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

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ABSTRACT

Background: Frequent start movements occurred during the day, yielding high upper-extremity stress. The high incidence and impact of shoulder injury on daily life wheelchair use 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 Wilcoxon Signed Rank test was used.
Findings: Intensity of mechanical shoulder loading 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.
Clinical trial registration number: NTR2661.

1. Introduction

The high incidence of shoulder injuries in hand-rim wheelchair users (Boninger et al., 2003; Dyson-Hudson and Kirshblum, 2004; McCasland et al., 2006) 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 (Dyson-Hudson and Kirshblum, 2004; Arnet et al., 2013; Burnham et al., 1993; Mercer et al., 2006; Van Drongelen et al., 2005; Veeger et al., 2002).

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 (Kloosterman et al., 2012, Kloosterman et al., 2015). In healthy subjects it was primarily the shoulder loading which was decreased by power-assisted propulsion (Kloosterman et al., 2012). 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 (Kloosterman et al., 2015).

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 1000 m is estimated to be 141.8 (60.0) (Tolerico et al., 2007); the daily distance traveled ranged from 1.5 to 2.5 km (Tolerico et al., 2007; Levy et al., 2010; Sonenblum et al., 2012) which means 212.7 till 354.5 starts/stops a day. Approximately 63% of the wheelchair propulsion bouts are shorter than 30 s, less than 13 m, and slower than 0.5 m/s (Sonenblum et al., 2012). The acceleration during start-up requires more force than maintaining a constant velocity.

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Stresses on the upper extremity are assumed to be 1.8–3.5 times higher during acceleration than during constant velocity propulsion (Koontz et al., 2005).

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.

2. 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. (2015).

2.1. 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.

2.2. 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 min) 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 m. The experimental wheelchair used prototype power-assist wheels and allowed three dimensional force measurements at the hand-rim. The 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 (Boninger et al., 1999; Vegter et al., 2013), 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 < 0 m/s) in the sagittal plane and the recovery phase by the backward movement of the radial styloid process (velocity > 0 m/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., Natick, MA, USA, www.mathworks.com).

2.3. Instrumented power-assisted wheelchair

The experimental instrumented wheelchair consisted of prototype power-assist wheels with 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.

2.4. 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 (Wu et al., 2005), distal point of the

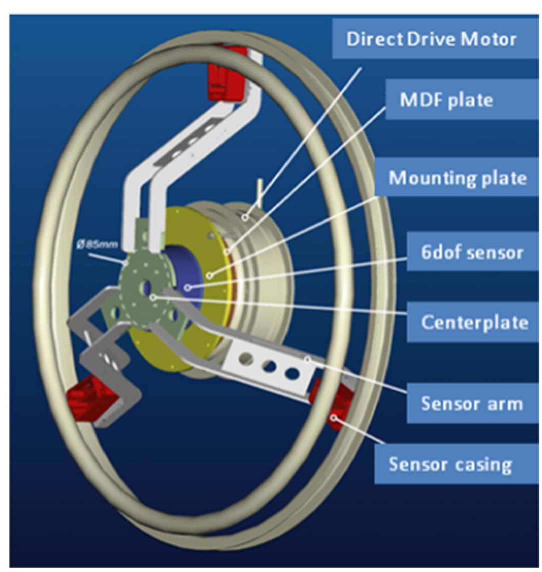

Fig. 1. Schematic of six degrees of freedom force and torque sensor mounted on the wheel and axis of the power-assist wheel. The assisting motor was mounted in the axis itself. A mounting plate and a medium-density fiberboard (MDF plate) were placed between the motor and the sensor. The hand-rim was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