.20	1.40	1.60	1.80	2.00	2.20	2.40	2.60
35.0	10.62	12.39	14.16	15.93	17.70	19.47	21.24	23.01
40.0	12.12	14.14	16.16	18.18	20.20	22.22	24.24	26.26
45.0	13.62	15.89	18.16	20.43	22.70	24.97	27.24	29.51
50.0	15.12	17.64	20.16	22.68	25.20	27.72	30.24	32.76
55.0	16.62	19.39	22.16	24.93	27.70	30.47	33.24	36.01
60.0	18.12	21.14	24.16	27.18	30.20	33.22	36.24	39.26
65.0	19.62	22.89	26.16	29.43	32.70	35.97	39.24	42.51
70.0	21.12	24.64	28.16	7.00	35.20	38.72	42.24	45.76

In Table 8 the RSI$_2$ scores calculated with a MVC = 60 are depicted. The range from 10.62 to 45.76 is smaller than those in the other two matrices, one for shoulder, one for wrist, but still all values are higher than 10.0 and therefore considered hazardous. But, the range of the red square is with 18.16 to 33.22 quite small in comparison to the others.

It should be noted that the RSI model was not designed to analyze shoulder physical exposure. Nevertheless, the RSI construct should be broadly applicable to shoulder exertions with the exception of posture (which is receiving no penalty in these analyses — see below).

3.6.HAND/WRIST POSTURE

The forces applied to the hand rim consist of an internal and an external part. Posture affects the strain on the body because it affects the relationship between internal and external forces. When the body part is in its neutral posture, external forces are efficiently transferred to internal forces. But if that changes into a deviated posture, internal forces become relatively higher and could increase risk for injury.

In this case the postures used for wrist and shoulder do not change substantially from exertion to exertion. Considering that and the fact that this variable has not such a big impact on the RSI score as others, the posture variable will be ignored in the calculation and the multiplier will be assumed as 1 which describes neutral hand/wrist posture.

3.7. HOURS PER DAY

The RSI is a tool to analyze routinized exposure of the hand/wrist. When looking at wheelchair propulsion on a normal day in a life of an adult it can be described as an intermediate activity just like walking for non-paralyzed people. There are usually alternating sequences of exposure blocks – wheelchair propulsion (push phase) and recovery blocks – no propulsion (recovery phase).

The value estimated for the hours per day multiplier (HM) has been 1 until now which assumes 8h per day of continuous exposure. This is clearly an overestimation and therefore the hours per day variable is a tool which can only reduce the RSI scores in this case looking at the multiplier table provided by Garg, Moore and Kapellusch [32].

Looking at the matrices created for $RSI_2 = IM*DM*EM$ all the RSI_2 scores are higher than 10.0 which means the exertion is hazardous. Now the hours per day multiplier is added to the multiplication: $RSI_3 = IM*DM*EM*HM$ and posture is still estimated as 1. The vector for the hours per day variable starts at three minutes and continues in distinct steps up to four hours.

3.7.1. WRIST

TABLE 9: RSI$_3$ MATRIX WRIST

	RSI$_2$							
hours/day (h)	22.00	25.00	28.00	31.00	34.00	37.00	40.00	43.00
0.833	5.65	6.42	7.19	7.96	8.73	9.50	10.27	11.04
0.167	7.10	8.07	9.04	10.01	10.97	11.94	12.91	13.88
0.25	7.98	9.07	10.16	11.24	12.33	13.42	14.51	15.60
0.50	9.58	10.89	12.20	13.50	14.81	16.12	17.42	18.73
0.75	10.62	12.07	13.51	14.96	16.41	17.86	19.30	20.75
1	11.42	12.98	14.53	16.09	17.65	19.20	20.76	22.32
2	13.71	15.58	17.45	19.32	21.20	23.07	24.94	26.81
4	16.93	19.24	21.55	23.86	26.17	28.48	30.79	33.10

The scores in Table 9 range from 5.65 to 33.10 so it starts with scores considered safe and changes when the third RSI$_2$ score is multiplied with the third HM value which can be seen in the upper left corner of the red square with the score 10.16. In other words, is the exertion considered a RSI$_2$ score 28 applied for 15 minutes or longer is not safe for the worker.

3.7.2. SHOULDER

TABLE 10: RSI$_3$ MATRIX SHOULDER MVC = 30

	RSI$_2$							
3hours/day (h)	41.00	47.00	53.00	59.00	65.00	71.00	77.00	83.00
0.833	10.53	12.07	13.61	15.15	16.69	18.23	19.78	21.32
0.167	13.23	15.17	17.11	19.04	20.98	22.92	24.85	26.79
0.25	14.87	17.05	19.22	21.40	23.58	25.75	27.93	30.11
0.50	17.86	20.47	23.09	25.70	28.32	30.93	33.54	36.16
0.75	19.79	22.68	25.58	28.47	31.37	34.27	37.16	40.06
1	21.28	24.39	27.51	30.62	33.74	36.85	39.96	43.08
2	25.56	29.30	33.04	36.78	40.52	44.26	48.00	51.74
4	31.56	36.18	40.80	45.42	50.03	54.65	59.27	63.89

As shown in Table 10 the RSI_3 scores range from 10.53 to 63.89. They are obviously smaller than the RSI_2 scores for shoulder with a maximal strength of 30 which can be seen in Table 7 but still all combinations of RSI and the hours per day multiplier are considered hazardous as they all exceed the threshold of 10.0. The scores in the red square in the middle of the matrix range from a minimum of 19.22 to a maximum of 36.85. The minimum is already more than twice as high as the highest safe RSI score.

TABLE 11: RSI_3 MATRIX SHOULDER MVC = 60

		RSI_2							
		18.50	20.50	22.50	24.50	26.50	28.50	30.50	32.50
hours/day (h)	0.083	4.75	5.26	5.78	6.29	6.81	7.32	7.83	8.35
	0.167	5.97	6.62	7.26	7.91	8.55	9.20	9.84	10.49
	0.25	6.71	7.44	8.16	8.89	9.61	10.34	11.06	11.79
	0.50	8.06	8.93	9.80	10.67	11.54	12.42	13.29	14.16
	0.75	8.93	9.89	10.86	11.82	12.79	13.75	14.72	15.68
	1	9.60	10.64	11.68	12.72	13.75	14.79	15.83	16.87
	2	11.53	12.78	14.03	15.27	16.52	17.77	19.01	20.26
	4	14.24	15.78	17.32	18.86	20.40	21.94	23.48	25.02

In Table 11 the RSI_3 values for the shoulder with a maximum strength of 60 are shown. The range from 4.75 to 25.02 and therefore persist out of safe and hazardous values. The same applies for the red square where the scores range from 8.16 to 14.79. The first combinations which are not considered safe anymore are (18.50/2h), (10.64/1h), (22.50/0.75h) and (24.50/0.50h). For five minutes (0.083h) is no combination hazardous and for ten minutes (0.167h) only the one with the highest HM value.

4. CONCLUSION

The Revised Strain Index distal upper limb physical exposure quantification method was developed to identify and quantify the effects of job physical exposure risk factors. Several studies showed that jobs are correctly assessed as either safe or hazardous concerning DUE MSD. The RSI is a model which consists of five variables. The values for the variables are chosen by ergonomists so that the corresponding multipliers can be calculated. All five multipliers are multiplied to get the RSI scores.

Boninger et al and Mercer et al have already linked the fact that the connection between repetitive loading tasks and musculoskeletal disorders in the work field may apply for wheelchair propulsion as well because the movements executed to propel a wheelchair match the definition of repetitive activities [13], [29]. This hypothesis was further examined in this pilot study.

To analyze wheelchair propulsion with the Revised Strain Index method several limitations occur. The first limitation is that the changes in the force over an exertion cannot be considered separately in the RSI assessment. Only one value is designated to describe the force during one whole exertion. Thus, a matrix was created out of the mean, peak and 90th percentile values of all trials in the same condition. Another problem is, that whether the value in the vector is a mean, peak or 90th percentile the duration it was multiplied with always covers the whole exertion. The vector for duration of exertion consists of all exertion lengths for all exertions executed under the same conditions. Also, the efforts per minute variable cannot be changed in the calculation of the RSI. But comparing wheelchair use to walking the frequency is quite different over a day. Another limitation is that the RSI model does not account for long recovery times between the exertions. But thinking about daily living there are not equal sequences of exposure and recovery blocks. Furthermore, in most cases the hands are used during recovery blocks. Especially because electronic devices play such a huge part in everyday life and are most often operated by hand. Due to those not meaningful recovery periods no reset can happen because the use of the hands interferes with the recovery. The total time a wheelchair is propelled per day without taking sport activities into account would probably still underestimate the exposure because it does not consider the different level of forces needed to start propelling a wheelchair and stop it again.

At first, only the forces concerning the wrist were taken into account when considering the self-collected data but when adding the measurements from Robertson et al [14] the shoulder was analyzed as well. Injuries in wrist and shoulder are the most common ones resulting from wheelchair propulsion, the most reported being shoulder impingement followed by CTS [17]. Regarding the factor risk itself, risk for upper extremity disorders due to wrists is unlikely to occur compared to the shoulder. Dependent on the technique the wrist is somewhat protected by the shoulder.

All in all, it is important to publish guidelines for the analysis because for example, the duration per exertion values were quite a bit different whether they were calculated via MATLAB or analyzed by video. For sure, further research needs to be done in this field to be sure if the RSI method can predict upper extremity disorders in manual wheelchair users.

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APPENDIX

FIGURES

TABLES