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Influence of training on biomechanics of wheelchair propulsion

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Abstract — A quasi-experimental longitudinal design was used to compare pre- and posttraining biomechanical and physiological characteristics of wheelchair propulsion in manual wheelchair users (MWCU) across fresh and fatigue states. An instrumented wheelchair ergometer, 3D motion analysis, and computerized open-circuit spirometry were used to collect joint kinetics and kinematics, handrim kinetics, propulsion temporal characteristics, and oxygen uptake pre- and posttraining during a submaximal exercise test to exhaustion. Each subject (n=19) participated in a specific intervention program of supervised therapeutic exercise (strengthening, stretching, and aerobic exercise) for 6 weeks. Pre- and posttraining measurements were compared using ANOVA with repeated measures. Significant training effects included increased exercise loads for all strengthening activities, decreased stroke frequency, increased maximum elbow extension angle, increased trunk and shoulder flexion/extension range of motion (ROM), increased handrim propulsive moment, increased wrist extension moment and increased power output. Results suggest that this training program increased biomechanical economy (as defined by propulsive moment) without increasing shoulder or elbow joint stresses.

Key words: *biomechanics, kinematics, therapeutic exercise, training kinetics, wheelchair.*

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INTRODUCTION

The functional consequences of lower-limb disability include diminished independence, fitness, work capacity, and recreational/employment opportunities. Physical performance (1,2) and quality of life (3-5) can be limited by upper-limb pain resulting from overuse injury in manual wheelchair users (MWCU). Chronic conditions such as carpal tunnel syndrome (6,7), rotator cuff injuries (8,9), elbow/shoulder tendinitis (7), and osteoarthritis (9,10) have been associated with long-term manual wheelchair use. Shoulder or wrist joint pain has been reported in 64-73 percent of MWCU with spinal cord injuries (2,6,7,11). In a study by Davidoff et al., 67 percent of MWCU had upper-limb mononeuropathies defined by strict electrodiagnostic criteria (12). These conditions can decrease function and increase health care costs for the wheelchair-using population.

In addition, ineffective biomechanics can decrease the economy of wheelchair operation and lead to excessive metabolic and cardiopulmonary demand (13). Investigators have identified several possible contributors to overuse injuries in MWCU, including duration of manual wheelchair use (7,14), frequency of arm use (15), and propulsion style kinematics (16). Several investigators have proposed that chronic wheelchair use creates imbalances in propulsion agonists and antagonists (17-20) and that training of the antagonists may correct these imbalances (17-19,21), thereby reducing the potential for associated upper-limb pain.

The significance of this study is in the identification of body mechanics used during wheelchair propulsion that are potentially injurious. In addition, information that contributes to better wheelchair locomotion economy and reduction of potentially harmful stresses could improve the performance of everyday activities (including job-related activities) for wheelchair users. They would be able to increase their activity levels without undue risk of musculoskeletal injury and cardiopulmonary stress.

The aim of this study was to determine the effect of a specific training program in manual wheelchair users. Our hypothesis was that an exercise program that combined stretching, strengthening, and aerobic training would result in more biomechanically economical wheelchair propulsion and decreased joint stresses. Biomechanical economy was defined by the propulsive moment.

METHODS

Subjects

The 19 MWCU who participated in this study (age = 44±11 yrs; height 174.5±16.1 cm; weight 79.1±19.6 kg; 3 women, 16 men) had 17±10 years of experience using a manual wheelchair and no upper-limb involvement. Of the 19 participants, 15 were spinal cord injured (T3-L5), 1 had spina bifida, 2 had multitrauma, and 1 had bilateral tarsal tunnel syndrome. Each potential subject was medically examined by a physician familiar with the requirements for participation to eliminate those not meeting inclusion criteria. Inclusion criteria included use of a manual wheelchair for at least 1 year prior to the study, wheelchair use for the majority of home and community mobility, and absence of upper-limb involvement or pain, ventilatory involvement, or systemic diseases that would preclude or limit exercise testing. Before the subjects were tested, written, informed consent was obtained in accordance with the procedures approved by the Institutional Review Board.

Instrumentation

All exercise tests were conducted on a prototypical wheelchair ergometer (**Figure 1**) with a handrim 22-in in diameter, wheels with no camber, and a seat adjustable for width and height. Components of a stationary bicycle ergometer were used to provide frictional propulsion resistance through a chain and sprocket system connected to the wheelchair axle at one end and to a flywheel at the other end. A nylon belt was used to create a pulley system to which known weights could be applied for precise control of resistance.

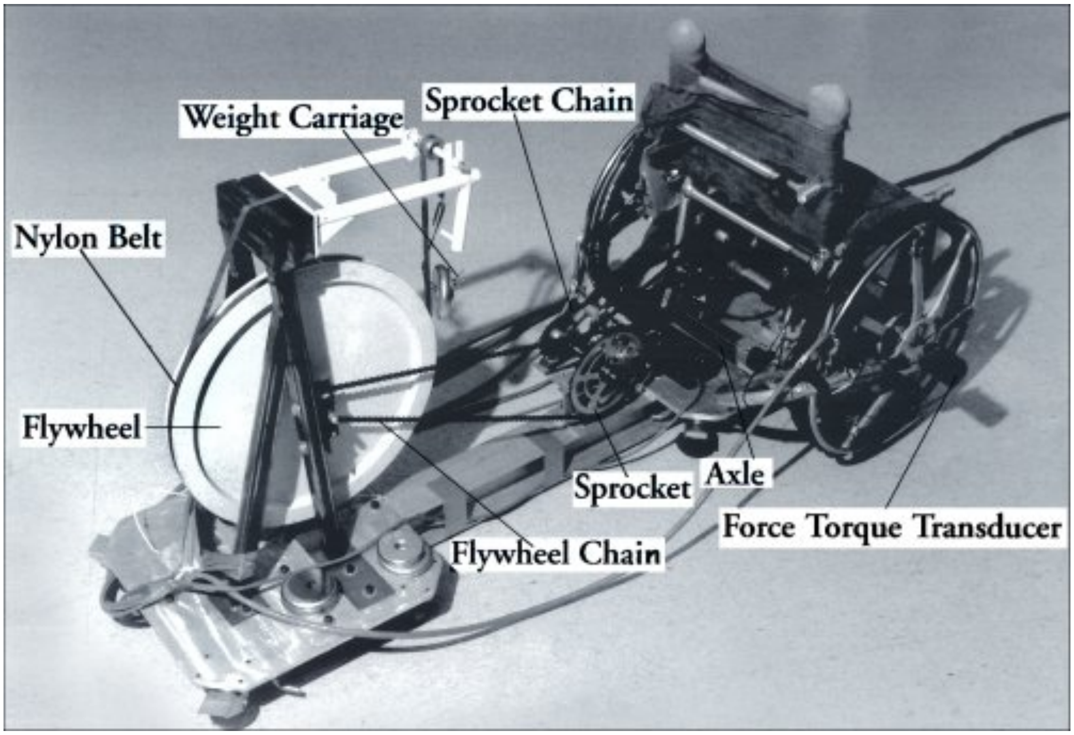

Figure 1.

Prototypical wheelchair ergometer used for biomechanical testing. The 22-in handrims are connected to force/torque transducers in the hubs for the measurement of 3D forces and torques. The chain and sprocket system connects the handrims to the flywheel weight assembly for the administration of resistance to propulsion.

The wheelchair measurement system included the instrumented wheelchair ergometer, 3 Peak 3D CCD cameras and video acquisition system (Peak Performance Technologies, Colorado Springs, CO), and a metabolic cart (Cardio 2, Medical Graphics Corp, St. Paul, MN). The wheelchair ergometer was instrumented with a PY6-4 six-component force/torque transducer (Bertec Corp., Worthington, OH) in its wheel hub. The Bertec transducer used bonded strain gauges to measure handrim forces and moments in 3 dimensions (6 channels). It had a maximum torque (Mz) capacity of 150 Nm and a maximum plane-of-wheel force (Fx and Fy) capacity of 3,500 N. A potentiometer monitored the angular position of the wheel, transducer, and handrim assembly. The amplified electrical signals from the strain gauges and potentiometer were collected with an analog to digital converter and acquisition software (Peak Performance Technologies, Colorado Springs, CO). Handrim kinetic, temporal, and potentiometer data were collected at 360 Hz. A bicycle speedometer with a digital display was attached to the right wheel of the chair and placed in view of the participant to provide visual feedback of propulsion velocity.

Kinematic data were collected at 60 frames/sec with the use of the video cameras and data acquisition system. The within-trial variability for all reconstructed angles as shown by the 95-percent confidence intervals was less than 1.5°. Spherical retroreflective markers were placed on the dorsal surface of the fifth metacarpal head, medial styloid process, lateral styloid process, radial head, acromion, and greater trochanter. Joint marker displacements were recorded with the camera, and joint angles (trunk, shoulder, elbow and wrist flexion/extension, shoulder abduction/adduction, and wrist radial/ulnar deviation), velocities and accelerations were calculated.

Joint kinetics were calculated with a 3D-linked segment model (22). This model used an inverse dynamics approach, employed the Newton-Euler method based on body coordinate systems, and assumed the arm to be three rigid segments (hand, forearm, and upper arm) connected by the wrist, elbow, and shoulder joints. Definitions for the global and local (handrim, hand, forearm, upper arm, and trunk) coordinate systems have been described in detail (22). Raw data were smoothed with use of a Butterworth low-pass filter with a cutoff frequency of 6 Hz. Contact phase was defined as the entire time of handrim loading. These motion vectors, forces, and torques together with anthropometric data were the input variables to a program that computes the forces and moments of the wrist with the use of an inverse dynamics process. The recursive program then determines the joint forces and moments of the wrist, elbow, and shoulder.

Heart rate was monitored by a telemetered pulse-rate monitor that included a transmitter attached by a belt to the thorax and a receiver with a digital display. Cardiorespiratory measurements were made with the use of breath-by-breath open circuit spirometry. The metabolic cart system included rapid response oxygen (zirconium cell) and carbon dioxide (infrared cell) analyzers and a pneumotachometer, all interfaced with a microcomputer. Cardiorespiratory measurements were averaged over 30 seconds for reporting purposes.

Pre- and Posttraining Wheelchair Exercise Tests

A maximal graded exercise test (GXT) on the wheelchair ergometer was used to establish resistance load for the fatigue test. For the GXT, subjects rested (6 min), propelled the wheelchair at a velocity of 3 km/h (32 rpm) without a load (3 min), then continued while weight was incrementally added at a rate of 0.3 kg every 3 minutes to increase power output. The test was terminated at volitional exhaustion, which was defined as the self-reported inability to maintain the target velocity. Subjects were monitored and encouraged to maintain the designated velocity. Heart rate was recorded at the end of each 3-minute stage and cardiorespiratory information was continuously recorded as 30-second averages.

Two to 7 days following the GXT, subjects completed the fatigue test. Load corresponded to 75 percent of the peak VO_2 that occurred during the GXT. For the fatigue test, subjects rested (6 min), propelled the wheelchair at 3 km/h without a load (3 min), then continued propelling at the submaximal load until volitional exhaustion. Subjects were monitored and encouraged to maintain the designated velocity. Heart rate was recorded at the end of each 3-minute stage and cardiorespiratory information was continuously recorded as 30-second averages. Propulsion mechanics, including handrim kinetics, joint kinematics, and temporal characteristics, were collected for 6 seconds (3 propulsion cycles) during the last 30 seconds of wheeling without a load, after 2.5 minutes of wheeling with a load (fresh), and just before exhaustion (fatigued).

Strength Measures

Handgrip strength was tested for each subject's dominant upper limb with a Baseline hydraulic hand dynamometer. Three maximal grips were averaged to represent grip strength. Strength training was accomplished with the use of progressive resistance. Strength changes were characterized by the increase in load from the pretest to the posttest for each strengthening exercise.

Training

Following the pretraining wheelchair exercise tests, subjects attended supervised therapeutic exercise sessions three times weekly for 6 weeks. Stretching exercises were performed for the anterior and internal rotation shoulder muscles (anterior deltoids, subscapularis, pectorals, latissimus dorsi, teres major), triceps, and wrist flexors. Strengthening activities were concentrated on the following muscle groups: the posterior deltoids, infraspinatus, teres minor, rhomboids, middle trapezius, erector spinae, biceps, and wrist extensors (17). These activities included limited repetitions (five repetitions) and relatively high resistance (75 percent of estimated maximum) performed with free weights. All strengthening exercises were performed within the subject's tolerance and stopped if pain or discomfort was experienced. The five free-weight activities included prone rowing, prone scapular retraction, reverse flies, and two shoulder external rotation exercises (23).

Aerobic exercise with the use of a rowing machine was included to improve cardiopulmonary fitness, endurance, and resistance to fatigue (**Figure 2**). This exercise included 30 minutes of continuous rowing at 60 percent of each individual's maximal heart rate reserve. Target heart rate (THR) was determined with the use of the following equation from the American College of Sports Medicine 24:

$$THR = 0.6\,[\text{Peak HR} - \text{HR(at rest)}] + \text{HR (at rest)}$$

Heart rate was monitored during aerobic exercise, and exercise was terminated if any subject experienced pain or discomfort.

Figure 2.

Subject demonstrating aerobic component of the training program. Each individual's wheelchair was secured in the location where the rowing machine seat would normally be located. The exercise intensity was based on target heart rate.

Data Analysis

Data from the right side of each participant were analyzed. Handgrip and execise load changes resulting from training were compared with the use of a paired t-test ($p<0.05$). Kinetic and kinematic data were averaged over three cycles (contact to contact) for each condition (fresh and fatigued) from the fatigue test. Joint kinetics and kinematics, handrim kinetics, and propulsion temporal data were compared before and after training during the fresh and fatigued states during the fatigue test. Oxygen uptake ($\dot{V}O_2$) during the fatigue test was characterized by absolute $\dot{V}O_2$ (ml/min) and metabolic economy (power output (W)/$\dot{V}O_2$ ($ml \cdot min^{-1}$)). These variables were compared at times corresponding to one third, two thirds, and completion of the test for both groups. Significant differences were determined with two-way Analyses of Variance with both effects repeated. First effect was state with classes designated as fresh and fatigued. Second effect was time of analysis with levels identifying pre- and posttraining. Pearson product moments were calculated to determine the existence of interclass and level relationships. Type-I error threshold was held at $p<0.05$.

RESULTS

Target HR for training was 119±17 BPM. Exercise load significantly increased for all strengthening activities (**Table 1**). Handgrip strength measures were unchanged. The following results are taken from data collected during the wheelchair propulsion test to fatigue (fatigue test). Main effects for training are shown in **Tables 2-5**. As shown in **Table 2**, stroke frequency significantly decreased following training. Although power output significantly increased after training, the length of time the wheelchair was propelled (endurance time) and the $\dot{V}O_2$ were similar before and after training. Three kinematic measures significantly increased with training (**Table 3**). These included shoulder flexion/extension ROM ($p=0.013$), maximum elbow extension ($p=0.030$), and trunk flexion ($p=0.001$).

Table 1.

Strength measures.

Sample	Variable	Pretest	Posttest	
19	Prone rowing	69±24	100±25	*
19	Scapular retraction	12±18	31±23	*
19	Reverse flies	11±6	24±8	*
19	External rotation	7±3	16±6	*
19	Empty cans	6±4	16±7	*
18	Handgrip (kg)	47±11	48±13	

Values are means±sd (in pounds); *=significant difference (p<0.01).

Table 2.
Temporal and physiologic measures.

Sample	Variable	Pretest	Posttest	p-value
19	Stroke frequency (cycles/sec)	1.23±0.21	1.17±0.16	**0.039** *
19	Endurance time (minutes)	28±20	31±20	0.475
19	Power output (Watts)	45.8±29.4	52.5±35.4	**0.012** *
12	Heart rate (bpm); exhaustion	139±28	144±24	0.436
15	$\dot{V}O_2$; 1/3 of test	984±435	1004±383	0.767
15	$\dot{V}O_2$; 2/3 of test	1021±370	1039±383	0.621
15	$\dot{V}O_2$; exhaustion	1025±356	1103±428	0.229
15	metabolic economy; 1/3 of test	0.053±0.027	0.048±0.018	0.501
15	metabolic economy; 2/3 of test	0.046±0.016	0.045±0.016	0.493
15	metabolic economy; exhaustion	0.047±0.018	0.043±0.015	0.111

Metabolic economy=power output in Watts/$\dot{V}O_2$ in milliliters per minute
*=significantly different main effect (p<0.05); scores are means±sd.

Table 3.
Trunk, shoulder, and elbow kinematics (n=19).

	Trunk flexion		Shoulder flexion		Elbow extension	
	Pre	Post	Pre	Post	Pre	Post
Maximum angle (entire cycle)	85°±12°	80°±16°	18°±12°	23°±11°	**149°±9°**	**154° ±7°** *
ROM (entire cycle)	11°±7°	16°±9°	**68°±13°**	**75°±11°**	47°±11°	51°±9°
ROM (during contact)	**10°±6°**	**15°±9°**	63°±15°	69°±10°	45°±11°	48°±9°

ROM=range of motion; * significantly different main effect (p<0.05); scores are means±sd.

Of the wheelchair kinetic measures (shown in **Table 4**), only the propulsive moment (Mz) significantly increased with training. This increase represents a 14-percent improvement in propulsive moment. Correlational analysis determined that this increase was not related to the increased resistance during either the fresh state (r=0.21, p=0.40) or the fatigued state (r=0.30, p=0.22). Wrist extension moment was the only joint kinetic measure to significantly increase after training (**Table 5**). Two significant interactions between training and fatigue were found. Trunk flexion/extension ROM and wrist flexion moment both significantly increased with fatigue following training (p<0.05).

Table 4.

Handrim kinetics (n=18).

Peak forces (N)	**Pretest**	**Posttest**	**p-value**
Fx (tangential)	70±22	72±21	0.643
Fy (radial)	-71±25	-78±33	0.126
Fz (medial)	12±11	10±11	0.561
Effective force	68±10	66±10	0.298
Peak moments (Nm)			
Mx	-3±3	-4±4	0.089
My	-3±2	-3±2	0.157
Mz (propulsive moment)	-21±6	-24±8	**0.010***
Effective moment	97±4	96±6	0.196

Effective force=(Fx/Fr)100; Effective moment=(Mz/Mr)100;
*=significantly different main effect (p<0.05); scores are means±sd.

Table 5.

Joint kinetics (n=18).

Peak moments (Nm)	**Pretest**	**Posttest**	**p-value**
Shoulder Mx	29±30	29±38	0.964
Shoulder Mz	65±22	70±25	0.373
Elbow Mz	43±14	47±17	0.171
Wrist Mx	5±6	7±8	**0.033 ***
Wrist Mz	40±12	43±14	0.156

Shoulder Mx=adduction moment; shoulder Mz=flexion moment;
wrist Mx and elbow Mz=extension moment; wrist Mz=ulnar deviation moment;
scores are means±sd.

DISCUSSION

To our knowledge, this is the first study to document the effects of exercise training on wheelchair propulsion mechanics and oxygen uptake in manual wheelchair users. Although several studies describe effects of training on oxygen uptake (25-28), muscular strength or endurance (29,30), or wheelchair propulsion endurance (30,31), none has assessed the effects of training on propulsion mechanics. Assessing the effects of training on propulsion mechanics is important, since wheelchair propulsion is mechanically inefficient (32-34), implicating propulsion mechanics as a mechanism for overuse injury. The training regimen employed in this study was chosen to address muscular imbalances and inflexibility that have been postulated to occur in manual wheelchair users (17-19) and documented in one study (20). Olenik advocated exercises for strengthening and stretching upper-limb muscles to address these imbalances, since they may lead to injury (19). Muscular imbalance occurs when the opposing muscles are unevenly developed. As a result of this imbalance, the integrity of the joint is compromised and the likelihood of injury increases. Such injuries often involve stretch weakness, resulting from the prolonged elongation of the inadequately developed opposing muscles. The objectives of preventive exercise are to stretch those muscles most likely to be overdeveloped and to strengthen those muscles most likely to show stretch weakness to provide a protective effect for the joints (20,35). Our results indicate that strength of these opposing muscle groups significantly improved with the use of our training regimen.

Training affected selected kinematic and kinetic characteristics of MWCU. Although the absolute increase in propulsive moment appears small (3 Nm), the relative increase of 14 percent over the pretraining value is functionally important. The increase in propulsive moment with a decreased stroke frequency indicates a more mechanically economical method of propulsion was achieved following training. More effective turning moment was applied to the handrim without significantly increasing shoulder or elbow joint moments. The implication is that an increase in biomechanical economy was achieved without a concomitant increase in stresses at these two joints. Although a direct link to the potential for overuse injury prevention cannot be achieved without long-term follow-up of the subjects, certainly the ability to keep joint stresses minimized, even during fatigue, would suggest a positive training effect.

Training produced a kinematic increase in motion at the trunk, shoulder, and elbow. This movement pattern allowed the MWCU to rely on trunk and shoulder excursion to generate translational forces necessary for wheelchair propulsion. The trunk movement pattern may have been compensatory for peripheral muscle fatigue, since it was more pronounced in the fatigued state. Whether this adaptation is beneficial is unclear. Further investigation of propulsion pathomechanics may identify additional factors contributing to injury.

Investigators have used a variety of approaches to delineate links between biomechanical characteristics and musculoskeletal injury (16,21,36-38). Along with the work of others, our study has provided foundational data for the generation of hypotheses associating wheelchair biomechanics with pathology. Prospective longitudinal studies are needed to establish the causal links for these hypotheses.

Summary

Based on our results, we conclude that a 6-week period of strength and endurance training of the muscles critical to propulsion significantly improved biomechanical economy without increasing shoulder and elbow stresses. Training may be important in preventing long-term overuse injuries in MWCU. Definitive studies on pathomechanical mechanisms of upper-limb injuries in MWCU may support these findings and facilitate interventions for the resulting impairment and disability.

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