

Original Article

Changes in oxygen uptake, shoulder muscles activity, and propulsion cycle timing during strenuous wheelchair exercise

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Study design: Cross-over study.

Objective: To determine the effect of strenuous wheelchair exercise on oxygen uptake ($\dot{V}O_2$), muscle activity and propulsion cycle timing (including the push time and recovery time during one full arm cycle).

Setting: Laboratory of Sport Sciences at the University of France-Comte in France.

Methods: Two exercise bouts of 6-min duration were performed at a constant workload: (1) non-fatigable exercise (moderate workload) and (2) fatigable exercise (heavy workload). Measurement of $\dot{V}O_2$, surface electromyographic activity (EMG) from shoulder muscles, and temporal parameters of wheelchair ergometer propulsion were collected from eight able-bodied men (26 ± 4 years).

Results: A progressive increase in $\dot{V}O_2$ associated with EMG alterations ($P < 0.05$), and a decrease of the cycle and recovery time ($P < 0.05$) during the heavy exercise. Whereas the push time remained constant, an increased muscle activation time ($P < 0.05$) was found during heavy exercise.

Conclusion: Observations during wheelchair ergometry indicate the development of fatigue and inefficient muscle coordination, which may contribute to deleterious stress distributions at the shoulder joint, increasing susceptibility to injury.

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Keywords: able-bodied; electromyography; fatigue; manual wheelchair; oxygen uptake; shoulder

Introduction

Manual wheelchair propulsion is an inefficient mode of ambulation, with a gross mechanical efficiency in the range of 2–10%.^{1,2} The main mechanical factors associated with the poor efficiency of wheelchair propulsion are: (1) the explicit necessity to stabilize the highly flexible shoulder complex and the hand-wrist system during propulsion;^{3,4} (2) the inefficient resultant vector produced by the hand on the wheel during the propulsion phase;^{2,5,6} (3) the discontinuity of hand rim propulsion which requires an amount of energy;^{7,8} and (4) the small muscle mass engaged in the propulsion task.^{9,10}

Hand rim wheelchair propulsion has been extensively studied with respect to external force parameters;^{2,5,11,12} kinematics^{13–16} and myoelectric parameters of arm muscles.^{4,17,18} These studies demonstrated that both

the environmental constraint and the level of expertise modify biomechanical and electromyographical responses of a wheelchair user.

However, only a few authors have investigated the propulsion movement and its consequences on oxygen uptake ($\dot{V}O_2$) and muscles activity during fatigue.^{18–21} These studies examined movement and muscle activation to develop more specific strength-training programs to avoid upper limb injuries. Within this framework, little is known regarding adjustments of propulsion cycle timing and muscle coordination during fatiguing wheelchair-exercise.

The purpose of this study was to determine the effect of constant-load exercise on $\dot{V}O_2$, muscle fatigue, and movement cycle timing at two different intensities. We hypothesized that moderate exercise below ventilatory threshold (VT) would not induce fatigue. However, heavy exercise above VT would induce fatigue and thus alter oxygen uptake, muscle activity, and movement cycle timing.

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Methods

Subjects

After providing written informed consent, eight able-bodied men (age: 26 ± 4 years; height: 176 ± 4 cm; and weight: 73 ± 7 kg) participated in the study. All participants were right handed and had no prior experience in wheelchair propulsion. All applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Procedure

Each exercise bout was performed on a standard wheelchair (Quickie EX, Sunrise Medical, England), placed on an ergometer (VP100H, H.E.F. Tecmachine, Andrezieux Boutheon, France), at a constant velocity of 5 km/h, with subjects choosing a propulsion frequency.

Subjects first performed incremental exercise to determine $\dot{V}O_{2peak}$ and VT. $\dot{V}O_{2peak}$ was defined as maximal $\dot{V}O_2$ reached during the incremental exercise.²² VT was determined using the ventilatory equivalents method according to Wasserman *et al*²³ and Vallier *et al*.²⁴ The initial power output (PO) was set at 28 ± 3 Watts (W) for 2 min and further increased by 10 W for each subsequent 2 min until the subject could no longer maintain the compulsory velocity.

Subjects came back 2 days after the incremental exercise test to perform two constant-load exercise bouts of 6 min duration. The first exercise bout was performed at a PO corresponding to $\sim 80\%$ of the PO at VT and was referred to as the moderate intensity exercise bout. Following a minimum of 15 min of passive recovery, the subject performed a second exercise bout at a PO corresponding to $\sim 50\%$ between the PO at VT and the PO at $\dot{V}O_{2peak}$. This exercise bout was referred to as the heavy intensity exercise bout.

Data acquisition

During each exercise bout, oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), and ventilation were determined breath-by-breath (K4b², Cosmed, Roma, Italy) and averaged every 30 s. O_2 and CO_2 analyzers were calibrated together with signal volume according to manufacturer instructions before each test session, using reference gases of known concentrations and a 3-l calibration syringe.

The wheelchair ergometer system, extensively detailed in Devillard *et al*,²⁵ simulated inertia of the user-chair system and allowed the measurement of instantaneous force and velocity during exercise at a sampling rate of 200 Hz. Temporal characteristics of the propulsion cycle pattern were calculated using speed and acceleration/deceleration recordings during all tests: cycle time (time to complete one full arm cycle in s), push time (period corresponding to the acceleration of the wheels in s), and recovery time (difference between the cycle time and the push time in s). For both exercise conditions, the

mean values of each cycle parameter (ie cycle, push and recovery time) were calculated over the last 15 s before minutes 3 and 6 (moderate exercise) or every minute (heavy exercise).

Electromyographic activity (EMG) was recorded from the biceps brachii, the long head of the triceps brachii, the anterior deltoid, the middle part of the trapezius, the infraspinatus, and the latissimus dorsi muscles of the right shoulder. The rectus abdominis was also studied to evaluate the stabilization of the trunk. Myoelectric signals were recorded using an eight-channel EMG recorder (ME3000P8, Mega Electronics, Kuopio, Finland) with a bandwidth of 8–500 Hz (Common Mode Rejection Ratio = 110 dB) at a sampling rate of 1000 Hz. Bipolar surface electrodes were positioned on the contracted muscle belly after appropriate skin preparation with a center-to-center distance of 30 mm, along a line approximately parallel to the direction of the underlying muscle fibers. All EMG cables were taped down to prevent movement artifact. Myoelectric signals were collected during the last 15 s of the third and the sixth minute during the moderate exercise, and at the end of each minute during the heavy exercise. The raw EMG signal was converted into root-mean-square (RMS) with a time constant of 25 ms and into mean power frequency (MPF) using Hamming windowing and 512 points Fast Fourier Transform.

RMS of all muscles studied were summed and averaged to provide an index of the total muscle activity,²⁶ further referred to as the average RMS response. The same procedure was applied to MPF to provide the average MPF response. Each parameter was then normalized to the third minute of exercise.

Activation time was determined for each muscle during the last 15 s (at least eight cycles) of minute 3 and of minute 6 with careful visual inspection during both exercise bouts (method adapted from Wilen *et al*²⁷). Muscles were considered active when the RMS was above 10% of maximal amplitude for at least 50 ms. Conversely, muscles were considered inactive when the RMS was below 10% of maximal amplitude during 50 ms. Maximal amplitude was defined as the highest RMS value obtained during the exercise. Activation time was then expressed as a percentage of the cycle time and averaged across 15 s at minutes 3 and 6.

Statistical analyses

All data are presented as means \pm SD unless otherwise specified.

Nonparametric tests were performed when data displayed unequal variances (Bartlett test) or were not normally distributed (Kolmogorov-Smirnov test). The Friedman repeated measures test was used to compare $\dot{V}O_2$ across time and Student–Newman–Keuls *post hoc* test was performed to determine when $\dot{V}O_2$ became stable across time for each exercise bout. Paired *t*-tests were used to compare cycle time, push time, recovery time, RMS, MPF, and activation time between the third and the sixth minute during the moderate exercise bout.

A repeated measures ANOVA was performed to compare the same parameters across time during the heavy exercise bout. Multiple comparisons were performed using Student–Newman–Keuls *post hoc* test. The level of significance was set at 0.05 for all tests.

Results

Oxygen uptake

$\dot{V}O_{2peak}$ during the incremental exercise test was 2478 ± 486 ml/min (34.49 ± 8.39 ml/min/kg). During the moderate exercise bout ($PO = 41 \pm 6$ W), $\dot{V}O_2$ stabilized during the third minute (1042 ± 200 ml/min) (Figure 1). However, no $\dot{V}O_2$ stabilization was observed during the heavy exercise bout ($PO = 66 \pm 6$ W) between minutes 3 and 6, with a progressive increase of 437 ± 224 ml/min ($+26.62 \pm 11.38\%$). $\dot{V}O_2$ was 2042 ± 453 ml/min at the end of the heavy exercise bout.

EMG parameters

RMS, MPF, mean RMS, and MPF responses, and activation time of the seven muscles were similar between the third and the sixth minute during the moderate exercise bout. Only the MPF of the anterior deltoid muscle significantly ($P < 0.05$) decreased ($-3.12 \pm 3.37\%$) between the third and sixth minute.

During the heavy exercise bout, RMS from all muscles significantly ($P < 0.05$) increased (Figure 2), except for the middle part of the trapezius muscle. The mean RMS response significantly ($P < 0.05$) increased ($+39.47 \pm 11.68\%$) between the third and sixth minute, and the mean MPF response decreased ($-5.80 \pm 4.56\%$) between the first and third minute only (Figure 3). MPF parameters also significantly ($P < 0.05$) decreased for the triceps brachii and anterior deltoid between the first and third minute and for pectoralis major muscles between the second and the third minute (Figure 4).

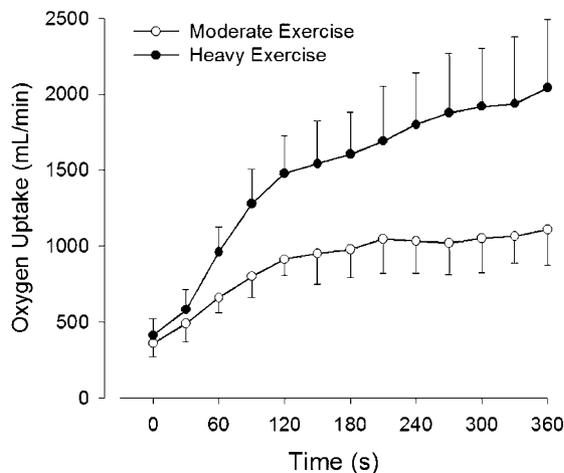


Figure 1 Oxygen uptake kinetic during moderate (○) and heavy (●) exercise bouts

Muscle activation time

Muscle activation time did not significantly change during the moderate exercise between the third and sixth minute. During the heavy exercise bout, muscle activation time of the triceps brachii, anterior deltoid, pectoralis major, and rectus abdominis muscles were significantly ($P < 0.05$) longer during the sixth minute than during the third minute (Figure 5).

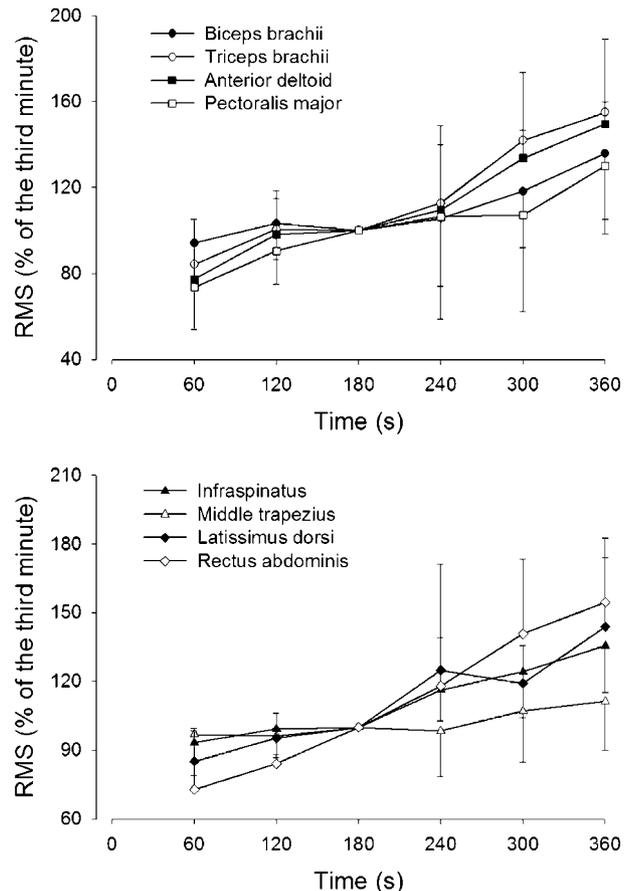


Figure 2 RMS during the heavy exercise bout

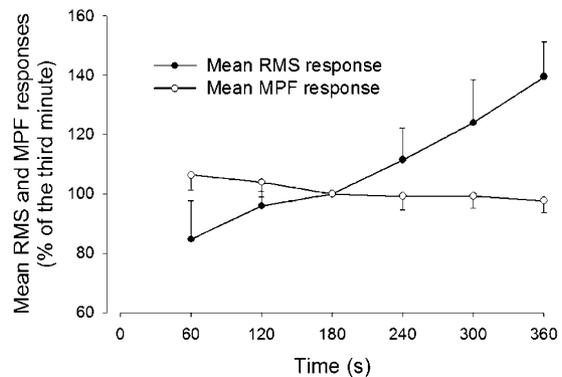


Figure 3 Mean RMS (●), and MPF (○) responses during the heavy exercise bout

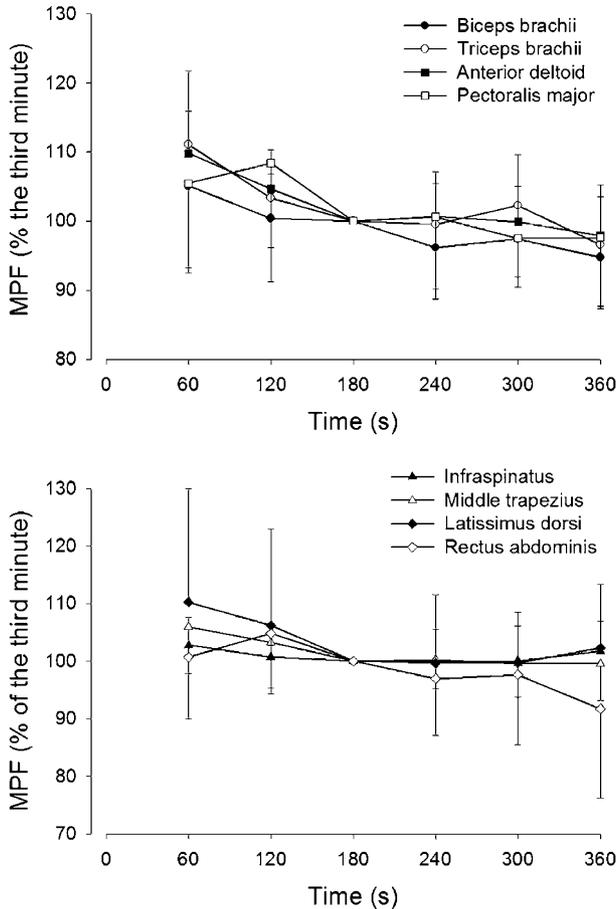


Figure 4 MPF during the heavy exercise bout

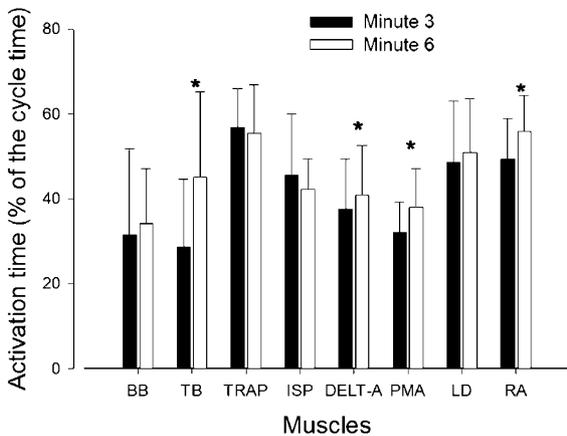


Figure 5 Activation time during the heavy exercise bout at minutes 3 and 6. * $P < 0.05$. (BB: biceps brachii; TB: triceps brachii; TRAP: trapezius, middle part; ISP: infraspinatus; DELT-A: anterior deltoid; PMA: pectoralis major; LD: latissimus dorsi; RA: rectus abdominis)

Temporal parameters

No significant difference between the third and sixth minute was observed for cycle (1.62 ± 0.33 s), push (0.36 ± 0.04 s), and recovery (1.26 ± 0.31 s) times during

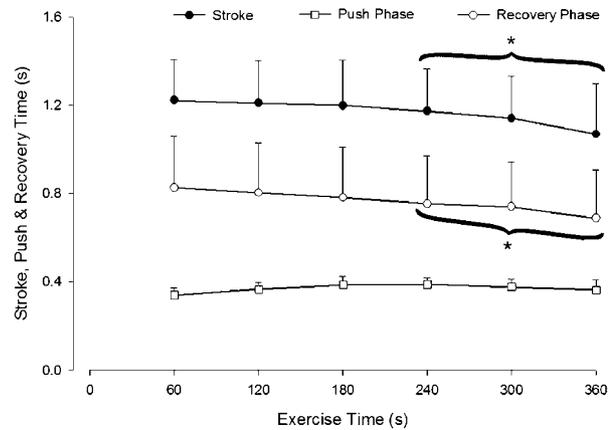


Figure 6 Cycle (●), push (□), and recovery (○) times during the heavy exercise bout. *Significantly different from minute 3 ($P < 0.05$)

the moderate exercise bout. However, the cycle and recovery times (Figure 6) significantly ($P < 0.05$) decreased between the third and sixth minute during the heavy exercise bout ($-10.99 \pm 9.15\%$ and $-11.68 \pm 9.56\%$, respectively).

Discussion

This study focused on adaptations of oxygen uptake, propulsion cycle timing, and muscle coordination during nonfatiguing and fatiguing wheelchair ergometry. Two exercise conditions were applied: one moderate exercise bout below VT (nonfatiguing), and one heavy exercise bout above VT (fatiguing).

Moderate exercise

Our results show constant $\dot{V}O_2$ after 3 min of moderate exercise, as well as no modification of propulsion cycle timing (characterized by the cycle, push, and recovery times), or of muscle activity and activation time for seven muscles surrounding the shoulder complex and the trunk over the exercise.

However, whereas the RMS of the anterior deltoid remained stable, MPF of the anterior deltoid muscle slowly decreased from minutes 3 to 6 despite low PO values (approximately 40 W), De Groot *et al*⁸ have shown that the peak activity of this muscle at a PO of 20 W corresponds to 40% of its maximal voluntary contraction during wheelchair propulsion for able-bodied men. As our study involves a PO approximately twice the PO of the previous study, we suggest that the decrease in MPF observed in our study was a consequence of fatigue. Several phenomena could provoke a reduction in MPF during fatigue, such as reduction of muscle membrane excitability^{28,29} and synchronization of active motor units.^{30,31} Considering the intensity of the exercise, synchronization of motor units is not a plausible hypothesis because it occurs when motor units are close to exhaustion.^{30,32} There-

fore, we suggest that the MPF decrease could be due to a decline of the firing frequency of active motor units to preserve muscle membrane excitability. This adaptation has been proposed by previous authors during fatiguing exercises and is referred to as muscle wisdom.^{33,34}

Heavy exercise

Several changes were observed during the heavy exercise bout, which may be attributed to fatigue.

$\dot{V}O_2$ increased by 437 ± 224 ml/min between minutes 3 and 6 (Figure 1). This increase is often observed during heavy square-wave exercise bouts and corresponds to a slow component of $\dot{V}O_2$, as described by several authors.^{35–38} The amplitude of the $\dot{V}O_2$ slow component in our study is consistent with the amplitude observed during arm cranking exercise,^{22,39–41} despite the lower mechanical efficiency^{9,42,43} and the higher cardiorespiratory stress ($\dot{V}O_2$, cardiac output...)⁴⁴ during wheelchair propulsion.

One factor that has been proposed to explain the $\dot{V}O_2$ slow component is recruitment of fast-twitch muscle fibers as a consequence of fatigue.^{26,45,46} One method to identify muscle fatigue is to study the neuromuscular activity over time during exercise.^{47–50} Our results show a RMS increase during the exercise bout for seven muscles (Figure 2), which suggests the development of muscle fatigue and the recruitment of additional muscle fibers to maintain the required PO.^{29,51} The mean RMS response (Figure 3), as an index of whole neuromuscular activity,²⁶ also suggests a recruitment of additional muscle fibers from the onset of the exercise bout.

Furthermore, mean MPF response (Figure 3) and MPF of the pectoralis major, the anterior deltoid, and the triceps brachii muscles (the prime movers for the push phase) (Figure 4) also decreased during the first minutes. As the MPF reduction occurs only during the first minutes of exercise, we suggest that muscle wisdom (a decline in the firing frequency of active motor units to preserve the muscle membrane excitability) is the most likely explanation for our findings.

Our finding of alterations in the EMG activity of seven muscles supports our second hypothesis that muscle fatigue occurs during wheelchair ergometry. During the push phase, the prime movers of shoulder flexion (pectoralis major, anterior deltoid, and biceps brachii muscles),^{52,53} and the triceps brachii muscle are mostly active.^{18,54,55} This involves flexor and extensor muscle coordination around the elbow, leading to an increased tendency to fatigue in individual muscles of the upper extremity.

The infraspinatus muscle, representing the rotator cuff muscles,⁵⁶ stabilizes the humeral head laterally⁵³ and counteracts the action of the medial rotator muscles on the shoulder.^{53,57} The infraspinatus muscle also prevents the superior translation of the humeral head during shoulder abduction, a movement occurring during the recovery phase of the manual wheelchair propulsion cycle.

Previous studies⁵⁴ have shown that the latissimus dorsi muscle is principally active during the recovery phase. However, it also stabilizes the humeral head during shoulder flexion,⁵³ an action necessary during the push phase. We hypothesize that the activity of the latissimus dorsi during both muscle coordination and the recovery phase can explain the observed fatigue of this muscle.

Rodgers *et al*²¹ observed a power shift from the shoulder to the elbow and wrist joints during fatiguing wheelchair exercise. This finding supports the need to study muscle patterns during exercise and, therefore, the effects of fatigue on muscle activation time. An unexpected result of the present study was the observed increase of muscle activation time for the prime movers of the push phase (pectoralis major, anterior deltoid, triceps brachii) (Figure 5), despite a decrease in the duration of the cycle propulsion (Figure 6). This effect was likely due to the impact of fatigue on muscle function. Rodgers *et al*²⁰ previously observed the same effect. The increase of the relaxation half-time previously observed during fatiguing exercise may have caused the increased activation time during the wheelchair exercise.^{33,58,59} A reduction of calcium pump activity of the sarcoplasmic reticulum^{59,60} resulting from an accumulation of inorganic phosphate⁶¹ or changes in the action potential shape⁶² are the most plausible explanations for the decline of the relaxation half-time. These two alterations also contribute to an increase in RMS and a decrease in MPF, electromyographical changes observed in our study.

Furthermore, the increase in activation time during exercise, as fatigue occurs, could induce an increase of the coactivation between agonist and antagonist muscles and, therefore, reduce motor efficiency. This reduction could partly explain the $\dot{V}O_2$ slow component, and warrants further investigation.

The second major finding of the present study relates to the observed changes in propulsion cycle characteristics resulting from fatigue (Figure 6). The temporal characteristics of the propulsion cycle at minutes 3 and 6 were different during the heavy exercise bout. The cycle time decreased because the recovery time declined, while the push time remained constant. The push time as a proportion of the cycle time also increased with fatigue.

Rodgers *et al*²⁰ observed no temporal characteristic modifications of the propulsion cycle timing over time during exercise bouts at 50 and 75% of $\dot{V}O_{2peak}$ for wheelchair users. However, in nonwheelchair users, Rodgers *et al*²¹ found the same fatigue effects at 75% of $\dot{V}O_{2peak}$ as were observed in the present study. Furthermore, measures of cycle time in the present study (~ 1.17 s) were within the 0.8–1.5 s range reported in other studies.⁶³ The push time (24–43% of the cycle time) and recovery time (57–76% of the cycle time) values observed in our study were also similar to previous values.^{18,19,21,64}

Our findings are consistent with the literature and support the belief that fatigue results in modifications of intersegmental coordination. Consequences of these

modifications are: (1) an increase of the muscle activation time, which could contribute to the $\dot{V}O_2$ slow component effect but has not yet been investigated; and (2) possible alterations of muscle coordination during exercise, which play a critical role in the development of musculoskeletal injuries.⁶⁵ Changes in muscle coordination suggest that muscles crossing the joint fatigue at different rates during exhausting activities and produce an unbalanced force distribution around the joint. This unbalanced force distribution could potentially cause unnatural motions of the joint, creating abnormal joint loading. Trying to find a less strenuous propulsion technique could be a valuable perspective to help the wheelchair users and reduce the injury prevalence of this population. However, the mechanisms leading to muscular imbalances remain unclear.

Conclusion

The present study reveals that several effects occur during a heavy intensity bout of wheelchair exercise. The fatiguing exercise induces: (1) a $\dot{V}O_2$ slow component; (2) fatigue of numerous muscles acting around the shoulder joint, particularly muscles involved throughout the propulsion phase; and (3) modifications of propulsion and muscle activation timing. These effects could alter muscle coordination around the joint and increase the risk of injury.

References

- 1 Van der Woude LH, De Groot G, Hollander AP, Van Ingen Schenau GJ, Rozendal RH. Wheelchair ergonomics and physiological testing of prototypes. *Ergonomics* 1986; **29**: 1561–1573.
- 2 Dallmeijer AJ, Van der Woude LH, Veeger HE, Hollander AP. Effectiveness of force application in manual wheelchair propulsion in persons with spinal cord injuries. *Am J Phys Med Rehabil* 1998; **77**: 213–221.
- 3 Van der Helm FC, Veeger HE. Quasi-static analysis of muscle forces in the shoulder mechanism during wheelchair propulsion. *J Biomech* 1996; **29**: 39–52.
- 4 Veeger HEJ, Van Der Woude LHV, Rozendal RH, Bieleman HJ, Paul JA. EMG and movement pattern in manual wheelchair propulsion. In: Wallinga W, Boom HBK, Vries JD (eds). *Electrophysiological Kinesiology*. Elsevier Science Publishers (Biomedical Division) 1988, pp 489–492.
- 5 Veeger HE, Van der Woude LH, Rozendal RH. Effect of handrim velocity on mechanical efficiency in wheelchair propulsion. *Med Sci Sports Exerc* 1992; **24**: 100–107.
- 6 Van der Woude LH, Veeger HE, Dallmeijer AJ, Janssen TW, Rozendaal LA. Biomechanics and physiology in active manual wheelchair propulsion. *Med Eng Phys* 2001; **23**: 713–733.
- 7 Van der Woude LH, Van Kranen E, Ariens G, Rozendal RH, Veeger HE. Physical strain and mechanical efficiency in hubcrank and handrim wheelchair propulsion. *J Med Eng Technol* 1995; **19**: 123–131.
- 8 De Groot S, Veeger HE, Hollander AP, Van der Woude LH. Short-term adaptations in co-ordination during the initial phase of learning manual wheelchair propulsion. *J Electromyogr Kinesiol* 2003; **13**: 217–228.
- 9 Sawka MN. Physiology of upper body exercise. *Exerc Sport Sci Rev* 1986; **14**: 175–211.
- 10 Glaser RM. Arm exercise training for wheelchair users. *Med Sci Sports Exerc* 1989; **21**(5 Suppl): S149–S157.
- 11 Robertson RN, Boninger ML, Cooper RA, Shimada SD. Pushrim forces and joint kinetics during wheelchair propulsion. *Arch Phys Med Rehabil* 1996; **77**: 856–864.
- 12 Boninger ML, Cooper RA, Robertson RN, Shimada SD. Three-dimensional pushrim forces during two speeds of wheelchair propulsion. *Am J Phys Med Rehabil* 1997; **76**: 420–426.
- 13 Van der Woude LH, Veeger HE, Rozendal RH. Propulsion technique in hand rim wheelchair ambulation. *J Med Eng Technol* 1989; **13**: 136–141.
- 14 Shimada SD, Robertson RN, Boninger ML, Cooper RA. Kinematic characterization of wheelchair propulsion. *J Rehabil Res Dev* 1998; **35**: 210–218.
- 15 Newsam CJ, Mulroy SJ, Gronley JK, Bontrager EL, Perry J. Temporal-spatial characteristics of wheelchair propulsion. Effects of level of spinal cord injury, terrain, and propulsion rate. *Am J Phys Med Rehabil* 1996; **75**: 292–299.
- 16 Boninger ML, Cooper RA, Shimada SD, Rudy TE. Shoulder and elbow motion during two speeds of wheelchair propulsion: a description using a local coordinate system. *Spinal Cord* 1998; **36**: 418–426.
- 17 Harburn KL, Spaulding SJ. Muscle activity in the spinal cord-injured during wheelchair ambulation. *Am J Occup Ther* 1986; **40**: 629–636.
- 18 Mulroy SJ, Gronley JK, Newsam CJ, Perry J. Electromyographic activity of shoulder muscles during wheelchair propulsion by paraplegic persons. *Arch Phys Med Rehabil* 1996; **77**: 187–193.
- 19 Rodgers MM, Keyser RE, Gardner ER, Russell PJ, Gorman PH. Influence of trunk flexion on biomechanics of wheelchair propulsion. *J Rehabil Res Dev* 2000; **37**: 283–295.
- 20 Rodgers MM, Gayle GW, Figoni SF, Kobayashi M, Lieh J, Glaser RM. Biomechanics of wheelchair propulsion during fatigue. *Arch Phys Med Rehabil* 1994; **75**: 85–93.
- 21 Rodgers MM, McQuade KJ, Rasch EK, Keyser RE, Finley MA. Upper-limb fatigue-related joint power shifts in experienced wheelchair users and nonwheelchair users. *J Rehabil Res Dev* 2003; **40**: 27–37.
- 22 Koga S, Shiojiri T, Shibasaki M, Fukuba Y, Fukuoka Y, Kondo N. Kinetics of oxygen uptake and cardiac output at onset of arm exercise. *Respir Physiol* 1996; **103**: 195–202.
- 23 Wasserman K, Whipp BJ, Koyal SN, Beaver WL. Anaerobic threshold and respiratory gas exchange during exercise. *J Appl Physiol* 1973; **35**: 236–243.
- 24 Vallier JM, Bigard AX, Carre F, Eclache JP, Mercier J. Determination of lactic and ventilatory thresholds. Position of the Societe Francaise de Medecine du Sport (French Sports Medicine Society); Determination des seuils lactiques et ventilatoires. Position de la Societe Francaise de medecine du sport. *Sci Sports* 2000; **15**: 133–140.
- 25 Devillard X et al. Validation of a new ergometer adapted to all types of manual wheelchair. *Eur J Appl Physiol* 2001; **85**: 479–485.
- 26 Burnley M, Doust JH, Ball D, Jones AM. Effects of prior heavy exercise on $\dot{V}O_2$ kinetics during heavy exercise are related to changes in muscle activity. *J Appl Physiol* 2002; **93**: 167–174.

- 27 Wilen J, Sisto SA, Kirshblum S. Algorithm for the detection of muscle activation in surface electromyograms during periodic activity. *Ann Biomed Eng* 2002; **30**: 97–106.
- 28 Moxham J et al. Changes in EMG power spectrum (high-to-low ratio) with force fatigue in humans. *J Appl Physiol* 1982; **53**: 1094–1099.
- 29 Moritani T, Muro M, Nagata A. Intramuscular and surface electromyogram changes during muscle fatigue. *J Appl Physiol* 1986; **60**: 1179–1185.
- 30 Krogh-Lund C. Myo-electric fatigue and force failure from submaximal static elbow flexion sustained to exhaustion. *Eur J Appl Physiol Occup Physiol* 1993; **67**: 389–401.
- 31 Broman H, Bilotto G, De Luca CJ. Myoelectric signal conduction velocity and spectral parameters: influence of force and time. *J Appl Physiol* 1985; **58**: 1428–1437.
- 32 Bigland-Ritchie B, Donovan EF, Roussos CS. Conduction velocity and EMG power spectrum changes in fatigue of sustained maximal efforts. *J Appl Physiol* 1981; **51**: 1300–1305.
- 33 Enoka RM, Stuart DG. Neurobiology of muscle fatigue. *J Appl Physiol* 1992; **72**: 1631–1648.
- 34 Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev* 2001; **81**: 1725–1789.
- 35 Barstow TJ, Mole PA. Linear and nonlinear characteristics of oxygen uptake kinetics during heavy exercise. *J Appl Physiol* 1991; **71**: 2099–2106.
- 36 Poole DC, Barstow TJ, Gaesser GA, Willis WT, Whipp BJ. O₂ slow component – physiological and functional-significance. *Med Sci Sport Exerc* 1994; **26**: 1354–1358.
- 37 Whipp BJ. The slow component of O₂ uptake kinetics during heavy exercise. *Med Sci Sports Exerc* 1994; **26**: 1319–1326.
- 38 Bearden SE, Henning PC, Bearden TA, Moffatt RJ. The slow component of $\dot{V}O_2$ kinetics in very heavy and fatiguing square-wave exercise. *Eur J Appl Physiol* 2004; **91**: 586–594.
- 39 Casaburi R, Barstow TJ, Robinson T, Wasserman K. Dynamic and steady-state ventilatory and gas exchange responses to arm exercise. *Med Sci Sports Exerc* 1992; **24**: 1365–1374.
- 40 Koppo K, Bouckaert J, Jones AM. Oxygen uptake kinetics during high-intensity arm and leg exercise. *Respir Physiol Neurobiol* 2002; **133**: 241–250.
- 41 Schneider DA, Wing AN, Morris NR. Oxygen uptake and heart rate kinetics during heavy exercise: a comparison between arm cranking and leg cycling. *Eur J Appl Physiol* 2002; **88**: 100–106.
- 42 Van der Woude LH et al. Manual wheelchair propulsion: effects of power output on physiology and technique. *Med Sci Sports Exerc* 1988; **20**: 70–78.
- 43 Tropp H, Samuelsson K, Jorfeldt L. Power output for wheelchair driving on a treadmill compared with arm crank ergometry. *Br J Sports Med* 1997; **31**: 41–44.
- 44 Sawka MN, Glaser RM, Wilde SW, von Lührte TC. Metabolic and circulatory responses to wheelchair and arm crank exercise. *J Appl Physiol* 1980; **49**: 784–788.
- 45 Saunders MJ, Evans EM, Arngrimsson SA, Allison JD, Warren GL, Cureton KJ. Muscle activation and the slow component rise in oxygen uptake during cycling. *Med Sci Sports Exerc* 2000; **32**: 2040–2045.
- 46 Shinohara M, Moritani T. Increase in neuromuscular activity and oxygen uptake during heavy exercise. *Ann Physiol Anthropol* 1992; **11**: 257–262.
- 47 Takaishi T, Yasuda Y, Moritani T. Neuromuscular fatigue during prolonged pedaling exercise at different pedaling rates. *Eur J Appl Physiol* 1994; **69**: 154–158.
- 48 Vollestad NK. Measurement of human muscle fatigue. *J Neuro Meth* 1997; **74**: 219–227.
- 49 Dimitrova NA, Dimitrov GV. Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *J Electromyogr Kinesiol* 2003; **13**: 13–36.
- 50 Nussbaum MA. Static and dynamic myoelectric measures of shoulder muscle fatigue during intermittent dynamic exertions of low to moderate intensity. *Eur J Appl Physiol* 2001; **85**: 299–309.
- 51 Kuroda E, Klissouras V, Milsum JH. Electrical and metabolic activities and fatigue in human isometric contraction. *J Appl Physiol* 1970; **29**: 358–367.
- 52 Parratte B, Tatu L, Vuillier F, Diop M, Bonniaud V, Monnier G. Anatomie fonctionnelle de l'épaule (functional anatomy of the shoulder). *Rev Med Trav* 2001; **28**: 149–159.
- 53 Kronberg M, Nemeth G, Brostrom LA. Muscle activity and coordination in the normal shoulder. An electromyographic study. *Clin Orthop Relat Res* 1990; **257**: 76–85.
- 54 Veeger HE, van der Woude LH, Rozendal RH. Within-cycle characteristics of the wheelchair push in sprinting on a wheelchair ergometer. *Med Sci Sports Exerc* 1991; **23**: 264–271.
- 55 Schantz P, Björkman P, Sandberg M, Andersson E. Movement and muscle activity pattern in wheelchair ambulation by persons with para-and tetraplegia. *Scand J Rehabil Med* 1999; **31**: 67–76.
- 56 Bressel E, Bressel M, Marquez M, Heise GD. The effect of handgrip position on upper extremity neuromuscular responses to arm cranking exercise. *J Electromyogr Kinesiol* 2001; **11**: 291–298.
- 57 David G, Magarey ME, Jones MA, Dvir Z, Türker KS, Sharpe M. EMG and strength correlates of selected shoulder muscles during rotations of the glenohumeral joint. *Clin Biomech (Bristol, Avon)* 2000; **15**: 95–102.
- 58 Bigland-Ritchie B, Furbush FH, Gandevia SC, Thomas CK. Voluntary discharge frequencies of human motoneurons at different muscle lengths. *Muscle Nerve* 1992; **15**: 130–137.
- 59 Dawson MJ, Gadian DG, Wilkie DR. Mechanical relaxation rate and metabolism studied in fatiguing muscle by phosphorus nuclear magnetic resonance. *J Physiol* 1980; **299**: 465–484.
- 60 Berchtold MW, Brinkmeier H, Muntener M. Calcium ion in skeletal muscle: its crucial role for muscle function, plasticity, and disease. *Physiol Rev* 2000; **80**: 1215–1265.
- 61 Westerblad H, Allen DG, Lannergren J. Muscle fatigue: lactic acid or inorganic phosphate the major cause? *News Physiol Sci* 2002; **17**: 17–21.
- 62 Giannesini B, Cozzone PJ, Bendahan D. Non-invasive investigations of muscular fatigue: metabolic and electromyographic components. *Biochimie* 2003; **85**: 873–883.
- 63 Sanderson DJ, Sommer HJ. Kinematic features of wheelchair propulsion. *J Biomech* 1985; **18**: 423–429.
- 64 Thoumie P, Thevenin-Lemoine E, Bedoisseau M. Membre supérieur et locomotion en fauteuil roulant – Etude cinésilogique. In: Pélissier J, Jacquot J-M, Bernard P-L (eds). *Le fauteuil roulant*. Paris: Masson 1997, pp 96–102.
- 65 Kumar S. Theories of musculoskeletal injury causation. *Ergonomics* 2001; **44**: 17–47.