| Author Year<br>Country<br>Research Design<br>Score<br>Total Sample Size | Methods | Outcome |
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| Qi et al. 2019<br>China<br>RCT Crossover<br>PEDro=6<br>N=11 | **Population:** Mean age: 42.1 yr; Gender: males=8, females=3; Injury Etiology: SCI=9, Spina Bifida=2; Level of injury range (SCI AIS): T6-T12; Mean time since injury: 10.4 yr.<br>**Intervention:** Participants performed a set of 3-min propulsion bouts at three different speeds: 1m/s (minimal safe speed to cross an intersection with traffic lights), 1.3m/s (equivalent to able-bodied walking speed), 1.6m/s. The order of the exercise bouts were randomized, with a 5min rest period between bouts.<br><br>**Outcome Measures:** EMG Measures: anterior deltoid (AD), middle deltoid (MD), posterior deltoid (PD), infraspinatus (IS), upper trapezius (UT), sternal head of the pectoralis major (PM), biceps brachii (BB), and triceps brachii (TB); Kinetics: peak resultant force ($F_{tot}$), push frequency, push length; Energy expenditure (W); Heart rate (HR). Principal component analysis (PCA) to identify the impact of propulsion speed on shoulder muscle coordination. | 1. Propulsion at 1.6m/s generated significantly higher EMG intensity in BB, AD, PM, and MD muscles than propulsion at 1m/s (p<0.05).<br>2. Propulsion at 1.6m/s required significantly higher energy expenditure than at 1m/s (p<0.05).<br>3. No significant differences were found in peak resultant force, push frequency, and push length between propulsion speeds.<br>4. No significant difference in the average HR betweenpropulsion speeds, though HR showed an upward trend with increasing speed.<br>5. Relative increase in BB, AD, PM, and IS activity in the early push phase and more activity in MD and PD during the late recovery phase.<br>6. The transition between push and recovery phase at higher speeds is maked by increased activity of UT, MD, PD (recovery muscles) and AD and BB (propulsive muscles). |
| Cloud et al. 2017<br>USA<br>RCT Crossover<br>PEDro=6<br><br>N=21 | **Population:** Mean age= 42 yr; Gender: males=16, females=5; Level of injury range: C6-L2.<br>**Intervention:** Participants' manual wheelchairs (MWC) were modified to have seat dump angles of either 0° or 14°. Seating condition order was randomly assigned. Participants then completed 3 propulsion cycles in each condition to measure spine and shoulder motion data.<br><br>**Outcome Measures:** Thoracolumar spinal curvature, glenohumeral kinematics, scapulothoracic kinematics: at start push (SP), midpush (MP), end of push (EP), mid recovery (MR). | 1. Participants had significantly less lordosis in the 14° condition for all propulsion events (p<0.05).<br>2. Scapulothoracic internal rotation was increased in the 14° condition at SP and MP (mean differences of 2.5° and 2.7°, respectively).<br>3. Relative downward rotation increased in the 14° condition at SP and MP (mean differences of 2.4° and 2.1°, respectively).<br>4. No glenohumeral rotations were significantly different between the conditions.<br>5. Lordosis differences were more pronounced in those with low SCI. Scapulothoracic differences were more pronounced in those with high SCI. |
| Gil-Agudo 2014<br>Spain<br>RCT<br>PEDro=6<br>N=14 | **Population:** Mean age: 35.2 yr; Gender: males=14, females=0; Mean time since injury: 90.2 mo.<br><br>**Intervention:** Participants used a study wheelchair on a treadmill, with the propulsion power output monitored. | 1. In high intensity test, significant differences were found between early and late propulsion for all parameters analyzed (except adduction and abduction shoulder peak moments) (p<0.05). |

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| | Ultrasound screening was completed on the non-dominant shoulder before testing and immediately after each test protocol. Test protocols were completed with at least 48hr between them to ensure full recovery, Protocols were randomly assigned; one protocol was propulsion at high intensity with an incremental workload (start at 20W, increased by 5 W every 2 min until fatigue), the second protocol was propulsion at low intensity with constant workload (20W for maximum of 20 min).<br>**Outcome Measures:** Shoulder joint kinetics measured using ultrasound screening technology; shoulder kinematics measured on the non-dominant side using four camcorders and passive markers placed at C7, left and right acromioclavicular joints the hand, forearm and arm, and the wheel hub. power output measured using the SMART$^{Wheels}$; Borg scale for fatigue. | 2. Increases in medial peak shoulder force were correlated with increases in long-axis biceps tendon thickness (LBTT) ($p<0.05$) and with decreases in sub-acromial space ($p<0.05$).<br>3. Increments in biomechanical were higher in high intensity propulsion for all parameters ($p<0.05$) except lateral peak force ($p=0.19$) and peak adduction and abduction moments ($p=0.06$).<br>4. No differences were found in ultrasound screening before and after each test protocol; effective mechanical force was similar in both protocols but increases in the forces and moments was greater in the high intensity protocol. |
| Julien et al. 2014<br>USA<br>RCT Crossover<br>PEDro=6<br>N=7 | **Population:** Mean age: NR; Gender: males=5, females=2; Tetraplegia=7 (C5-7); AIS A=3, AIS B=2, AIS C=1, AIS D=1; Mean w/c use: 3.3 yrs.<br>**Intervention:** Participants' normal speed of propulsion was established, with fast speed calculated as 20% above normal and slow speed as 20% below normal. Each participant was randomly asked to propel down a long hallway (smooth level surface) at one of the three different speeds for 10 sec. Three trials were done for each speed.<br>**Outcome Measures:** A six-camera video motion capture system with reflective markers at vertex, left and right zygomatic process, left and right clavicle, sternum, C4, T4, T7 spinous processes and 3rd metacarpals, both w/c axles, and top of front caster barrels. Wireless speedometer. Measurements were of trunk motion relative to the w/c and neck motion relative to the trunk. Variables investigated included trunk flexion, lateral flexion and axial rotation, and neck flexion, lateral flexion and axial rotation. Movement were compared to propulsion cycle – push, recovery and total. | 1. At all phases of the push cycle, no identifiable pattern was evident for lateral flexion or axial rotation for either the trunk or neck.<br>2. Participants fell into 1 of 2 groups; those who had substantial trunk and head movement regardless of speed of propulsion and those who had less movement in slow speeds but increasing movement with increasing speed.<br>3. Some participants changed their stroke pattern with different speeds.<br>4. Neck and trunk flexion significantly increased for all participants as speed increased ($p=0.034$ total push, $p=0.031$ for push phase).<br>5. Forward flexion at the trunk or neck did not significantly increase during the recovery phase.<br>6. Significant difference between slow and fast speed for neck flexion ($p=0.018$) and trunk flexion ($p=0.016$) with large effect size during the total propulsion ($r=0.6$, $r=0.6$) and push phase ($r=0.5$, $r=0.6$).<br>7. Forward trunk flexion was significantly greater at fast |

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| | | speeds compared to slow speeds during the total propulsion cycle (slow=11.7±3.0°, fast=16.4±3.8, p<0.05) and during the push phase (slow=9.9±2.7°, fast=14.2±3.3°, p<0.05). |
| Triolo et al. 2013<br>USA<br>RCT Crossover<br>PEDro=4<br>N=6 | **Population:** Mean age:46.2 yr; Gender: males=4, females=2; Level of severity: AIS A=3, AIS B=2, AIS C=1; Injury level: C6-C7=2, T5-T10=4; Mean injury duration=8.6 yr.<br>**Intervention:** Participants received intramuscular electrode implantations at the L1-2 spinal nerves bilaterally to stimulate the lumbar erector muscles for trunk extension and intramuscular or epimysial stimulating electrodes to activate the gluteus maxmius muscles for hip extension. Participants propelled their own wheelchairs at a self-selected walking speed on a 10-m surface, a 100-m sprint, and a 30.5 m ramp (4.7% grade) incline. 20 trials of the self-selected speed condition were completed, 10 with stimulation, 10 without. A trial consisted of 3-6 steady state cycles (i.e., stroke that was not transitioning from start or stop). The sprint condition consisted of three trials of stimulation and three without. Incline condition consisted of three trials each with and without stimulation, randomly assigned.<br>**Outcome Measures:** Peak force, Peak shoulder movement, Fraction of electrical force (FEF), Average forward lean, Cadence, Stroke length, Usability rating scale (URS). Data gathered using SMARTwheel, vicon kinematic measures using reflective markers at key body points, Usability Rating scale. | 1. For the self-selected walking speed, four participants did not experience significant changes in average velocity for self-selected walking speed between stimulation and no stimulation conditions (p>0.113) while 2 varied by <10%; no changes in average power between stimulated and non-stimulation condition. Peak resultant force during the contact phase decreased significantly with stimulation in three of the five participants (p<0.014); the other two had zero percent change with stimulation.<br>2. Cadence and peak shoulder moment during stimulation increased significantly in two participants (p<0.021, p<0.001).<br>3. FEF and average forward lean increased significantly in the same three participants (p<0.048, p<0.001) during self-selected walking speed.<br>4. Stimulation had no significant effects on cadence, stroke length, average velocity, and peak resultant force in any of the six participants during the 100-m sprint (p>0.05) or during the incline (p>0.397).<br>5. In one participant, stimulation caused a significant decrease in FEF during the 100-m sprint (p=0.034).<br>6. Combined data across the participants indicated that stimulation significantly affected overall kinetics and kinematics (p<0.001, F=7.679); there were no significant differences between trials with and without stimulation for the 100m sprint or the incline.<br>7. Perceived effort as measured by the URS increased significantly post stimulation during the 100-m sprint (p<0.001). |

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| Goins et al. 2011<br>USA<br>RCT Crossover<br>PEDro=6<br>N=7 | **Population:** Mean age: 33.0 yr; Gender: males=5, females=2; Level of injury: C5=1, C5-6=1, C6=3, C6-7=1, C7=1; Severity of injury: AIS A=3, AIS B=2, AIS C=1, AIS D=1; Mean duration of manual w/c use: 11.1 yr.<br>**Intervention:** Describe the linear and angular movements because of speed during manual wheelchair over ground propulsion in individuals with tetraplegia. Three speeds in random order on two different surfaces (40m of tile and of low pile carpet) using participants' own w/cs.<br>**Outcome Measures:** Kinematic data collected using a video motion capture system: elbow translation in the anterior-posterior direction (cm), elbow translation in the medial-lateral direction (cm), elbow translation in the vertical direction (cm), and elbow angle. A wireless speedometer was used to capture speed. | 1. Right elbow anterior-posterior was significantly different during slow [26.7 (2.7)] and fast [31.3 (3.5)] and slow and normal [30.9 (2.6)] speeds.<br>2. Right elbow translation vertically was significantly different between slow [7.5 (3.3)] and fast [9.6 (5.4)] speeds.<br>3. Right elbow translation in the medial-lateral direction was significantly different between slow [13.1 (4.1)] and fast [14.7 (5.2)] speeds.<br>4. No effect for speed during left elbow translation.<br>5. No significant difference for elbow angle across speed.<br>6. There were no significant differences examining the effects of speed on side-to-side (right versus left) elbow symmetry. |
| Gil-Agudo et al. 2016<br>Spain<br>Prospective Controlled Trial<br>N=34 | **Population:** *Manual Wheelchair (MWC) Group:* Mean age= 35.5 yr; Gender: males=22, females=0; Level of injury range: T2-L3; Mean time since injury: 8.7 yr. *Healthy Control Group*: Mean age= 31.3 yr; Gender: males=12, females=0.<br>**Intervention:** Subjects performed high-intensity wheelchair propulsion test on a treadmill (TM) to compare shoulder joint forces and moments as well as ultrasound changes. TM speed was set to achieve 20W for all subjects, increases of 5W were added every 2min. The trial was completed until participants could no longer propel their wheelchair.<br><br>**Outcome Measures:** Shoulder pain: Visual Analog Scale (VAS), Wheelchair User's Shoulder Pain Index (WUSPI); Shoulder Joint Forces and Moments; and Shoulder Pathology via ultrasound examination: acromioclavicular distance (ACD): Cholewinski Index (CHI), Girometti Index (GI); long-axis biceps tendon thickness (LBTT); short-axis supraspinatus thickness (SST). | 1. High intensity propulsion results in greater shoulder forces and moments in almost all directions.<br>2. No relevant change in ultrasound parameters following TM test.<br>3. More shoulder pain according to the WUSPI or VAS was associated with a greater LBTT ($p<0.05$, respectively) for the MWC group.<br>4. Greater shoulder pain in the VAS was associated with a shorter ACD ($p<0.05$), and a larger SST ($p>0.05$).<br>5. A statistically significant between group difference was found in LBTT relative change ($p<0.05$).<br>6. The control group had a significant within group increase in GI ($p<0.01$). |
| Kim et al. 2015<br>Korea<br>Prospective Controlled Trial | **Population:** *Paraplegic group (n=8):* Mean age: 37.0 yr; Gender: males=8, females=0; Level of injury range: T1-T12. *Control group (n=8):* Mean age: 22.8 yr; Gender: males=8, females=0. | 1. There were no significant differences between the control and study groups in weight and height, ($p>0.05$) but the |

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| N=16 | **Intervention:** All participants propelled the wheelchair 200m three times at a comfortable speed on the ground. Electrodes were placed and recorded along different upper limb and neck muscles; Latissimus dorsi (LSD), Pectoralis major (PCM), Anterior/posterior deltoids (AD/PD), Triceps brachii (TRB), Extensor carpi radialis (ECR), and Sternocleidomastoid (SCM).<br>**Outcome Measures:** Muscle activity using surface electromyography during the push phase of the propulsion cycle. | difference in age was significant ($p<0.05$).<br>2. SCM activity was higher in the paraplegic group than the control group ($p<0.05$).<br>3. LSD activity was higher in the test group than the control group but was not significant ($p=0.07$).<br>4. There were no significant differences in any other muscle activities between groups ($p>0.05$). |
| Rodgers et al. 2000<br>USA<br>Prospective Controlled Trial<br>N=19 | **Population:** Mean age:44.0 yr; Gender: males=16, females=3; Injury etiology: SCI=17, spina bifida=1, bilateral tarsal tunnel syndrome=1; Level of injury range: T3-L5; Mean duration of w/c use: 16.8 yr.<br>**Intervention:** Participants propelled the study wheelchair at a velocity of 3 km/hr for 3min, then continued while load was added at a rate of 0.3 kg every 3 min until self-reported exhaustion was reached (i.e., unable to maintain target velocity) (GXT test). 2-7 days later participants completed the fatigue test where they rested for 6 min then propelled without a load for 3 min, and then continued propelling with the sub-maximal load (75% of peak VO2 from the GXT) until exhaustion reached. Participants were divided into two groups based on the angle of their trunk in upright sitting; if trunk was flexed more than 10° and/or those whose flexion increased more than 10° from fresh to fatigued states were in the flexion group (n=9). All others were in the non-flexion group (n=10). Wheelchair propulsion was completed in a study wheelchair and on an ergometer. Kinematics were recorded in participants during fresh and fatigued states.<br>**Outcome Measures:** Shoulder flexion and extension, Wrist flexion and extension, Elbow flexion and extension using a 3D cameras and video acquisition system, Force kinematics using a force/torque transducer in the wheel hub, Graded | 1. The only difference between the two study groups was concentric shoulder extension movement which was significantly greater in the non-flexion group than flexion group ($p<0.04$).<br>2. The flexion group demonstrated significantly greater shoulder flexion and elbow extension than the non-flexion group at contact ($p<0.006$, $p<0.013$ respectively) and release ($p<0.004$, $p<0.031$ respectively).<br>3. Joint kinetics revealed that the flexion group had significantly less posterior force ($p<0.022$) and significantly more medial force ($p<0.046$) at the elbow than the non-flexion group.<br>4. The flexion group demonstrated significantly earlier cessations of flexor carpi ulnaris ($p<0.001$) and pectoralis major ($p<0.031$) muscle activity.<br>5. Total biceps activity was significantly greater for the flexion group than the non-flexion group ($p<0.034$).<br>6. There were no significant differences between groups for resistance applied measured by the GXT, length of time in wheelchair, and $VO_2$ max during the fatigue test ($p>0.05$).<br>7. Both groups demonstrated significantly more shoulder flexion during contact ($p<0.047$) and at release ($p<0.018$), handrim force ($p<0.03$) when fatigued than in fresh state. |

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| | exercise test (GXT), $VO_2$ max, Muscle activity using EMG. | 8. Both groups demonstrated significantly less wrist flexion ($p<0.024$), radioulnar shear force ($p<0.022$), peak amplitude of biceps ($p<0.006$), pectoralis major muscles ($p<0.025$), earlier onset ($p<0.02$), and peak activity of triceps ($p<0.01$).<br>9. Trunk flexion increased 7-10% for the FG group when fatigued; shoulder flexion increased by 6% when fatigued for the FG group but not the NFG group. |
| Jayaraman et al. 2015<br>USA<br>Cohort<br>N=22 | **Population:** *Shoulder Pain (SP, n=10):* Mean age: 25.8 yr. *No Shoulder Pain (NP, n=12)*: Mean age: 22.0 yr; Injury etiology: SCI=13, spina bifida=5, spinal cyst=1, amputee=2.<br>**Intervention:** Participants propelled their own manual wheelchairs fitted bilaterally with SMARTwheels on a roller dynamometer for 3 min at a pace of 1.1 m/s. Data was collected during propulsion (push phase and recovery phase) after participants had a chance to acclimatize to the dynamometer.<br>**Outcome Measures:** Kinematic data was collected using a 10-camera motion analysis system, with 18 markers on body and wheelchair. Kinetic data was collected using the SMARTwheel. Data collected included: peak force, push time, contact angle and push speed, peak resultant force at and rim; recovery phase (hand movement after propulsion) kinematics; and jerk kinematics of the wrist, elbow and shoulder joints. Data related to shoulder pain was collected using a visual analog scale (VAS) and for those who indicated shoulder pain, further data was collected using the wheelchair user's shoulder pain index (WUSPI). | 1. No significant differences between groups in demographics as a function of recovery phase stroke pattern of shoulder pain ($p>0.05$); no differences noted in shoulder pain (as measured by the WUSPI) between the two stroke pattern groups.<br>2. No significant differences between recovery phase patterns were observed in regard to peak resultant force, push speed or contact angle ($p>0.05$).<br>3. Peak magnitude of the absolute jerk (Pmax) for the participant with shoulder pain was lower than for those without pain.<br>4. Push time was significantly greater in patients that used a semi-circular (SC) recovery phase pattern compared to a double loop (DLOP) pattern (mean SC=1.12±0.04 m/s, DLOP=1.17±0.08 m/s).<br>5. Significant main effect of both recovery phase patterns was observed for jerk criteria at the wrist ($p<0.05$), elbow ($p=0.05$), and shoulder joint ($p<0.05$).<br>6. Significantly lower mean jerk criteria were observed for patients using a SC pattern compared to patients using a DLOP pattern ($p<0.05$).<br>7. Peak jerk criteria (0-30%) magnitude was significantly lower in the shoulder pain group compared to the no pain group for the wrist ($p<0.05$), elbow ($p<0.05$) and shoulder joints ($p<0.05$).<br>8. No significant differences were observed between SP and NP |

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| | | groups in regard to peak jerk criteria (70-100%) ($p>0.05$). |
| Champagne et al. 2016<br>Canada<br>Pre-Post<br>N=13 | **Population:** Mean age= 40.4 yr; Gender: males=10, females=3; Level of injury range: C5-T11; Mean time since injury: 3.1 yr.<br>**Intervention:** Cardiorespiratory demand and rate of perceived exertion were measured for manual wheelchair (MWC) users with and without traction by a mobility assistance dog (MAD). The course used had level propulsion, followed by an inclined concrete ramp, and finally level propulsion.<br><br>**Outcome Measures:** Oxygen Consumption (VO2), Ventilation (VE), Tidal Volume (VT), Respiratory Quotient (RQ), Respiratory Rate (RR), Heart Rate (HR), Time, Perceived Rate of Exertion (RPE). | 1. Significant reductions were observed in all cardiorespiratory and heart rate measures when participants completed course with MAD ($p<0.05$).<br>2. Participants RPE was significantly improved with the use of a MAD ($p\leq0.001$).<br>3. Significantly less time was required to complete the course with the use of a MAD ($p=0.0007$). |
| Gagnon et al. 2016<br>Canada<br>Pre-Post<br>N=15 | **Population:** Mean age= 32.7 yr; Gender: males=14, females=1; Level of injury range: C8-T12.<br>**Intervention:** Manual wheelchair (MWC) users performed three propulsion tests (MWPT): 20m Test, 18m Slalom Test, and 6 min test. Tests and measures were completed within 72 hours prior to discharge from inpatient rehabilitation program. **Outcome Measures:** Upper Extremity (U/E) strength, Trunk strength, Seated reaching capability. Bivariate correlation and multiple linear regression analyses to ascertain best determinants and predictors of wheelchair propulsion performance. | 1. MWPT performance was moderately or strongly correlated with anterior and lateral flexion trunk strength, anterior seated reaching distance, and shoulder, elbow, and handgrip strength measures.<br>2. U/E strength best predicts the 20 m Propulsion Test, with shoulder adductor strength on the weakest side best predicting performance at maximal velocity.<br>3. U/E strength and seated reaching capability best predict the Slalom Test, with shoulder adductors on the strongest side and forward reaching being the two key predictors.<br>4. Handgrip strength best predicts the 6-Minute Propulsion Test. |
| Russell et al. 2015<br>USA<br>Pre-Post<br>N=40 | **Population:** Mean age: 35 yr; Gender: males=32, females=8; Level of injury range: T2-L3; Mean time since injury: 8.3 yr.<br>**Intervention:** Upper extremity kinematics and pushrim reaction forces were measured for participants on a stationary ergometer at self-selected free and fast propulsion speeds for 40 sec (data collection at last 10 sec or 6-10 push cycles) for each speed condition. Participants used their own manual wheelchairs except for 13/40 as their | 1. Wheelchair propulsion speed significantly increased between free and fast conditions across all participants ($p=0.0001$); mean velocity at self-selected free condition was 1.02±0.3 m/s, during fast condition was 1.72±0.3). The average increase from free to fast propulsion was 0.70±0.2m/s.<br>2. Duration of hand rim contact significantly decreased across all participants during fast propulsion ($p=0.001$) and |

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| | wheelchairs didn't fit on the ergometer; in these cases, they used a study wheelchair that was set up to match their own.<br>**Outcome Measures:** Wheelchair propulsion speed, Net joint movement (NJM), Net joint force (NJF), reaction force orientation, forearm orientation, elbow angles. Outcomes were measured using a SMARTwheel, and a CODA motion analysis system. | resultant Reaction Force magnitude (RF) increased significantly for fast propulsion as compared to free propulsion, across all participants (p=0.001). With-in group comparisons showed that 26 of the 40 participants increased resultant RF magnitude with 22 of these increasing the RF force by 10 N or more.<br>3. Resultant reaction force magnitude, resultant shoulder NJM and NJF at time of peak push increased significantly for the fast as compared to the free speed condition for all participants (p=0.0001). With-in participant comparisons indicated 30/40 participants increased shoulder NJM during fast propulsion condition with 15 of these increasing NJM by 10 Nm or more. NJF increased on average by 23N or more in the fast condition compared to the free condition.<br>4. No significant differences in elbow angle at peak push between fast and free speeds (p>0.05). |
| Soltau et al. 2015<br>USA<br>Post-Test<br>N=80 | **Population:** Mean age: 37.0 yr; Gender: males=74, females=6; Mean disease duration=9.0 yr.<br>**Intervention:** Participants used their wheelchairs on a stationary ergometer in three conditions: level propulsion at self-selected speed (free), fastest comfortable speed (fast), and an 8% graded speed. A 10 second trial was recorded for each condition, with data being collected separately for the left and right sides. Kinematics were recorded via an instrumented handrim (SMARTwheel) and a motion capture system (CODA system) between dominant and non-dominant sides.<br>**Outcome Measures:** Joint kinematics (elevation plane ROM, elevation angle ROM, shoulder rotation ROM, elbow flexion ROM, forearm protonation ROM); Handrim kinetics (Average total force, average tangential force, peak total force, | 1. The following outcome measures were significantly greater for the dominant side in the graded conditions: Elevation plane ROM (p=0.006), shoulder rotation ROM (p=0.002), forearm protonation (p<0.001).<br>2. Elevation angle ROM and elbow extension ROM was significantly larger on the dominant side than non-dominant side (p=0.015, p=0.044).<br>3. There were no significant main effects in any of the handrim kinetic variables (p>0.05).<br>4. Push angle had a significantly larger dominant side value in the graded condition (p=0.025). |

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| | peak tangential force, fraction of effective force (%); Spatiotemporal variables (Cycle time, push percentage, push angle, net radial thickness (NRT), total radial thickness (TRT)). | |
| Yang et al. 2012<br>USA<br>Score<br>Post-Test<br>N=36 | **Population:** Mean age: 39.0 yr; Gender: males=26, females=10; Level of injury: T8-L2; Mean time since injury: 11.8 yr; Duration of w/c range: 2.7-32.1 yr.<br>**Intervention:** Propulsion biomechanics for two different back support and back support frame heights (16"&½ of participants back height) on two different slopes (0°&3°) on a w/c treadmill. Participants used a standard study w/c and no cushion. Protocol: 2 min propulsion for warm up followed by 30 sec of each of four test situations, with a 5 min rest in between.<br>**Outcome Measures:** Instrumented rear wheel (SMART wheel) captured propulsion kinetics; six camera Qualisys motion analysis system to capture body movement; outcome measures were: cadence, stroke angle, peak shoulder extension angle, shoulder flexion/extension range of motion and mechanical effective force. | 1. With the low backrest set up push times were longer ($p<0.01$), cadence was lower ($p=0.01$), stroke angles were larger ($p<0.01$), start position was further back on rim ($p=0.07$), and release was further forward on rim ($p<0.01$).<br>2. Average height of low back rest was 27.6±3.2 cm compared to the 40.6cm (16") length of the high back support<br>3. Significantly larger shoulder extension angles at start of push ($p=0.02$); greater shoulder range of motion ($p<0.01$) with lower backrest.<br>4. No significant effect of backrest height on propulsion kinematics<br>5. Increased slope resulted in increased cadence ($p<0.01$), start and end angles were smaller ($p<0.01$), greater range of shoulder flexion/extension motion ($p<0.01$), greater resultant force ($p<0.01$), tangential force ($p<0.01$), propulsion torque ($p<0.01$) and Mechanical effective force ($p<0.01$).<br>6. No interaction effects between back support/back support frame height and angle of slope. |
| Raina et al. 2012a<br>USA<br>Post-test<br>N=18 | **Population:** Mean age: NR; Gender: males=18, females=0; Level of injury: T1-T12=11, C6-C8=7; Range of time since injury: 5-28 yr.<br>**Intervention:** A study w/c (lightweight, rigid frame) was used on a stationary ergometer with limited adjustments for each participant. Participants were strapped to the back of the w/c as requested for additional balance support. Motion analysis system to capture body motion; Instrumented wheel (SMART wheel) to capture forces at the hand rim in 2 differenet load conditions. | 1. Push phase average peak resultant forces at the hand rim were significantly higher ($p<0.05$) for all participants for the loaded condition.<br>2. Participants with paraplegia exhibited significantly more downwardly rotated ($p<0.05$) and less retracted ($p<0.05$) scapula during loaded condition compared to non-loaded. Additionally, a range of 5°-15° of scapular motion in the A/P and P/R direction under the loaded condition was noted compared to 5° ROM during the level condition. Rate of change in scapular movements was |

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| | **Outcome Measures:** Rotation of the scapula at peak force [anterior posterior (A/P) tilting around the medial-lateral axis, upward/downward (U/D) rotation around the anterior-posterior axis and retraction/protraction (R/P) around the inferior-superior axis]. | significantly higher (p<0.05) during the loaded condition) but only in the P/R direction<br>3. Participants with tetraplegia exhibited variations in scapular movement, with 3/7 having an upwardly rotated scapula and the rest having downward rotation. On average, there was less retraction during the loaded condition compared to the non-loaded. Similar changes with scapular range were observed as for participants with paraplegia. Rate of change in scapular movement was significantly higher (p<0.05) in loaded condition for the U/D and P/R directions.<br>4. Between the patient populations, under the loaded conditions the scapula of participants with tetraplegia showed a significantly higher rate of anterior tilting that those with paraplegia but no other significant differences were noted. |
| Koontz et al. 2012<br>USA<br>Post test<br>N=24 | **Population:** Mean age: 40.0 yr; Gender: males=21, females=3; Level of injury: C=7, T=13, L=2, 2=other (not SCI); Mean duration of wheelchair use: 17.0 yr.<br>**Intervention:** (1) investigate the relationship between key kinetic and temporal discrete point variables and (2) compare qualitative and quantitative characteristics of the force and movement curves between a dynamometer and a level smooth surface (tiled over ground).<br>**Outcome Measures:** Kinetic data: maximum resultant force (FR), radial force (Fr), tangential force (Ft), medial-lateral force (Fz), movement about the hub (Mz); push angel; stroke frequency; average wheel velocity; and average mechanical effective force (mef). Experimental set-up included a dynamometer designed in house (2 independent steel tubular rollers, one for each wheel) and for the overland portion, two instrumented wheels (SmartWheel) attached to individual's own wheelchair. | 1. Individuals produced larger peak force on the dynamometer compared to tile over ground.<br>2. All kinetic outcome variables were positively correlated for the two surface conditions except peak Fz.<br>3. Self-selected velocity for tile was higher than for the dynamometer and was not correlated.<br>4. Mechanical efficiency, push angel, and frequency were positively correlated between conditions.<br>5. Subject body weight was significantly correlated with all maximum forces and Mz (movement around the hub) except Fz force for both surfaces (r ranging from 0.427 to 0.783, p<0.01) and Fr for the dynamometer (R ranging from 0.467 to 0.623, p<0.01).<br>6. The dynamometer maximum resultant force and body weight best predicted maximum resultant force on tile (R=0.826, p<0.001).<br>7. Mz curves (moment about the hub) were normalized and positively correlated between surfaces (R ranging from 0.74 to 0.00, p<0.001). |

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| | | 8. There was significant association between curve type (bimodal, unimodal and flat) and surface using chi-square test ($x^2$=9.489, p=0.008); bimodal was most common on the dynamometer and unimodal was most common on the tile. |
| Gil-Agudo et al. 2010<br>Spain<br>Post-test<br>N=16 | **Population:** Age range: 18-65 yr; Level of Injury: T1-T12; Severity: AIS A or B; Time since injury: ≥6 mo.<br>**Intervention:** Participants complete propulsion trials on a treadmill using a standard lightweight study wheelchair; a 2 min adaption period followed by 1 min at 3 km/hr, 3 min rest, and 1 min at 4 km/hr.<br>**Outcome Measure:** Right shoulder joint net forces and moments as measured by a right side instrumented rear wheel on a study w/c, and a set-up of four video recorders and reflective markers on the hand, forearm, arm, trunk and AC joint. Joint net moments were referenced to the trunk not the humerus. Measurements included: cadence, total force (Ftot) propulsion moment (Mp moment around the hub) and tangential force (Ft). | 1. Changing propulsion speed from 3 to 4 $kmh^{-1}$ increased cadence, Ftot, Ft, and Mp (p<0.01), as well as the propulsion angle (p<0.05), whereas the release angle decreased (p<0.01).<br>2. During the push when increasing propulsion velocity, both maximal (anterior direction) and minimal peak (posterior direction) shoulder forces of Fx were increased (p<0.01), whereas for Fy maximal value decreased and minimal value increased its magnitude (both inferior direction, p<0.05).<br>3. During the recovery phase both maximal (posterior direction) shoulder forces of Fx were increased (p<0.01). Maximal (lateral direction) and minimal (anterior direction) peaks were also increased for Fz (p<0.05)<br>4. During the push when increasing propulsion velocity maximal (adduction) and minimal (abduction) Mx peak, My peak (internal rotation), and Mx peak (flexion) values improved (p<0.05).<br>5. During the recovery phase, minimal Mx peak (abduction) and My maximal peak (internal rotation, p<0.05) increased. |
| Bregman, 2009<br>Netherlands<br>Post-test<br>N=16 | **Population:** Gender: males=16, females=0; *Able bodied (AB; n=5):* Mean age: 22.0 yr. *Paraplegia (PP; n=8):* Mean age: 39.0 yr; Injury level: T3-T12; Mean time since injury: 14.0 yr. *Tetraplegia (TP; n=3)*: Mean age: 28 yr; Injury level: C6-C7; Mean time since injury: 7 yr.<br>**Intervention**: Participants propelled an instrumented wheelchair on a level treadmill simulating a low load for 30sec at a constant pace while 3D external forces and moments, and 3D kinematics of the | Kinematics:<br>1. The average propulsion cycle duration was 1.34 (0.27), which was comparable for the three groups (AB, TP and PP).<br>2. The push phase of the propulsion cycle represented 51.7% (6.3) of the entire propulsion cycle.<br>Kinetics:<br>1. No significant differences in the magnitude of exerted force were |

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| | right upper extremity Compared forces of tangential propulsion with total propulsion force (experimental condition). Data gathered for forces was inputted into the Delft Shoulder and Elbow Model (DSEM) to calculate physiological cost/demands to calculate mean glenohumeral contact force, net joint moments and muscle powers.<br>**Outcome Measures:** Kinematic and kinetic data, Physiological cost, Moments, Muscle powers, Glenohumeral contact forces, Percentage of glenohumeral constraint activity. Tools used: Standard study wheelchair with six-degree-0f-freedom force transducer, Optotrak motion analysis system using 17 active markers of the body and wheelchair, Delft Shoulder and Elbow Model (DSEM). | found between the three subgroups; mean force=18.8(0.27) N.<br>2. No significant differences in the magnitude of the tangential component and the FEF (11.7(2.8) and 63.2(12.6%) respectively) were found between the three subgroups.<br>Results from the DSEM:<br>1. No significant differences in increase in physiological cost found between three groups (p=0.58).<br>2. Both the produced energy and the dissipated energy of all muscles were significantly higher in the tangential force condition then in the experimental force condition (p<0.01).<br>3. The mean peak glenohumeral contact force was significantly higher in the tangential force condition (p<0.01) but no significant difference between the three subgroups (p=0.92).<br>4. The glenohumeral contact force was peaked in the middle of the push phase for both conditions; however, the force was significantly greater in the tangential condition (p<0.01) and the force was higher for the duration of the push phase. No differences were noted between groups. |
| Mercer et al. 2006<br>USA<br>Post-test<br>N=33 | **Population:** Mean age: 37.8 yr; Gender: males=23, females=10; Level of injury: below T1; Mean time since injury=12.4 yr.<br>**Intervention:** Participants propelled their own w/cs on a dynamometer set to mimic the resistance of a tile floor at speeds of two mph and 4mph. Data was captured for 20 sec once a steady state speed was reached, with 1min rest periods between trials; the number of trials was not provided.<br>**Outcome Measures:** 1) Magnetic Resonance Imagining (MRI) of non-dominant shoulder for eight rotator cuff pathologies, scored on a 4 point scale (0=absent; 1=mild; 2=moderate; | 1. All participants except one presented with 1+ abnormality in the MRI results with all pathologies present (except osseous spur) in at least half of participants; distal clavicular edema=55%, AC joint DJD=52%, AC joint edema=58%, Osseous spur=30%, entheseal edema=67%, CA ligament edema=89%, CA ligament thickening=64%.<br>2. Physical exam scores ranged from 0 to 10 with an average score of 1.03, the mode and median scores were 2; 30% of participants expressed discomfort during the physical exam. |

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| | 3=severe); 2) Physical examination for signs of shoulder pathology related to pain or discomfort during resisted abduction and internal rotation, resisted internal rotation, resisted external rotation, resisted abduction, palpation of the sub-deltoid bursa and biceps tendon as measured on a 3 point scale; 3) Motion Analysis System to track movement and moments of upper extremity with five markers on the body and markers on the wheel hub (# not stated); 4) two instrumented rear wheels placed on participants own w/c to measure forces and moments during propulsion; measurements were used only from the non-dominant side. | 3. Age was not significantly related to the physical exam score or any MRI score<br>4. Participants' mass was significantly associated with the physical exam (p=0.05), acromioclavicular joint edema (p=0.04) and coracoacromial ligament thickening (p=0.02); higher body mass increases the odds of having shoulder pathology as indicated by a physical exam; higher body mass associated with increased association with posterior force (p=0.007), lateral force (p=0.006), internal rotation moment (p=0.02) and extension moment (p=0.0009).<br>5. Speed significantly increased all biomechanical variables (p<0.01) for posterior force, superior force, lateral force abduction moment, internal rotation moment, extension moment, stroke frequency and mean velocity.<br>6. Age did not significantly influence shoulder force and moments but was associated with increased stroke frequency (p=0.006) and lower mean velocity (p=0.07).<br>7. Dichotomized MRI and physical exam results compared to biomechanical variable indicated that participants with 1) higher posterior forces had significantly higher prevalence of coracoacromial ligament edema, (OR=1.29, p=0.03); 2) higher lateral forces were more likely to have CA ligament edema (OR=1.35, p=0.045) and CA ligament thickening (OR=4.35, p=0.045); 3) Internal rotation moment increased odds of pathology signs in the physical exam. |
| Ambrosia 2005<br>USA<br>Post-Test<br>N=22 | **Population:** Mean age: 43.0 yr; Gender: males=16, females=6; Mean time since injury: 16.6 yr; Level of injury range: T2 to L1.<br>**Intervention** Participants' muscle strength was measured first with five measured of maximum effort in flexion/extension, abduction/adduction, internal and external rotation, from which muscle ratios were | 1. Strong relationship between right and left sides for shoulder isokinetic torque values (p=0.001).<br>2. For pushrim values, right and left sides correlated for all variables (p=0.001).<br>3. Significant correlation between pushrim variables for 0.9m/s trial |

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| | calculated. Following this testing, participants propelled their wheelchair on treadmill at a comfortable speed for 3-5 min, and then performed two trials at 0.9 m/s and 1.8 m/s for approximately 60 sec. Strength and pushrim biomechanical variables (tangential (motive) force (Ft), radial force (Fr), axial force (Fz), total (resultant) force (FR), fraction of effective force (FEF), and cadence) were correlated.<br>**Outcome Measures:** Kinematic data was collected using the OPTOTRAK system of 3-dimensional motion analysis and kinetic data (Shoulder strength, torque) was collected using the SMARTwheel. | ad 1.8m/s trial ($p<0.001$ for FR, Ft, Fr and Fz).<br>4. Ft, Fr, and FR were significantly correlated with all muscle strength variables ($p<0.05$).<br>5. Fz, FEF, and cadence were not correlated with any of the strength variables ($p>0.05$).<br>6. None of the muscle ratios were significantly correlated to pushrim variables ($p>0.05$). Abduction was 15% greater than adduction.<br>7. Shoulder isokinetic peak torque: flexion was 51% greater compared to extension; internal rotation was 13% greater than external rotation. |
| Dallmeijer, 1998<br>Netherlands<br>Post-test<br>N=29 | **Population:** *Tetraplegia (TP; n=17):* Mean age: 34.3 yr; Gender: males=16, females=1; Mean weight: 78.1 kg; Level of injury: C5-C7; Mean time since injury: 7.3 yr. *Paraplegia (PP; n=12)*: Mean age: 39.8 yr; Gender: males=10, females=2; Mean weight: 80.3 kg; Level of injury: T5/6-L3/4; Mean time since injury: 1.7 yr.<br><br>**Intervention:** All subjects performed a maximal exercise test on a wheelchair ergometer using a study wheelchair that was adjusted to standard set up for each participant. Two 1 min exercise bouts were used for analyses (30 to 50% and 60 to 80% of the maximal power output) to examine effectiveness of force application, ratio power output/energy expenditure and timing parameters of wheelchair propulsion in persons with TP and PP. Velocity was standard for each group (1.11 m/s PP; 0.83 m/s TP and prolusion was until exhaustion.)<br>**Outcome Measures:** Forces (3D force application (N) Fx, Fy, Fz – horizontal forward, horizontal outward, vertical downward respectively), Direction of force application DAxz (tangential force), DAyz (place of the wheel) velocity, power output (PO), Hand position data (beginning angle (BA), End angle (EA), Stroke angle (SA), Cycle time (CT), Push time (PT)), Oxygen uptake. Outcome tools used: 2D video recording system, Forces at the rear wheel gathered through the ergonmeter, Oxycon Ox4. | 1. Mean maximal exercise test duration was 7.3±2.0 min for TP and 8.1±1.9 min for PP.<br>2. POmax showed a significantly higher value in PP (63±3W) compared with TP (19±10W) ($p<0.05$); mean velocity remained constant over the test condition for both groups.<br>3. Effectiveness of force application: a) no differences between groups for Fy; b) Fy relative to F to tpeak significantly higher force in TP ($p<0.05$); Fymean showed a positive force in PP and negative in TP ($p<0.001$); c) Fymean and Fypeak showed significantly higher force at high intensity condition ($p<0.05$); d) with increased load, significant increase seen ($p<0.001$) between groups.<br>4. Direction of force application (based on only 16 participants due to technical errors): A0 DAyz was significantly higher in TP ($p<0.05$); b) In the high intensity condition DAxz significantly lower ($p<0.05$) but DAyz showed no significant differences suggesting forces were applied more effectively in the plane of the wheel at high intensity.<br>5. Ratio power output/energy expenditure: a) was considerably lower in TP compared to PP ($p<0.01$); power output/energy expenditure increased |

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| | | significantly; b) a higher load in both groups (p<0.01).<br>6. Timing and stroke angle: a) TP compared to PP showed a larger BA (p=0.042), and a longer cycle time (p=0.003) and push time (p<0.001) b)<br>7. The effect of intensity on (SA) was significantly different between TP and PP (p=0.032) c).<br>8. (BA) showed a shift forward at the high intensity condition for both lesion groups (p=0.006) d).<br>9. Cycle time tended to decrease (p=0.070), whereas push time increased significantly (p=0.023) at the higher intensity condition. |
| VanLandewijck et al. 1994<br>Belgium<br>Post-test<br>N=40 | **Population:** Mean age: 31.8 yr; Mean weight: 68.11 kg, Mean time since injury:18.38 yr; Injury etiology: Polio myelitis=13, spina bifida=2, hip disarticulations=2, below the knee amputee=1; Level of injury range: T3-L5.<br>**Intervention:** Participants used a standard test wheelchair on a treadmill to perform a maximal test and then four submaximal tests, at least 1hr post maximal. At each stage of the maximal test the load was increased for 4min followed by a 2-min active recovery period without the additional load. During the last minute of each stage Metabolic, Kinematic and EMG data was taken for 8.2 sec simultaneously. After a period of at least 1 hr, participants were put through four submaximal tests, each 6min in duration. These tests were done at two different velocities and were performed in a random sequence. The velocities were tested against two levels of power output (60% and 80% of each individuals' peak-$VO_2$).<br>**Outcome measures:** Metabolic Data: Minute ventilation, Oxygen uptake, Carbon dioxide output, Respiratory exchange ratio, Heart rate, Gross mechanical efficiency, Kinematic Data hand contact, Hand release, Push time, Recovery time, Cycle time, Cycle frequency, Start angle, End angle, Push angle, Trunk inclination, Lateral humeral epicondyle, , Ulnar styloid | 1. Gross mechanical efficiency did not exceed 11.5%. Increased energy consumption and significant decreases in efficiency were noted with increased velocity to 60% level (p=0.001) and 80% level (p=0.001). Some participants reached maximum oxygen consumption when their wheelchair was at 2.22m/s at 80% exercise level.<br>2. Cycle time and Push time both decreased as velocity increased across both exercise levels but recovery time remained constant. Cycle frequency and End angle both increased as velocity went up across both exercise levels. Start angle, Push angle and Trunk range of motion all vary across the increasing velocities of both exercise levels.<br>3. As the velocity increased the distance that the hand traveled during the recovery period also increased at 60% exercise level.<br>4. Peak activity for Biceps brachialis muscle was at initial hand contact, activity of triceps brachialis increased progressively reaching maximum value at hand release. Pectoralis major, Deltoids anterior and Latissimus dorsi all reach their max levels during push phase. Deltoids medialis and posterior and Trapezius all reach maximum activity during recovery phase. |

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| | process, a dnrear wheel axle, Mechanical Work, EMG data at biceps, Triceps, Brachialis longum, Decapods, Latissimus dorsi, Trapezius. | |