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Published in:
The Journal of Spinal Cord Medicine

DOI:
10.1080/10790268.2020.1803659

Publication date:
2022

Document version:
Accepted manuscript

Citation for published version (APA):

Go to publication entry in University of Southern Denmark's Research Portal

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Assessment of shoulder rotation strength, muscle co-activation and shoulder pain in tetraplegic wheelchair athletes - A methodological study

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ABSTRACT

Objective. To develop a feasible protocol for testing maximum shoulder rotation strength in tetraplegic wheelchair athletes, and investigate concurrent validity of maximum isometric handheld dynamometer (HHD) towards maximum isokinetic dynamometer (ID) strength measurements; secondly, to study shoulder muscle activation during maximum shoulder rotation measurements, and the association between shoulder strength and shoulder pain.

Design: Descriptive methodological.

Setting: Danish Wheelchair Rugby (WCR) association for WCR tetraplegic athletes from local WCR-clubs.

Participants: Twelve adult tetraplegics.

Interventions: N/A

Outcome measures. Wheelchair User’s Shoulder Pain Index (WUSPI) and Visual Analog Scale (VAS) measured shoulder pain, isometric HHD and ID (60°/s) measured maximum internal (IR) and external (ER) shoulder rotation strength. Surface Electromyography normalised to maximum EMG measured muscle activity (mm Infraspinatus and Latissimus Dorsi) during maximum shoulder rotation strength.

Results. Concurrent validity of isometric HHD towards ID showed Concordance Correlation Coefficients of left and right arms 0.86 and 0.90 (IR), and 0.89 and 0.91 (ER), with no difference in muscle activity between isometric HHD and ID, but larger co-activation during ER. There was no association between shoulder strength and pain, except for significantly weak negative associations between ID and pain during ER for left and right arms (P=0.03; P=0.04).

Conclusion. Standardized feasible protocol for tetraplegic wheelchair athletes for measuring maximum shoulder rotation strength was established. Isometric HHD is comparable with ID on
normalised peak torques and muscle activity, but with larger co-activation. Strength was not clearly associated with shoulder pain.

Keywords
Isometric handheld dynamometry, isokinetic dynamometry, electromyography, WUSPI, feasible protocol.
Introduction

Prevalence of musculoskeletal pain in people with SCI is high in the neck and shoulder regions, varying from 30%-73% \(^1-3\), and this prevalence corresponds to three-fold the prevalence of the general population \(^4\). One of the protective factors for shoulder pain is improved shoulder strength balance \(^5,6\), indicating a role for strength training implementation \(^7\).

Muscle strength also plays an important role in individuals with spinal cord injury (SCI), due to a direct influence on functional capacity, daily activities and quality of life \(^7,8\). Sufficient strength in the upper body is especially important in sports active wheelchair users as it impacts their performance \(^9\), with the group of tetraplegics facing high functional demands due to severe muscle weakness. Tetraplegic individuals are mostly reported to have reduced muscle strength and muscle imbalance in external rotation (ER) relative to internal rotation (IR) strength \(^10,11\).

However, research is limited on feasible and valid methods for strength measurements in tetraplegics. Establishment of valid strength measurements for this group may form the basis for unravelling detailed relationships between muscle weakness and shoulder pain in tetraplegics, besides be important outcomes in clinical efficacy trials.

For strength measurements isokinetic dynamometer (ID) is considered the ‘gold’ standard \(^12\). However, this method has limited feasibility in clinical and sports settings, besides being expensive, time consuming, and difficult to access for wheelchair users \(^13,14\). Therefore, isometric handheld dynamometer (HHD) has been suggested as alternative, also for SCI-populations \(^14\).

Unfortunately, relatively poor relationship between isometric HHD and ID in shoulder rotation strength has been reported for tetraplegics, especially in lying positions, where tetraplegics have limited possibilities for stabilization \(^14\). Therefore, further development of feasible and valid
protocols for isometric HHD compared with ID for tetraplegics are needed in a more functional position, e.g. upright sitting. Therefore, the aims of this study were to develop a feasible protocol for testing maximum shoulder rotation strength in tetraplegic wheelchair athletes, and investigate concurrent validity of isometric handheld dynamometer (HHD); secondly, to study the amount of shoulder muscle activation during maximum shoulder rotation strength measurement, and the associations between shoulder strength and pain.

Methods

Participants

Tetraplegic WheelChair Rugby (WCR) athletes were recruited consecutively from XXX WCR-clubs in the period from January 2017 to February 2017. An information letter was distributed electronically through the national XXX WCR association to all registered WCR-clubs in XXX, followed by eligibility screening by telephone. Eligible participants were tetraplegic WCR-athletes, aged 18-65 years, ability to speak and read XXX. Exclusion criteria were resting shoulder pain exceeding eight of ten (Numeric Pain Rating Scale), inability to abduct the arms above 90°, shoulder surgery or luxation within the past three months, diagnosed fracture, symptomatic labrum lesion, glenohumeral and acromioclavicular osteoarthritis, besides serious comorbidity (e.g. cancer, rheumatic arthritis, fibromyalgia and psychiatric diagnoses).

Demographic data included sex, age, body mass and height, cause of injury, time since injury, level and completeness of lesion, International Wheelchair Rugby Federation (IWRF)-
classification (0.5-3.0 with 0.5 being the most impaired), duration of WCR-participation and weekly time spent on WCR and other training.

The Regional Committees on Health Research Ethics for Southern XXX decided this study did not require ethics approval (journal number S-20162000-90). Prior to testing, written informed consent and oral acceptance was obtained from each participant. The study was approved by the XXX Data Protection Agency (journal number 2015-57-0008).

Procedure
Initially, selfreported demographic data and questionnaires on pain were obtained. Participants were all athletes playing Wheel-Chair Rugby (WCR), and therefore data from classification of function during WCR playing were added. Based on self-reported information, level of injury was registered. Afterwards, two pairs of surface Electromyography (sEMG) electrodes were placed, on the external and internal rotators (mm Infraspinatus (IS), Latissimus Dorsi (LD)), and maximum voluntary isometric contractions were performed in ER and IR. Further, bilateral isometric (HHD) and isokinetic (ID) shoulder rotation strength measurements were performed with simultaneous registrations of shoulder muscle activity. Finally, self-reported physical activity during leisure time was registered in a questionnaire. Total duration of each test session was 120 min per participant, and test sessions were performed at the Department of Sports Science and Clinical Biomechanics, University of XXX.

Assessments

Questionnaires
In Wheelchair User’s Shoulder Pain Index (WUSPI) participants rated pain intensity on a visual analogue scale (VAS, no pain=0 and worst imaginable pain=10) for each activity in WUSPI, a 15-item questionnaire providing information on pain intensity within the past week during transfers, wheelchair mobility and activity of a daily living. The total score is 150 (150=worst pain). A performance corrected score (WUSPI-PC) was calculated (the total WUSPI score divided by number of activities performed, multiplied by 15).

Participants with inadequate hand function for filling out the questionnaires were allowed assistance from a helper outside the study.

Leisure Time Physical Activity Questionnaire for People With Spinal Cord Injury (LTPAQ-SCI), a self-reported questionnaire, was used to assess time spent on leisure time physical activity (LTPA) of mild, moderate, and heavy intensity. Participants rated number of days with LTPA during the past week at each intensity, and number of minutes spent at each intensity. Number of days and minutes were multiplied yielding the total LTPAQ-score.

Current shoulder pain was rated on Visual Analogue Scale (VAS) before and after testing with isometric HHD and ID. VAS is considered valid and reliable.

Muscle activity

Surface EMG (sEMG) was used to measure muscle activity unilaterally, on primarily the most painful shoulder, secondly the dominant arm during isometric HHD and ID testing. Bipolar electrodes (Ambu Blue Sensor N Ref: N-00-S) were placed on m Infraspinatus (IS) and m Latissimus Dorsi (LD). Electrodes were placed in line with the muscle fibre direction with an inter-electrode centre-to-centre distance of 20 mm. On IS the electrode was positioned 4 cm below spina scapula at the lateral part just above the infrascapula fossa. On LD the electrode was
positioned 1 cm laterally and 4 cm caudally of the lateral and inferior angulus scapularis. Before the electrodes were attached, the skin was shaved, rubbed and cleaned with alcohol to ensure an inter-electrode resistance <10 KOhm \(^{19}\).

The maximum voluntary electrical activation (MVE) during an isometric maximum voluntary contraction was used for sEMG normalisation during strength tests, and performed during sitting for IS and LD. Participants were sitting in the wheelchair and instructed to keep a firm grip around the chair handle with the opposite arm not being measured. For MVE of IS the participants had neutral shoulder position, while for MVE of LD the shoulder was in 90° abduction. For MVE of both IS and LD the elbow was flexed in 90°, and manual resistance was applied to the outer respectively inner side of the participants wrist during ER and IR \(^{20,21}\).

The participants were instructed to perform the test with a slow force increase, maintain a maximum contraction for five seconds, followed by a slow force decrease. MVE was repeated three times, and between each contraction participants had 30 s of rest. Familiarization was performed before each MVE, and resting sEMG activity was measured before each test during 20 s of rest \(^{22}\).

**Strength**

Following a standardized protocol, bilateral maximum shoulder strength was assessed by isometric HHD and ID with 20 min of rest between each test session. In case of a unilateral painful shoulder, this shoulder was tested first, while in all other cases, the dominant shoulder was tested first. Participants were encouraged verbally to exert maximum strength, and neither tester nor participants were allowed to have visual feedback of the performance during testing. Preceding the strength testing a systematic warm-up session of the shoulder was performed.
Bilateral maximum isometric strength in shoulder IR and ER was measured using isometric HHD (Commander Echo® Muscle Testing Dynamometer, JTECH Medical Industries Inc., Utah, USA). The isometric make-test was preferred to the eccentric break-test as it requires least experience from the examiner and has satisfactory reliability. The tester (male, 80 kg) was placed with his back against the wall for support, and the participant was sitting with the wheelchair side towards the tester for IR and ER measurements, to perform manual resistance perpendicular to the line of action. Isometric HHD with a curved pad was placed 2 cm proximal to the processus styloidei ulnae on the ventral or dorsal antebrachium for measuring IR and ER, respectively. ER was tested before IR. Participants upper arm was placed in 30° glenohumeral abduction (scapular plane), with a bolster under the arm (figure 1a), as this allowed for generating maximum strength without excessive stress on the supraspinatus tendon. Stabilisation of the trunk was provided by the participant placing her/his own opposite arm on the wheelchair side. Trials were rejected if the elbow joint was not maintained in 90°. Participants were familiarized with the position and procedure before testing. Four repetitions (each lasting five seconds) of maximum isometric contractions were performed as a ‘make-test’, where resistance was gradually increased to maximum (during 2 s), holding the strength (5 s) without ‘breaking’ the participants strength, including at least 30 s of rest between trials.

Bilateral maximum isokinetic strength in shoulder ER and IR was measured using Cybex Norm dynamometer (Cybex, division of Lumex Inc., Ronkonkoma, New York, USA). Torque calibration and gravity correction were performed before each test according to the Cybex manual. Participants were transferred from wheelchairs to the Cybex chair using a custom-built ramp. The Cybex chair was rotated 35° with the back seat angle in 85° (figure 1b), while all
other adjustments were fitted individually to secure the optimum alignment between the axis of
the power head and the axis of shoulder rotation. The shoulder was abducted 45° in the
scapular plane with the elbow flexed in 90°, to mimic the position with previously reported high
reliability for IR and ER strength assessments. Due to impaired wrist function in tetraplegics,
the involved hand was fixed to the lever arms handle with a special glove (Active Hands, The
Active Hands Company, Solihull, UK). To stabilise the trunk, the contralateral hand was fixed to
a handle at seat height, and straps were placed around the waist, trunk and shoulders. The
angular velocity was 60°/s, assuming that 60°/s relates mostly to maximum voluntary contraction
for comparison with maximum isometric strength. Three trial repetitions were performed for
all directions for familiarization before data collection. Five maximum repetitions were
performed, alternating concentric IR and concentric ER with 20 s rest between repetitions, in
100° ROM.

Data analysis

For all isometric HHD contractions peak torque was defined as the maximum torque measured
over the last three repetitions out of four, using the JTECH software. For all ID movements peak
force was the maximum force of the middle three repetitions out of five, using the Cybex
software. Data were reported as peak torque values, where the force in kg was converted to
Newton, multiplied by the lever arm in meters (from olecranon to processus styloideus ulnae)
All peak torque values were normalised to body mass (Nm/kg) to allow comparison of
shoulder torque between participants of different size and sex across studies. In addition, ratios
between IR and ER peak torque were calculated.
sEMG signals were recorded with 4-channel system (Myon 320 EMG System - Myon AG, Switzerland) with preamplifier (gain factor 1000). The raw sEMG signals were filtered (high pass at 5 Hz and low pass at 500Hz). The amplified sEMG was analog to digital converted into a computer using a NI-USB 6210, 16 bit A/D converter, with a sampling rate of 1000 Hz (National Instruments Corporation, USA). Data were analysed with customised software (Hedera; University of XXX). All sEMG data were reported as Root Mean Square (RMS) in %MVE, and for MVE, the mean root-mean-square (RMS) values were calculated as a moving window of 100 ms in steps of 20 ms with an average of 1 s. The contraction with the highest muscle activity (μV) was selected for each muscle as representative of MVE. Resting sEMG was subtracted from the raw sEMG signal of each muscle.

For sEMG measurements during strength testing, the mean RMS values were calculated in 100 ms segments. For each participant, muscle activity was calculated relative to MVE (%MVE) of each muscle during ER (IS) and IR (LD), for each of the two strength tests (HHD, ID), and data was expressed as total mean value for each strength test. SEMG analyses during isometric tests were performed on the middle 1500 ms of the total test time of 5 s. SEMG analysis during isokinetic tests began 100 ms after movement start and ended 100 ms before movement stop, as estimated from the position indicator in the Hedera software.

Furthermore, co-activation ratios of two opposite working muscles were calculated (i.e. IS/LD during ER, and LD/IS during IR). Low co-activation ratio represents high co-activation, high co-activation ratio represents low co-activation.

Statistics
For demographics descriptive statistics were used for the total group, with percentage for
dichotomous data, and for non-normally distributed data (EMG) with medians (25, 75
percentiles), and with means (SDs) for comparison across studies.

Concurrent validity between isometric HHD and ID was assessed by the concordance correlation
coefficient (CCC) with 95% confidence intervals (95% CI), and CCC point estimates ≥ 0.70
were interpreted as satisfactory. To describe the agreement between isometric HHD and ID
graphically, Bland Altman plots with 95% limits of agreement (LOA) were presented 32.

Wilcoxon signed rank test was used to test for differences between isometric HHD and ID in
muscle activity (%MVE), and co-activation ratios. Linear regression was used to test for
associations between strength (ID, HHD) and pain (WUSPI-PC score), with strength as
dependent variable and pain as independent variable. As the current study was not a between
subjects design, a formal sample size calculation was decided not to be relevant to perform.

All statistical analyses were conducted using IBM statistics SPSS® (v24, IBM Corp, Armonk,
NY, USA) with a significance level of P<0.05.

Results

A total of twelve tetraplegic WCR-athletes, 11 males, aged 40.8 (10.9), most participants (n=7)
were in the C6-7 range.

participated in the study (table 1). Seventy-five percent of the participants reported some
shoulder pain during activity the past week, with a mean WUSPI-PC score of 17.8 (18.9). Two
participants were excluded from the analyses of ER strength, due to these participants’ lack of
power to perform ER strength with ID. Generally, IR displayed higher mean peak torque values
than ER, and isometric HHD produced higher mean peak torque values compared with ID (table 2).

Normalised torque in ER and IR, left or right, (figure 2a-2d) displayed no systematic bias in Bland Altman plots. Concurrent validity of isometric HHD compared with ID was high for normalized peak torque (Nm/kg), with CCC values between 0.86 (95% CI: 0.72; 0.97) and 0.91 (95% CI: 0.77; 0.97) (table 3).

Relative muscle activity showed no significant difference between isometric HHD and ID, except for larger activity in ID for IS during ER compared with isometric HHD (median difference: -17.35 %MVE; 25, 75 perc: -24.91, 2.26; P=0.047), not shown in table. Also, larger co-activation ratio was seen in ID for IS/LD during ER (median difference -0.58 %MVE; 25, 75 perc: -2.30, -0.34; P=0.028), not shown in table, meaning less muscle co-activation in ID than in isometric HHD (table 4).

There was no significant association between isometric peak torque shoulder strength (HHD, ID) and shoulder pain, except for significantly negative associations between ID and pain (WUSPI-PC) during ER for left and right arm (β= -0.008, P=0.036; β= -0.007, P=0.029), respectively (figure 3a-b). Although six of eight investigated associations were non-significant, the corresponding R² values showed that 15.3 - 46.7% of the variation in strength was explained by the model containing only shoulder pain.

**Discussion**

A standardized and feasible protocol for tetraplegic wheelchair athletes for measuring shoulder rotation strength was established. Concurrent validity of isometric HHD compared with ID was
satisfactory on point estimates for normalised peak torques, with indications of higher co-
activation in isometric HHD than in ID during ER. No clear association was seen between
shoulder rotation strength and shoulder pain, except for a negative association between ID and
pain in ER.

The hypothesis that isometric HHD strength would display satisfactory concurrent validity with
ID at 60°/s was confirmed. Assuming that both instruments are reliable, and ID is the gold
standard in measuring shoulder rotation strength in tetraplegics 12, isometric HHD consistently
overestimated shoulder strength compared with ID. Thereby the current results are in line with
previous results showing that maximum static strength is higher than maximum concentric
strength 33.

However, ID may not be the ideal reference standard in testing shoulder rotation strength in
tetraplegics due to insufficient stabilisation 14, which makes it hard to determine whether ID
represents the accurate value of torque. In order to use the two methods interchangeably, the
clinician/tester must decide whether the present LOA is acceptable for a clinical/sports setting. In
favour of isometric HHD is that it is feasible to measure shoulder strength, due to portability, ease of
use and lower cost than ID, besides a satisfactory concurrent validity towards ID. Therefore,
isometric HHD can be recommended in clinical and sports settings.

The subtle differences between isometric HHD and ID indicate that the isometric contraction mode
of isometric HHD relates successfully to isokinetic testing at 60°/s. No previous study has
investigated concurrent validity of isometric HHD using the make-test compared with ID in
measurements of shoulder rotation strength in tetraplegics. The present study found a stronger
agreement between isometric HHD and ID than previously reported \(^{14}\), possibly due to different test protocols for isometric HHD and ID at 60°/s. Due to previous challenges with trunk stabilization of tetraplegics in lying positions, the current standardized test procedures focused on increasing trunk stabilization in several ways: selection of the sitting position, placement of the opposite hand on the wheelchair side during isometric HHD tests; and during ID tests, placement of straps around the waist, trunk and shoulders, in addition to fixation of the contralateral hand to a handle at seat height. Test-retest reliability of tetraplegics during these test procedures, is, however, still unknown. The current results support the previous recommendation that isometric HHD is most valid towards ID using the make-test in a gravity eliminated position \(^{27}\).

The hypothesis that isometric HHD would display similar muscle activity as in ID at 60°/s however, with larger muscle activity in isometric HHD, was mostly confirmed with no difference in muscle activity between the two strength measures (except for larger activity in ID for IS during ER). For the current population of tetraplegics a higher co-activation was generally anticipated due to the limited muscle function of this group \(^{9}\). The high co-activation during isometric HHD implies that although the two types of strength measurements are highly correlated, the underlying activation properties may be different. The hypothesis that participants with highest shoulder pain intensity would display the lowest shoulder strength, was not confirmed. Only for ER the significant negative influence of pain on ID strength was found (for both left and right shoulder). The mechanism contributing to the association between shoulder strength and pain has been suggested to be pain acting as an inhibitor of shoulder muscle strength, as previously measured in individuals with impingement.
syndrome. The reason may be that the presence of shoulder pain may cause participants to constrain their maximum effort to avoid pain, thereby reducing their peak torque. A reversed causality with weakness of rotator cuff muscles leading to shoulder pain due to secondary impingement in SCI-populations has also been reported. Importantly though, increased shoulder muscle strength has been suggested to be a protective factor in the development of shoulder pain in wheelchair users and in tetraplegics.

One of the reasons for the current lack of pain-strength association may be that the current mean WUSPI-PC (pain) score was very low, and lower (less pain) than previously reported for tetraplegics. This may be due to the current larger amount of physically active participants. Another explanation for the lacking association may be that the current participants were generally stronger in IR than in ER, with mean IR/ER-ratios of 1.3-1.5, suggesting a normal shoulder muscle balance and dynamic stability. The current mean IR/ER-ratios of tetraplegic WCR-athletes are in line with previous studies of elite tetraplegic WCR-athletes of 1.45, and higher than those of active athletes of 1.23 and sedentary tetraplegics of 0.99.

The current contraction mode of 60°/s was selected as it was anticipated to be more functional, besides being closer related to the isometric mode. Overall the current results are in line with a previous study reporting no association between isokinetic strength at 60°/s and shoulder pain. A limitation of the present study is the convenience sampling method and the small sample, limiting generalisability. Considering the exploratory nature of the study and the limited studies on this area, power calculations were not performed. Another limitation may be the wide range of injury level. However, this wide range was selected on purpose, in order to develop a feasible protocol for
tetraplegic athletes with varying impairments, as seen among rugby players. Despite the small
sample size, the wide range of impairment levels is assumed to increase the study generalizability.

Strengths are the standardised test procedures and the objective reliable and valid measurement
instruments used\textsuperscript{11,14,17,23,42}. In addition, for each of the two strength assessment methods, all
tests were conducted by the same examiner thus limiting the risk of inter-examiner bias.

**Conclusion**

A standardized and feasible protocol for tetraplegic wheelchair athletes for measuring shoulder
rotation strength was established. Concurrent validity of isometric HHD towards ID was satisfactory
in normalised peak torques. Relative muscle activity in isometric HHD was not different from ID
during maximum shoulder rotation, but higher co-activation in isometric HHD during ER was
indicated. There was no clear association between shoulder rotation strength and shoulder pain.
Measurement of shoulder rotation strength using isometric HHD is found to be feasible and valid in
tetraplegics and can be used in clinical and sports settings. Further research on test-retest reliability
of the current test procedures for isometric HHD is recommended.

**ACKNOWLEDGEMENT**

We thank all participating tetraplegic WCR-athletes from the WCR-clubs for being willing to be
included in the study, and the national WCR association for helping with recruitment.
DECLARATION OF INTERESTS

The authors have no conflicts of interest.

FUNDING

This work was funded by grants from the Danish Society of Polio and Accident Victims, the Danish Physiotherapy Research Foundation, the Jascha Foundation and the Vanføre Foundation.

References

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Table 1: Characteristics of study participants ((frequency, percentage, mean and standard deviation (SD)).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Athletes with tetraplegia (n=12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex [male], n (%)</td>
<td>11 (91.7)</td>
</tr>
<tr>
<td>Age [years]</td>
<td>40.8 (10.9)</td>
</tr>
<tr>
<td>Body mass [kg]</td>
<td>69.9 (15.6)</td>
</tr>
<tr>
<td>Height [cm]</td>
<td>178 (12)</td>
</tr>
<tr>
<td>BMI [kg/m²]</td>
<td>22 (3.4)</td>
</tr>
<tr>
<td>Time since injury [years]</td>
<td>22.3 (9.2)</td>
</tr>
<tr>
<td>Level of injury, n (%)</td>
<td></td>
</tr>
<tr>
<td>C4-C5</td>
<td>1 (8.3)</td>
</tr>
<tr>
<td>C5</td>
<td>2 (16.7)</td>
</tr>
<tr>
<td>C5-C6</td>
<td>1 (8.3)</td>
</tr>
<tr>
<td>C6-C7</td>
<td>7 (58.3)</td>
</tr>
<tr>
<td>&gt; C7</td>
<td>1 (8.3)</td>
</tr>
<tr>
<td>Complete lesion, n (%)</td>
<td>8 (66.7)</td>
</tr>
<tr>
<td>WCR-participation [years]</td>
<td>12.3 (7.7)</td>
</tr>
<tr>
<td>WCR/week [hrs/week]</td>
<td>2.5 (1.3)</td>
</tr>
<tr>
<td>Other training [hrs/week]</td>
<td>3.7 (2.8)</td>
</tr>
<tr>
<td>IWRF classification, n (%)</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>5 (41.6)</td>
</tr>
<tr>
<td>1</td>
<td>2 (16.7)</td>
</tr>
<tr>
<td>2</td>
<td>3 (25)</td>
</tr>
<tr>
<td>3</td>
<td>2 (16.7)</td>
</tr>
<tr>
<td>VAS-pain [mm] (range 0-100)</td>
<td></td>
</tr>
<tr>
<td>- Baseline</td>
<td>5.3 (9.8)</td>
</tr>
<tr>
<td>- Post HHD</td>
<td>8.5 (9.2)</td>
</tr>
<tr>
<td>- Post ID</td>
<td>7.17 (6.3)</td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>WUSPI-PC score (range 0-150)</td>
<td>17.8 (18.9)</td>
</tr>
<tr>
<td>LTPAQ-SCI, total [min/week]</td>
<td>1294 (1215)</td>
</tr>
<tr>
<td>Light</td>
<td>868 (1125)</td>
</tr>
<tr>
<td>Moderate</td>
<td>184 (137)</td>
</tr>
<tr>
<td>Hard</td>
<td>241 (117)</td>
</tr>
</tbody>
</table>
Table 2: Peak shoulder torques (mean (SD)) for left and right arm during internal and external shoulder rotation strength, measured with isometric Hand-Held Dynamometer and Isokinetic Dynamometer at 60°/s.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Left shoulder (n=12)</th>
<th>Right shoulder (n=12)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal rotation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Nm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HHD</td>
<td>41.0 (21.6)</td>
<td>44.3 (16.4)</td>
</tr>
<tr>
<td>ID 60°/s</td>
<td>37.7 (15.4)</td>
<td>35.3 (13.8)</td>
</tr>
</tbody>
</table>

| [Nm/kg]           |                      |                       |
| HHD               | 0.62 (0.38)          | 0.67 (0.31)           |
| ID 60°/s          | 0.58 (0.32)          | 0.53 (0.26)           |

| External rotation |                      |                       |
| [Nm]              |                      |                       |
| HHD               | 29.8 (12.7)          | 29.1 (12.0)           |
| ID 60°/s          | 27.4 (10.0)          | 27.3 (9.2)            |

| [Nm/kg]           |                      |                       |
| HHD               | 0.44 (0.22)          | 0.44 (0.22)           |
| ID 60°/s          | 0.41 (0.24)          | 0.40 (0.20)           |

| IR/ER ratio       |                      |                       |
| HHD               | 1.33 (0.29)          | 1.69 (0.75)           |
| ID 60°/s          | 1.50 (0.30)          | 1.38 (0.23)           |

IR: Internal Rotation, ER: External Rotation, Nm: Absolute torque, Nm/kg: Normalized torque to bodyweight, HHD: Hand-held dynamometer (isometric), ID: isokinetic dynamometer. a denotes n=10.
Table 3: Concurrent validity of Isometric Hand-Held Dynamometer compared with Isokinetic Dynamometer measurements.

<table>
<thead>
<tr>
<th>Normalised peak torque [Nm/kg]</th>
<th>CCC (95% CI)</th>
<th>Mean difference (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal rotation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR HHD – ID [60°/s], L</td>
<td>0.90 (0.72; 0.97)</td>
<td>0.04 (-0.26; 0.34)</td>
</tr>
<tr>
<td>IR HHD – ID [60°/s], R</td>
<td>0.86 (0.68; 0.94)</td>
<td>0.13 (-0.02; 0.29)</td>
</tr>
<tr>
<td><strong>External rotation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER HHD – ID [60°/s], L</td>
<td>0.89 (0.66; 0.97)</td>
<td>0.10 (-0.11; 0.3)</td>
</tr>
<tr>
<td>ER HHD – ID [60°/s], R</td>
<td>0.91 (0.77; 0.97)</td>
<td>0.07 (-0.01; 0.16)</td>
</tr>
</tbody>
</table>

Table 4. Muscle activity (%MVE, ratio of %MVE), presented as median (25th and 75th percentiles), and mean (SD), for internal and external rotation during isometric Hand-Held Dynamometer and Isokinetic Dynamometer.

<table>
<thead>
<tr>
<th></th>
<th>Isometric Hand-Held</th>
<th>Isokinetic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dynamometry</td>
<td>Dynamometry</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td></td>
<td>(25; 75 percentile)</td>
<td>(25; 75 percentile)</td>
</tr>
<tr>
<td>Internal rotation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LD</td>
<td>24.84 (19.08; 38.16)</td>
<td>29.34 (17.34)</td>
</tr>
<tr>
<td></td>
<td>30.74 (18.47; 37.05)</td>
<td>29.28 (10.84)</td>
</tr>
<tr>
<td>LD/IS-ratio</td>
<td>1.81 (1.23; 2.82)</td>
<td>2.04 (1.06)</td>
</tr>
<tr>
<td></td>
<td>2.17 (1.54; 2.65)</td>
<td>2.11 (0.86)</td>
</tr>
<tr>
<td>External rotation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IS</td>
<td>49.90 (34.35; 58.02)</td>
<td>46.93 (17.45)</td>
</tr>
<tr>
<td></td>
<td>57.78 (50.33; 69.40)</td>
<td>60.98 (17.96)</td>
</tr>
<tr>
<td>IS/LD-ratio</td>
<td>1.38 (1.17; 2.14)</td>
<td>1.96 (1.45)</td>
</tr>
<tr>
<td></td>
<td>1.86 (1.54; 4.05)</td>
<td>3.23 (3.12)</td>
</tr>
</tbody>
</table>

MVE: Maximum voluntary EMG, SD: Standard Deviation, LD: Latissimus Dorsi, IS: Infraspinatus.
**LEGEND to Figures.**

**Figure 1.** Test set-up demonstrating strength measurement with isometric Hand-Held Dynamometer, the participants stabilized their trunk with their opposite hand on the wheelchair side (a), and with isokinetic Dynamometer (ID), the trunk was stabilized using seatbelts/straps and fixation of the contralateral hand to a handle at seat height (b).

**Figure 2.** Bland-Altman plots of concurrent validity between isometric Hand-Held Dynamometer (HHD) and isokinetic dynamometer (ID) at 60°/s in normalized torque (Nm), (a) for left arm external rotation, (b) left arm internal rotation, (c) right arm external rotation, and (d) right arm internal rotation. Instrument differences are displayed at the Y-axis, and the mean of instruments at the X-axis with 95% Limits of Agreement. The black line (y = 0.0) is the perfect mean difference, the green (broken) line is the observed mean difference.

**Figure 3.** Association between measurements of strength and pain for (a) isometric Hand-Held dynamometry (HHD) strength, peak torque (Nm/kg), for Left (L), Right (R), External Rotation (ER), Internal Rotation (IR) and Pain with Wheelchair Users Pain Index, Performance Corrected (WUSPI-PC), and (b) with Isokinetic Dynamometry (ID) strength, peak torque (Nm/kg), for Left (L), Right (R), External Rotation (ER), Internal Rotation (IR) and Pain (WUSPI-PC).
Figure 2a

Figure 2b

Figure 2c

Figure 2d
Figure 3a

Figure 3b