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ORIGINAL CONTRIBUTION

Shoulder Muscular Demand During Lever-Activated Vs Pushrim Wheelchair Propulsion in Persons With Spinal Cord Injury

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Abstract

Background/Objective: The high demand on the upper limbs during manual wheelchair (WC) use contributes to a high prevalence of shoulder pathology in people with spinal cord injury (SCI). Lever-activated (LEVER) WCs have been presented as a less demanding alternative mode of manual WC propulsion. The objective of this study was to evaluate the shoulder muscle electromyographic activity and propulsion characteristics in manual WC users with SCI propelling a standard pushrim (ST) and LEVER WC design.

Methods: Twenty men with complete injuries (ASIA A or B) and tetraplegia (C6, n = 5; C7, n = 7) or paraplegia (n = 8) secondary to SCI propelled ST and LEVER WCs at 3 propulsion conditions on a stationary ergometer: self-selected free, self-selected fast, and simulated graded resistance. Average velocity, cycle distance, and cadence; median and peak electromyographic intensity; and duration of electromyography of anterior deltoid, pectoralis major, supraspinatus, and infraspinatus muscles were compared between LEVER and ST WC propulsion.

Results: Significant decreases in pectoralis major and supraspinatus activity were recorded during LEVER compared with ST WC propulsion. However, anterior deltoid and infraspinatus intensities tended to increase during LEVER WC propulsion. Participants with tetraplegia had similar or greater anterior deltoid, pectoralis major, and infraspinatus activity for both ST and LEVER WC propulsion compared with the men with paraplegia.

Conclusions: Use of the LEVER WC reduced and shifted the shoulder muscular demands in individuals with paraplegia and tetraplegia. Further studies are needed to determine the impact of LEVER WC propulsion on long-term shoulder function.

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Key Words: Spinal cord injuries; Tetraplegia; Paraplegia; Wheelchair propulsion; Shoulder; Electromyography; Assistive technology

INTRODUCTION

Nearly 11,000 new survivors of spinal cord injury (SCI) are added each year to the total population of approximately 253,000 persons now living with SCI in the USA (1). A substantial number rely on the use of a manual wheelchair (WC) as a daily means of ambulation. Manual WC use places significant stability and mobility demands on the upper limbs and is thought to contribute to the high incidence of upper extremity pain and injury, particularly at the shoulder. Because individuals with SCI are dependent on their upper extremities for both functional mobility and activities of daily living, shoulder joint pain can present a devastating loss of function and independence (2–4) and decreased quality of life (5,6).

During WC propulsion, anatomical structures in the shoulder region experience relatively large forces to provide joint stability and produce substantial shoulder moments for propulsion. Imposing both joint stability and moment requirements on the shoulder region adds complexity to the motor control and increases susceptibility to neuromuscular fatigue (7,8,14). Inadequate

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control of the shoulder joint may contribute to displacement of the humeral head superiorly from the center of the socket (9,10), which can compress the structures that lie within the subacromial space, including the rotator cuff tendons (notably the supraspinatus), the tendon of the long head of biceps brachii, and the subacromial bursae, resulting in chronic inflammatory and impingement syndromes (11,12) and bicipital tendinitis (13).

Use of an alternative WC propulsion design has the potential to preserve the shoulders of people at risk for overuse injury and yet maintain a more optimal level of activity and independence. Lever-activated (LEVER) WC propulsion has been described as more efficient and less physically straining than conventional pushrim (ST) WC propulsion. Energy expenditure studies performed on a crank-to-rod lever design (15,16), a prototype 1- and 2-arm use lever design (17), and a 3-wheeled multigear lever design (18) have shown that they are physiologically efficient and reduce energy consumption, compared with ST WC propulsion. Propelling with a lever mechanism is also thought to provide a more effective transfer of power by increasing mechanical advantage and placing the arms in a more natural segmental position and orientation (19). Unlike propulsion with a pushrim, the hands maintain contact with the lever to provide a less complex coupling of the hand with the pushrim. A LEVER propulsion mechanism further allows ergonomic optimization to suit an individual's characteristics and personal requirements, not only with respect to seat configuration but also the lever design elements, such as the lever length, spatial orientation, form and orientation of grip, and gear ratio (19).

Various attempts have been made to improve the design of LEVER WC propulsion drive systems for everyday use. Bruning et al (20) built a LEVER WC design that used a roller clutch to drive a sprocket. This allowed users to choose the length of the propulsion stroke and cycle frequency. However, this design required users to perform separate and prompt actions for going forward and backward and stopping. To overcome this issue, McLaurin et al (21) built several LEVER system prototypes that combined a brake with the drive system using roller and friction clutches to allow maneuverability similar to pushrims. In addition, Engel et al (22) developed a LEVER design that applied propulsive power during the push and pull of each cycle. Van der Woude et al (17) developed a bimanual asynchronous lever-propelled tricycle to overcome the drawbacks of earlier designs. In India, a commercially available, simple, and mass-produced lever-propelled tricycle was developed (23). Surprisingly, the use of LEVER WCs in the USA is still limited to recreational and sports-oriented activities and less commonly utilized in daily wheeled mobility. LEVER WCs received the impression of being heavy and difficult to maneuver in smaller spaces and overall do not meet the requirements of everyday use (19). More recently, however, manufacturers have developed advanced lever gear systems that are both lightweight and economical and promoted as a commercially available alternative mode of daily WC propulsion.

Recording of muscle activity using indwelling fine wire or surface electrodes has allowed detailed studies of the demands on the specific muscles or groups of muscles involved in WC propulsion (7,8,24,25). Electromyographic (EMG) activity patterns of the deltoid, rotator cuff, and deep and superficial scapulothoracic muscles have been used to provide critical insight into the mechanism of shoulder pathology associated with ST WC propulsion (7,8). Analysis of EMG activity of the shoulder muscles can be used to examine the shoulder muscular demands associated with LEVER WC propulsion and provide evidence-based recommendations for prescribing alternative modes of WC propulsion as a strategy for preserving upper limb function in manual WC users with SCI.

The purpose of this study was to evaluate propulsion characteristics and EMG activity of shoulder muscles primarily responsible for providing the propulsive force during ST and LEVER WC propulsion in individuals with tetraplegia or paraplegia. We hypothesized that a reduction in push-phase shoulder muscle demands, as determined by muscle intensity and duration of activity, would be seen during LEVER compared with ST WC propulsion. We also expected that the shift in muscular demands would differ for paraplegia and tetraplegia.

METHODS

Participants

Twenty men with complete injuries (ASIA A or B) tetraplegia (C6, $n = 5$; C7, $n = 7$) and paraplegia (ranging from T4 to T12-L1; $n = 8$) volunteered. Age, time since injury, height, and body mass are listed in Table 1. Participants were recruited from the outpatient services of the rehabilitation hospital. All participants reported using manual ST WC propulsion as their only means of community mobility. Individuals were excluded if they reported a history of shoulder pain that altered performance of daily function or required medical treatment. Prior to data collection, they were asked to read and sign an informed consent form that had been approved by the hospital institutional review board.

Lever Wheelchair Design

The LEVER WC propulsion and braking design (Wijit, Superquad, Inc, Roseville, CA) uses a gear system integrated into the rear wheels of the wheelchair (Figure 1). The gear shifts between forward and reverse by virtue of a roller mechanism, which grabs in one direction and slips in the opposite direction. The shift mechanism is activated by rotation of a shifter knob located on the top of the lever arm remote from the roller mechanism. For propulsion in the forward direction, the gear and wheel are turned by pushing the lever forward (push phase) to generate the torque needed to move forward. No

Table 1. Demographic Characteristics of People With Spinal Cord Injury (SCI) S

Subject	Diagnosis	Age (y)	Height (m)	Time Since SCI (y)	Body Mass Index
Tetraplegia					
1	C6	52	1.68	31.2	22.3
2	C6	57	1.88	36.3	25.8
3	C6	49	1.70	7.3	23.0
4	C6	45	1.83	7.1	16.4
5	C6	59	1.70	21.5	31.5
6	C7	39	1.68	7.4	20.3
7	C7	45	1.96	7.3	16.9
8	C7	48	1.83	30.0	21.5
9	C7	26	1.93	7.0	19.1
10	C7	30	1.78	7.4	21.1
11	C7	43	1.78	7.3	20.2
12	C7	55	1.75	6.7	25.5
Paraplegia					
13	T4	47	1.70	8	26.1
14	T6-T7	49	1.77	24	27.8
15	T7	33	1.68	13	27.3
16	T8	43	1.80	7	23.8
17	T11	37	1.75	7	25.5
18	T11-T12	45	1.78	20	26.5
19	T12	35	1.70	14	24.6
20	T12-L1	56	1.74	18	23.8

propulsive torque is produced during the recovery phase (pulling the lever backward). For propulsion in the reverse direction, the gear is activated by pulling the lever backward to generate the torque needed to move in reverse, and no propulsive force is produced during the recovery phase (pushing the lever forward). The rotation of the wheel relative to the lever is determined by the gear ratio that ranges from 1-to-1 (easy) to 5-to-1 (hard). In this study, a 1-to-1 gear ratio was utilized. Braking is activated by pulling the lever arm medially, toward the user, which pivots the breaking pads against the rotation of the wheel's hub. The LEVER wheel system is installed as a replacement for the ST WC's rear wheels.

Instrumentation

Two types of test WCs, a ST and a LEVER, were utilized. The ST WC was a rigid-frame, lightweight chair (Quickie GPV, Sunrise Medical, Fresno, CA) with an instrumented pushrim (26). The LEVER WC system was mounted on a similar rigid-frame chair. To accommodate people of varying sizes, 2 test WCs for each propulsion designs were available, either 16- or 18-inch seat width. A custom-fabricated wheel axle mounting plate allowed vertical and horizontal adjustability to achieve a standardized seat position for the person using the WC during ST and LEVER WC propulsion (27). A stationary WC ergometer was used to simulate propulsion over level surfaces and inclines. The ergometer consisted of single independent rollers on which the rear wheels rested. The rollers were coupled, by means of a differential, to an alternator to provide resistance. Resistance was controlled by a modified Velodyne bicycle-ergometer computer (Schwinn Bicycle Company, Madison, WI). Removable flywheels proportional to the weight of both the person in the WC and the WC were used to simulate the translational inertia of "over ground" propulsion. Jacks were placed under the frame of the WC to support some of the weight of the person and WC, thereby reducing the friction between the tires and rollers. A coast-down

Figure 1. *Wijit lever-activated WC propulsion design.*

test was used to determine the friction so the ergometer computer could utilize the friction load when calculating the appropriate load for the ST and LEVER WC propulsion at various propulsion conditions.

Shoulder muscle activity was recorded with indwelling bipolar, 50-μm Ni-Cr alloy wire electrodes (California Fine Wire, Grover Beach, CA), as previously described (7). A coaxial cable system transmitted the EMG signal to the data acquisition computer (Digital Equipment Corporation, PDP-11/73, Cambridge, MA). The EMG signal was filtered using a bandwidth of 150 to 1,000 Hz, with an overall system gain of 1,000. The data were sampled at a rate of 2,500 Hz.

Three-dimensional motion of the right upper extremity, trunk, and wheels was recorded using a 6-camera VICON motion analysis system (Oxford Metrics Ltd, Oxford, England). The motion markers were recorded at a 50-Hz sampling rate during each 10-second propulsion trial, as previously described (28).

PROCEDURES

Two forms of WC propulsion, ST and LEVER, were tested. Participants sat on their own cushion in the test WC, which was initially mounted on a stand for the purpose of seat positioning. The backrests and footrests of the test WCs were adjusted as close as possible to each individual's own WC configuration. The wheels were removed, allowing horizontal and vertical adjustment of the wheel axle mounting plate, as previously described (24).

EMG activities of 4 primary WC propulsion muscles (8) of the right shoulder were recorded using indwelling fine-wire electrodes: anterior deltoid (ADELT), sternal or clavicular portion of pectoralis major (PECMAJ), supraspinatus (SUPRA), and infraspinatus (INFRA). A 25-gauge needle was utilized to insert the electrodes into each muscle (29). Confirmation of electrode placement was achieved by palpation of muscle belly contraction and tendon movement during mild electrical stimulation through the wires.

A 5-second period of EMG data collection initially was recorded with participants seated in their own WCs with their hands relaxed and resting on their laps to document electronic noise inherent to the acquisition system. This served as a threshold for the detection of myoelectric activity. EMG activity was then recorded for each muscle during a 5-second maximum voluntary isometric contraction (MMT) for each muscle, as previously described (7).

A reflective marker was taped to bony landmarks of the right epicondyle and trunk. Three markers were taped to the right wheel of the ST and LEVER WCs. Prior to the acquisition of WC propulsion data, the friction force between the tire and ergometer was determined during a coast-down test with the subject sitting in the ST and LEVER test chairs on the ergometer. The 2 independent rollers were first locked and spun by an electric drill motor at 3.03 m/s as determined by the ergometer-controlling computer. The drill motor was then removed and the wheels were allowed to coast down to 0.58 m/s. The friction force, recorded during the coast down test, was utilized by the ergometer-controlling computer to determine the resistance applied to the rollers in subsequent data acquisition trials.

WC propulsion trials began in the ST WC. Prior to data collection, participants practiced propelling the WCs on the ergometer to accommodate to the test environment. Participants were allowed to practice 2 to 3 minutes in the ST and 3 to 5 minutes in the LEVER WC. During the data acquisition trials, participants propelled the WC until approximately 5 to 10 seconds of steady state was achieved prior to initiation of a 10-second data collection period. A single trial of ST WC propulsion was recorded at a self-selected free velocity and at a self-selected fast velocity without additional load applied to the ergometer rollers, simulating propulsion over level ground. Next, 1 trial of ST WC propulsion was recorded with the front end of the ergometer elevated with wooden blocks and resistance added to the ergometer rollers to simulate a 4% or 8% grade, depending on the participant's ability. Propulsion speeds were displayed to the participant during the propulsion trial and noted from the display of the ergometer-controlled computer. After completion of the ST WC propulsion, the LEVER chair was placed on the ergometer and LEVER WC propulsion was then recorded with the tester providing feedback to speed up and slow down in an attempt to match propulsion speeds within ±5% of that recorded during the ST WC propulsion trial (free, fast, and graded).

Data Management

EMG activity during the MMT was full-wave rectified and integrated over 0.02-second intervals. The greatest 1 second of EMG activity during MMT was located via a moving window, and the average served as the normalization value (100% MMT). The EMG activity recorded during WC propulsion was integrated over 0.01-second intervals and expressed as a percentage of the MMT.

The kinematics data were processed using Visual3D software (C-Motion Inc, Rockville, MD). The 3-dimensional marker trajectory data were smoothed with a 4-Hz low-pass second-order recursive Butterworth digital filter with forward and backward passes to eliminate phase shift. The positive wheel torque from the instrumented ST WC has previously been used to define the push phase timing of the propulsion cycle (7,30). Because wheel torque data were not available for calculation of propulsion cycle timing in the LEVER propulsion condition, lateral epicondyle (LEP) marker trajectory was utilized to determine propulsion cycle (0% to 100%) to provide consistent comparable cycle timing between the 2 chairs. Duration of the push phase was composed of anterior LEP movement from beginning (most posterior)

Table 2. Mean Velocity, Cadence, and Cycle Distance During Standard Pushrim (ST) and Lever-Activated (LEVER) WC Propulsion in Men With Paraplegia (Para) or Tetraplegia (Tetra)

	Free		Fast		Graded	
	ST	LEVER	ST	LEVER	ST	LEVER
Velocity (m/s)						
Para	1.18 ± 0.33	1.23 ± 0.33	2.30 ± 0.77	2.32 ± 0.83	1.05 ± 0.37	1.03 ± 0.42
Tetra	0.90 ± 0.25	0.93 ± 0.27*	1.43 ± 0.40*	1.40 ± 0.38*	0.48 ± 0.17*	0.57 ± 0.18*†
Cadence (Cycles/s)						
Para	1.00 ± 0.20	0.97 ± 0.15	1.57 ± 0.42	1.47 ± 0.43	1.25 ± 0.17	1.22 ± 0.25
Tetra	1.08 ± 0.25	0.95 ± 0.35	1.42 ± 0.15	1.28 ± 0.32	0.98 ± 0.17*	0.85 ± 0.22*
Cycle Distance (m/Cycle)						
Para	1.22 ± 0.40	1.31 ± 0.44	1.50 ± 0.51	1.66 ± 0.71	0.84 ± 0.30	0.87 ± 0.40
Tetra	0.84 ± 0.17	1.01 ± 0.24†	1.01 ± 0.24*	1.12 ± 0.26	0.49 ± 0.15*	0.65 ± 0.14†

*Significantly different from group with paraplegia ($p < 0.05$).
†Significantly different from ST WC data ($p < 0.05$).
Values are mean ± SD.

to end (most anterior), and recovery phase was defined by posterior LEP excursion. Pilot data comparing anterior LEP movement to positive wheel torque in the standard WC indicated that these events were highly associated ($r = 0.99$). EMG timing for every 1% of the propulsion cycle was calculated for both WCs during each propulsion condition. For each muscle and test condition, a composite propulsion cycle was derived by computing the median EMG intensity for each 1% of the push cycle from the second to sixth cycles collected. EMG onsets, cessations, and durations were determined from this composite cycle such that EMG activity ≥5% of MMT and lasting at least 5% of the propulsion cycle was selected. Peak EMG activity was identified as the greatest intensity over a 1% interval of the push cycle.

Data were analyzed utilizing SPSS 12.0 software (SPSS, Inc, Chicago, IL). Propulsion characteristics and EMG data were compared for ST and LEVER WC propulsion: free-, fast-, and graded-propulsion conditions; and between subject groups: paraplegia and tetraplegia. The Shapiro-Wilk statistic determined that propulsion velocity, cycle length, push phase duration, cadence, and EMG duration were normally distributed and that EMG peak and median intensities were not normally distributed. For each propulsion condition, repeated measures ANOVA was used to detect for differences in propulsion characteristics and EMG durations in participants with paraplegia and tetraplegia (between groups) and between ST and LEVER (within groups) WC data. For the EMG peak and median intensities, the Mann-Whitney *U* test was used to detect differences between participants with paraplegia and tetraplegia and the Wilcoxon signed-rank test was used to detect differences between ST and LEVER WC propulsion. A significance level of 0.05 was selected.

RESULTS

Propulsion Characteristics

ST vs LEVER WC Propulsion. All participants tended to utilize a slightly slower cadence in all propulsion conditions during LEVER WC propulsion in order to produce a velocity similar to the ST WC propulsion, although cadence was not statistically significantly different between the 2 chairs for any condition in either participant group (Table 2). During LEVER WC propulsion, cycle distance tended to increase compared with ST propulsion, but the difference was statistically significant only in individuals with tetraplegia. In the free-propulsion condition, men with tetraplegia significantly increased cycle distance from 0.84 ± 0.17 m in ST WC propulsion compared with 1.01 ± 0.24 m in LEVER propulsion (Table 2). In the graded-propulsion condition, those with tetraplegia significantly increased speed in LEVER WC propulsion compared with the ST WC propulsion, by significantly increasing cycle distance from 0.49 ± 0.15 to 0.65 ± 0.14 m.

Paraplegia vs Tetraplegia. Overall, participants with tetraplegia had markedly slower velocities in both ST and LEVER WC propulsion than those with paraplegia, with the reduction in velocity ranging from 0.30 to 0.92 m/s (Table 2). The slower velocities resulted primarily from shorter cycle distances in those with tetraplegia compared with participants with paraplegia (statistically significant in the ST-fast and ST-graded conditions only). Cadence was significantly slower in those with tetraplegia during the graded propulsion conditions in both WCs.

Shoulder Muscle EMG Activity

ST vs LEVER WC Propulsion. Overall, PECMAJ and SUPRA median, peak, and duration of EMG activity decreased in LEVER compared with ST WC propulsion for both

Table 3. Peak Electromyographic Activity (as % of Maximum Voluntary Isometric Contraction) During Standard Pushrim (ST) and Lever-Activated (LEVER) WC Propulsion in Men With Paraplegia (Para) or Tetraplegia (Tetra)

	Free		Fast		Graded	
	ST	LEVER	ST	LEVER	ST	LEVER
ADELT						
Para	24 ± 19	38 ± 24	99 ± 51	73 ± 32	84 ± 29	91 ± 32
Tetra	40 ± 36	41 ± 17	92 ± 54	83 ± 78	83 ± 38	90 ± 70
PECMAJ						
Para	56 ± 57	44 ± 38	143 ± 74	83 ± 32†	118 ± 45	93 ± 56
Tetra	66 ± 37	40 ± 58†	104 ± 49	71 ± 71	101 ± 47	62 ± 53†
SUPRA						
Para	92 ± 41	71 ± 63	153 ± 81	96 ± 101†	128 ± 49	92 ± 93
Tetra	46 ± 35*	42 ± 29	92 ± 51	51 ± 36†	73 ± 33*	58 ± 45
INFRA						
Para	37 ± 46	21 ± 37†	67 ± 36	51 ± 64	74 ± 38	84 ± 32
Tetra	36 ± 42	29 ± 23	81 ± 53	61 ± 36	88 ± 58	90 ± 43

*Significantly different from group with paraplegia ($p < 0.05$).
†Significantly different from ST WC data ($p < 0.05$).
Values are mean ± SD.
Anterior deltoid = ADELT; sternal or clavicular portion of pectoralis major = PECMAJ; supraspinatus = SUPRA; and infraspinatus = INFRA.

participant groups in all propulsion conditions (Tables 3 through 5). In contrast, ADELT and INFRA EMG peak and median intensities tended to increase in LEVER WC propulsion compared with ST WC propulsion during graded propulsion (Tables 3 and 4), although the increases in intensity did not reach statistical significance.

During the free propulsion condition, PECMAJ peak and median intensities significantly decreased by 26% and 21% MMT, respectively, and ADELT duration significantly increased 13% of the propulsion cycle in LEVER WC propulsion compared with ST WC propulsion in men with tetraplegia. Men with paraplegia had a

Table 4. Median Electromyographic Activity (as % of Maximum Voluntary Isometric Contraction) During Standard Pushrim (ST) and Lever-Activated (LEVER) WC Propulsion in Men With Paraplegia (Para) or Tetraplegia (Tetra)

	Free		Fast		Graded	
	ST	LEVER	ST	LEVER	ST	LEVER
ADELT						
Para	15 ± 12	19 ± 12	44 ± 27	37 ± 14	36 ± 15	52 ± 17
Tetra	20 ± 13	22 ± 9	40 ± 20	42 ± 31	47 ± 15	57 ± 51
PECMAJ						
Para	31 ± 30	24 ± 22	60 ± 25	47 ± 19†	66 ± 40	52 ± 31†
Tetra	39 ± 23	18 ± 20†	60 ± 27	32 ± 35†	64 ± 30	25 ± 17*†
SUPRA						
Para	40 ± 19	28 ± 19†	61 ± 38	40 ± 24†	48 ± 26	49 ± 54
Tetra	26 ± 22	20 ± 17	32 ± 17*	21 ± 15	41 ± 18	28 ± 22†
INFRA						
Para	18 ± 25	9 ± 13	31 ± 26	23 ± 30	31 ± 11	49 ± 24
Tetra	16 ± 18	16 ± 14	33 ± 23	27 ± 15	38 ± 17	51 ± 30

*Significantly different from group with paraplegia ($p < 0.05$).
†Significantly different from ST WC data ($p < 0.05$).
Values are mean ± SD.
Anterior deltoid = ADELT; sternal or clavicular portion of pectoralis major = PECMAJ; supraspinatus = SUPRA; and infraspinatus = INFRA.

Table 5. Electromyographic Activity Duration (as % of Propulsion Cycle) During Standard Pushrim (ST) and Lever-Activated (LEVER) WC Propulsion in Men With Paraplegia (Para) or Tetraplegia (Tetra)

	Free		Fast		Graded	
	ST	LEVER	ST	LEVER	ST	LEVER
ADELT						
Para	18 ± 10	22 ± 10	34 ± 12	39 ± 19	58 ± 7	55 ± 9
Tetra	25 ± 13	38 ± 9*†	48 ± 16	40 ± 11	62 ± 13	61 ± 13
PECMAJ						
Para	22 ± 10	18 ± 12	38 ± 12	32 ± 7	58 ± 12	48 ± 18
Tetra	41 ± 16*	33 ± 18*	51 ± 13*	42 ± 23	69 ± 11*	54 ± 19†
SUPRA						
Para	74 ± 20	68 ± 21	69 ± 21	63 ± 21	72 ± 24	63 ± 25
Tetra	33 ± 22*	46 ± 29	49 ± 25*	46 ± 31	44 ± 24*	50 ± 37
INFRA						
Para	33 ± 21	18 ± 27	45 ± 18	31 ± 27	64 ± 10	51 ± 9†
Tetra	22 ± 20	32 ± 21	47 ± 16	45 ± 12	51 ± 15	63 ± 14†

*Significantly different from group with paraplegia ($p < 0.05$).
†Significantly different from ST WC data ($p < 0.05$).
Values are mean ± SD.
Anterior deltoid = ADELT; sternal or clavicular portion of pectoralis major = PECMAJ; supraspinatus = SUPRA; and infraspinatus = INFRA.

significant decrease in SUPRA median (12% MMT) and INFRA peak (16% MMT) intensities in LEVER WC propulsion compared with ST WC propulsion, with no corresponding change in propulsion characteristics (Tables 2 through 4).

During the fast-propulsion condition, EMG peaks, medians, and durations overall reduced during LEVER compared with ST WC propulsion in both participant groups. Statistically significant reductions were recorded in the PECMAJ median (28% MMT) and SUPRA peak (41% MMT) intensities in the men with tetraplegia, whereas in the men with paraplegia significant reductions were identified in PECMAJ peak (50% MMT) and median (27% MMT) intensities and SUPRA peak (57% MMT) and median (21% MMT) intensities.

During the graded-propulsion condition, significant reductions were seen during LEVER compared with ST WC propulsion in the men with tetraplegia for PECMAJ peak (39% MMT), median (39% MMT), and duration (15% propulsion cycle) and SUPRA peak (15% MMT). Men with paraplegia had significant reductions only in PECMAJ median intensity (14% MMT) during LEVER compared with ST WC propulsion. Overall, participants with tetraplegia showed more numerous and more significant reductions in muscular demands in LEVER compared with ST WC propulsion than those with paraplegia.

Paraplegia vs Tetraplegia. Overall, participants with tetraplegia had considerably lower SUPRA EMG peak, median, and duration in both ST and LEVER WC propulsion compared with participants with paraplegia (Tables 3 through 5). The men with tetraplegia had greater PECMAJ EMG duration in both ST and LEVER WC propulsion than the men with paraplegia. During all propulsion conditions, the men with tetraplegia had similar or greater ADELT, PECMAJ, and INFRA peak, median, and duration in both ST and LEVER WC propulsion than the men with paraplegia (Tables 3 through 5), even when they propelled at a slower speed (Table 2), indicating relatively greater shoulder muscular demand experienced by these participants.

DISCUSSION

The reduced EMG intensity when propelling a LEVER WC at similar speeds documents a decreased muscular demand of the PECMAJ and SUPRA. Lowering the demand in these muscles may potentially improve muscular endurance for propulsion and reduce the potential for shoulder injuries, particularly because these are the muscles documented to experience the highest intensity of activation during ST WC propulsion. During ST WC propulsion, the demand on the SUPRA, PECMAJ, and INFRA muscles is generally high, leaving these muscles especially susceptible to fatigue (7,8). Fatigue of PECMAJ (as well as SUPRA) would result in the direct decrease in the humeral head depression forces during both the push and recovery phases. During this time, the serratus anterior muscle (although not studied here) is vigorously active during the push phase to protract and upwardly rotate the scapula. A decrease in its force output as a result of fatigue would reduce the upward scapular rotation that helps to pull the acromion process out of the way of the humeral head. During the recovery phase of ST WC propulsion, the hands must be brought back to initiate the next propulsion cycle, which requires activation of the superior rotator cuff muscles. In contrast to ST WC propulsion, the hands during LEVER WC propulsion are always in contact with the lever device. Consequently, the SUPRA muscle showed reduced demand during lever propulsion because lifting the arms backward in preparation for the next propulsion cycle is no longer required.

During ST WC propulsion, almost 50% of the forces exerted at the pushrim are not directed toward forward motion and, therefore, either apply medially directed force to create friction to the pushrim or radially directed force that is wasted (31). To investigate the effectiveness of force application during WC propulsion in persons with tetraplegia and paraplegia, Dallmeijer et al (32) calculated the fraction of effective force (FEF)—defined as the ratio of effective force to total force—at 2 different submaximal intensity conditions. This low FEF is associated with low gross mechanical efficiency of WC propulsion and is one of the factors contributing to the high peak physical strains in daily activities of manual WC users (33). Results showed that the low FEF in those with tetraplegia confirms the inefficiency in the way they apply force to the ST WC. This low FEF is mainly the consequence of a larger lateromedially directed force component, which is most likely a result of loss of arm muscle function, particularly elbow extensor function, which is absent or reduced in those with high levels of SCI. Further, loss of hand grip function requires additional hand rim friction to propel the WC. As such, ADELT and PECMAJ intensities in people with tetraplegia were greater than in people with paraplegia, despite the reduction in propulsion velocity. A LEVER gear system can provide a mechanical advantage by virtue of the lever increasing the propulsion moment arm relative to the wheel rotation axis and can transfer the entire propulsion effort to the wheel without lateromedially and with reduced radially directed forces, which may lead to greater efficiency. As such, the PECMAJ demand decreased during LEVER WC propulsion. Individuals with diminished upper limb strength may benefit from the use of this LEVER WC propulsion device.

LEVER WC propulsion also eliminates the complex coupling-decoupling of the hand and pushrim that takes place during each ST WC propulsion cycle. These impact forces experienced by the hand and wrist during ST WC propulsion have been linked to development of carpal tunnel syndrome in manual WC users (34). In relating the median and ulnar nerve function and wrist joint kinematics during WC propulsion, Boninger et al (35) concluded that those who had better nerve function had larger wrist range of motion. Individuals who had a larger range of motion used less pushrim force and fewer strokes. Further biomechanical investigations with an instrumented lever will be required to compare the peak hand forces during LEVER and ST WC propulsion.

The inconsistent tendency of increased intensity of EMG activities of ADELT and INFRA muscles during LEVER WC propulsion during the increased resistance propulsion conditions could be indicative of an increased muscular demand. It is possible that LEVER WC propulsion shifts the demand of WC propulsion to other muscles, including the latissimus dorsi and triceps brachii, although these were not tested in this study. Increase in cycle distance suggests an increased shoulder range of motion anteriorly in the sagittal plane during the push phase of lever propulsion; also, the mechanical advantage provided by this particular lever mechanism may cause an increase in the posteriorly directed load to the glenohumeral joint. Consequently, muscles located in the anterior region of the glenohumeral joint (ADELT) would be required to increase their contribution to bring the lever forward. A concomitant increase in INFRA activity would be required to depress the humeral head in order to balance the vertical pull of the ADELT muscle. However, further biomechanical investigation using joint kinetic and kinematic analysis is necessary to fully delineate the upper extremity joint loads during LEVER WC propulsion.

Several features of LEVER WC propulsion should be noted to provide general guidelines for future designs. First, the fixed low-gear ratio (1-to-1) lever system used here may have limited the improvement in muscular demand across all propulsion conditions, because at higher propulsion speeds, increased push frequency to maintain the same ground speed is required. A variable lever-gear mechanism that can allow the user to shift the gear ratio “on the fly” has the potential to further improve propulsion efficiency when traversing varied conditions. Next, the LEVER design tested in this study did not allow the length of the lever to be adjusted. Consequently, the radius of the arc of motion increased, causing increased glenohumeral joint extension angle at initiation of the push. This increased glenohumeral-extension angle places the muscles located in the anterior region of the glenohumeral joint (ADELT) at a greater force-generating requirement. Therefore, a dynamically variable length lever design is recommended.

For the LEVER propulsion system investigated here, force application was possible only during the push phase. Some LEVER designs allowed the propulsive force to be applied during both the push and the pull phases of the cycle (19,23). This may be viable for some users, but those with trunk weakness or limited hand function may find pulling more challenging. Finally, for individuals with high-level tetraplegia and limited hand function, effective operation of the levers necessitates additional use of adaptive equipment to keep the hands in contact with the lever handles.

This study was limited to analysis of the EMG activity of 4 shoulder muscles. PECMAJ and ADELT are the 2 muscles primarily responsible for generating the forces required for forward propulsion in the push phase. SUPRA and INFRA are rotator cuff muscles that are active during the push phase to provide glenohumeral stability and counter the upward pull of the anterior deltoid on the humeral head to keep it centered in the glenoid fossa to prevent impingement. In addition, SUPRA muscles are active during the recovery phase in two thirds of the participants and consequently are active for a long duration and susceptible to fatigue (8). EMG activities of the latissimus dorsi and subscapularis in some but not all of the participants were recorded. EMG activities of the latissimus dorsi were not recorded in all participants because of the lack of innervation for those with higher levels of injury. Subscapularis muscles were not included because of difficulty with fine-wire placement for several of the participants and functionally different phasing of activity (push phase for those with tetraplegia and recovery phase for those with paraplegia), making direct comparison problematic. This study found reduced muscular demands of PECMAJ and SUPRA in LEVER compared with ST WCs. Given the direction of the motions during lever propulsion, it is possible that activity was increased in triceps and serratus anterior during the push phase and in biceps and posterior deltoid during the recovery phase. Only increased demand for the serratus anterior would increase susceptibility for impingement. Because muscle activity for this scapular rotator typically corresponds to the demand on the propulsive muscles, it is more likely that activity was reduced rather than increased for serratus anterior with LEVER WC propulsion.

This study was primarily interested in the impact of LEVER WC propulsion on the muscular demands of the push phase. This is the phase of the propulsion cycle when the downward force exerted on the pushrim results in a superiorly directed joint reaction force at the shoulder (30). It is this vertical force that places the shoulder at risk for impingement of the subacromial structures on the overlying acromion. Alternative propulsion modes (eg, LEVER system) that reduce the intensity of muscle activation for the primary muscle groups would decrease the likelihood of fatigue and reduce the susceptibility for impingement.

CONCLUSIONS

The LEVER WC reduced and shifted the shoulder muscular demands in individuals with paraplegia or tetraplegia caused by SCI. Further studies are needed to determine the impact of LEVER WC propulsion on long-term shoulder function.

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