EVALUATION OF THE ROLE OF UPPER LIMB STRENGTH TO EXERCISE PERFORMANCE IN QUADRIPLEGICS

BY

BARBARA SHAY

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ABSTRACT

The purpose of this study was to evaluate the relationship of upper limb strength to exercise performance in quadriplegics. Six C6 and C7 quadriplegics and 6 age matched able bodied control subjects were recruited from the Rehabilitation Unit and the University of Manitoba Health Sciences Centre Campus. A maximum progressive power wheelchair exercise test was administered; expired gas, workload, heart rate and perceived exertion for both arm and breathing effort were recorded. Pimax at rest and maximum exercise tidal volume were determined. Muscle performance of the upper limb was assessed with the Kinetic Communicator (Kin-Com). Upper limb movements of elbow flexion and extension, wrist extension, shoulder abduction and shoulder flexion were tested concentrically in the iso-velocity mode at 60 degrees per second. Four maximal contractions were performed and recorded. All tests were administered before and after a 5 day/week intensive interval endurance wheelchair training program of 8 weeks duration.

The high intensity, interval endurance wheelchair training program resulted in an increased mean peak $\dot{V}O_2$ in both quads (0.739 $\pm$ .09 to 0.840 $\pm$ .12 l/min, $p < 0.025$) and in the able-bodied subjects (1.634 $\pm$ .26 to 2.465 $\pm$ .26 l/min, $p < .0025$). Maximum power output increased from a mean of 20 $\pm$ 4.5 to 27.3 $\pm$ 4.6 Watts ($p < 0.025$) in the quadriplegic group, and maximum power output increased from a mean of 31 $\pm$ 3.67 to 55 $\pm$ 3.04 Watts ($p < 0.0005$) in the able-bodied group. Maximum peak torque and area under the torque/angle curve increased significantly ($p < 0.007$) in all upper limb movements tested in the quadriplegic group. The increase in upper limb strength correlated with the change in maximum power output, ($R = 0.808$, $p < 0.05$). In the able-bodied group the elbow flexion movement

increased 25% ($p < 0.027$) and the wrist extension movement increased 18% ($p < 0.001$). Pimax increased from a mean of -77.67 $\pm$ 12.69 to -89.67 $\pm$ 11.47 cm H_2O, ($p < 0.004$) in the quadriplegic group and increased from a mean of -111.5 $\pm$ 9.376 to -127.3 $\pm$ 8.9 cm H_2O, ($p < 0.009$) in the able-bodied group. There was no significant correlation between Pimax and any index of strength performance. At matched submaximum exercise, perceived exertion ratings for both arm and breathing effort decreased significantly ($p < 0.05$) in both quadriplegic and able-bodied groups.

The results indicate that a high intensity, interval wheelchair training program is an effective means of increasing both upper limb strength and endurance performance with quadriplegic and able-bodied subjects. The increased upper limb strength may account for the decreased perceived exertion for both breathing and arm effort at sub-maximal exercise workloads, in both quadriplegic and able-bodied subjects. As well, the increased upper limb strength must contribute to the ability to increase maximum power output particularly in the quadriplegic subjects where peak $\dot{V}O_2$ increased marginally. High intensity, interval wheelchair exercise as a means of increasing strength, improving endurance, and enhancing ventilation is a directly applicable and training specific exercise for quadriplegics.

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EVALUATION OF THE ROLE OF UPPER LIMB STRENGTH TO EXERCISE PERFORMANCE IN QUADRIPLEGICS

INTRODUCTION

Previous studies have shown that following endurance training programs, quadriplegics significantly improve exercise test performance in spite of minimal changes in peak oxygen uptake (Loveridge 1989, Coutts 1983, Van Loan, 1987, Eriksson, 1988). Therefore, improvement in exercise performance must, at least in part, be due to other factors.

One of the factors which would appear to be operative in enhancing exercise performance relates to upper body strength. It has been demonstrated in young normal males that increased muscle strength contributes to enhanced endurance performance (Marcinik 1991). The study investigated the effects of strength training on lactate threshold and endurance performance. Plasma lactate responses during submaximal exercise were evaluated during four 10 minute bouts of cycling at intensities of 55%, 65%, 70% and 75% of the subjects' peak $\dot{V}O_2$. Endurance performance was assessed by measuring pedalling time to exhaustion on a cycle ergometer while monitoring peak $\dot{V}O_2$. The findings indicated that training on exercise machines directed primarily at increasing strength in the lower limbs, three times per week for 12 weeks, resulted in improved endurance performance. The subjects in the strength training group were able to increase their cycle time to exhaustion significantly, independent of changes in maximum oxygen uptake ($\dot{V}O_2$ max.) while there was no change in cycling time for the control group. It was concluded that the improved exercise performance was related to increases in lactate threshold, increased cycle time endurance and leg strength.

In quadriplegics, upper body musculature is primarily compromised by muscular loss below the level of the lesion, and secondarily due to muscle deconditioning. Improving muscle strength, specifically in the shoulder and shoulder girdle muscles, will contribute to increased exercise performance. This is particularly relevant to the quadriplegic population who cannot recruit other muscles or body stabilizing strategies to respond to increased workloads. They must rely exclusively on the remaining intact muscles (Eriksson, 1988 Martin, R.P., Haskell, W.L. 1977, Geigel 1975, Taylor 1979, Shephard 1988a).

The purpose of this study was to evaluate the effect of a high intensity, interval wheelchair exercise training program on upper limb and shoulder girdle muscle strength, and to determine the relationship between increased strength and parameters of exercise test performance (peak $\dot{V}O_2$ and power output).

Wheeling is the major functional activity for wheelchair bound individuals. Optimum upper limb strength and endurance of the upper limb are critical to maximize their mobility and independence. Ascertaining the effects of various exercise protocols on enhancing upper limb performance, and determining the relationship between the parameters used to assess improvement in exercise performance are important. Only then can the most optimum rehabilitation strategies be developed. The results would provide rehabilitation professionals definitive guidance in the development of effective and applicable training regimens for quadriplegics.

HYPOTHESIS

Improvement in exercise performance with quadriplegics following high intensity, interval wheelchair training is primarily due to increased strength of the upper limb musculature.

OBJECTIVES

1. To determine the relationship between upper limb strength and the parameters of exercise performance in quadriplegics involved in a high intensity, interval wheelchair training program.

2. To adapt the Kinetic Communicator (Kin-Com) to assess upper limb strength in quadriplegics without hand grip.

3. To compare the profile of changes in upper limb strength following wheelchair endurance training between quadriplegics and able-bodied subjects.

REVIEW OF THE LITERATURE

Exercise Performance in Spinal Cord Injured Subjects

To contract, skeletal muscles require stimulation from action potentials arising from alpha motor neurons. The command for voluntary control originates in the higher centres of the brain, which is conveyed down the spinal cord to the alpha motor neurons, which carry the information to skeletal muscles. Voluntary activation of skeletal muscle following spinal cord injury is not possible due to interruption of the command pathway.

In general, the higher the level of the lesion, the greater the impairment of both the somatic nervous system as well as the autonomic nervous system (ANS). Skeletal muscle paralysis and sensory information loss that occur with complete spinal cord injuries are accompanied by ANS dysfunction. Cervical lesions cause loss of the sympathetic division and the sacral portion of the parasympathetic division of the ANS. However, the cranial portion of the parasympathetic division remains intact (Glaser 1985, Drory 1990).

Diminished sympathetic outflow in spinal cord injured (SCI) persons, can limit aerobic exercise capability. Increased blood flow required by exercising muscle for delivery of O_2 and fuels, and for removal of metabolic waste products is related to sympathetically mediated vasoconstriction in inactive tissues. Additionally, lesions above T1 interrupt sympathetic outflow to the heart, and this would limit heart rate acceleration and improved myocardial contractility, which both contribute to the reduction in maximal cardiac output. Diminished sympathetic outflow also reduces thermoregulatory capacity during exercise, which is due to inadequate blood flow to active muscles, and the inability to activate a sufficient number of sweat glands by cholinergic sympathetic stimulation (Glaser 1985, Drory 1990, Fitzgerald 1990). Therefore, the cardiovascular system of SCI persons with lesion levels above T1 is significantly compromised when compared with able-bodied subjects.

It is clear from the literature that quadriplegics have significantly lower maximum oxygen uptakes ($\dot{V}O_2$ max) than either trained or untrained paraplegics or able-bodied populations (Davis 1981, Eriksson 1988, Glaser 1985, Hjeltnes 1986, VanLoan 1987). Hjeltnes (1986), investigated the cardiorespiratory capacity in quadriplegics and paraplegics (both complete and incomplete) shortly after injury. He investigated 100 relatively recent (SCI) patients in their ability to perform arm work on an electrically braked ergometer adapted for arm cranking. Heart rate, ventilation parameters, peak $\dot{V}O_2$, and lactic acid concentration were assessed during submaximal and maximal workloads. The mean peak oxygen uptake was found to be very low, (0.74

l/min) in complete quadriplegics when compared with 1.91 l/min in subjects with complete lesions at lower levels. Eriksson (1988), in his study of aerobic power during maximum exercise in untrained and well trained spinal cord injured persons, found that during maximal wheelchair exercise, the peak $\dot{V}O_2$ was higher in subjects with lower spinal cord injuries. At injury levels below C6-C7, he demonstrated that the trained subjects reached significantly higher peak $\dot{V}O_2$ than those subjects that were untrained. Untrained quadriplegics achieved a mean peak $\dot{V}O_2$ of 0.88 $\pm$ 0.16 l/min compared to trained quadriplegics with a mean peak $\dot{V}O_2$ of 1.11 $\pm$ 0.34 l/min. These differences may be due to the reduction of total active skeletal muscle mass in the untrained quadriplegics or to the ability to recruit more muscle mass as a result of training. He noted that a C6-C7 quadriplegic who was well trained, was comparable to an untrained T12 paraplegic on the basis of $\dot{V}O_2$.

Other studies have shown that little or no increase in $\dot{V}O_2$ max. has been observed with upper limb endurance training with quadriplegics (Coutts 1983, Glaser 1985, VanLoan 1987). Any improvement in $\dot{V}O_2$ following exercise training was primarily observed in deconditioned or recently injured quadriplegics. Minimal changes in $\dot{V}O_2$ have been noted with both arm cranking and wheelchair rolling exercise protocols in quadriplegic athletes or more highly conditioned subjects (Eriksson 1988, Loveridge 1989, Wicks 1983). Gass et al. (1980), investigated the effects of physical training on high level spinal lesioned patients. The study group consisted of 7 subjects (three subjects had complete lesions at C5-C6, one incomplete at C6, two with complete lesions at T1 and one with a complete lesion at T4). They participated in a wheelchair exercise training program five days a week for 7 weeks. The results indicated that despite significant increases in $\dot{V}O_2$ max with training, both pre and post test maximum $\dot{V}O_2$ were lower than $\dot{V}O_2$ max values reported with other disabled persons, such as those with cerebral palsy or paraplegia. They felt this was consistent with the high level of the spinal cord lesion proportional to the available muscle mass, and chronic inactivity of the subjects.

Thus, both the initial level of $\dot{V}O_2$ max, and the level of spinal cord lesion are important determinants of the percent gain in $\dot{V}O_2$ max with endurance training.

A number of studies have focused on spinal cord injured subjects, and have related their decreased physical performance to the level of injury and availability of functional muscle mass (Burkett 1990, Drory 1990, Figoni 1986). Several studies have demonstrated a lack of cardiovascular training effects such as decreased heart rate for a given workload and increased peak $\dot{V}O_2$, following endurance training in quadriplegics (Coutts 1983, Glaser 1985, VanLoan 1987). Figoni (1986) demonstrated that stroke volume and end diastolic volume decreased in untrained, complete C5-C6 quadriplegics as the exercise intensity was increased during arm crank ergometry. This was compared with increases in stroke volume and ejection fractions as exercise intensity was increased to 60% max. exercise in able-bodied subjects. In the able-bodied subjects, stroke volume and end diastolic volume only decreased at max. exercise. He suggested that limited cardiac preload and contractility may compromise the ability of quadriplegics to volume load the heart during exercise. Further, Figoni suggested that this would preclude a central cardiovascular training effect in quadriplegics.

However, with quadriplegics, it has been established that wheelchair training programs improve exercise performance with respect to power output and peak $\dot{V}O_2$ (Dreisinger 1982, Engel 1973, Glaser 1981, Loveridge 1989, Magel 1978). As well, it has been demonstrated that perceived exertion for both arm and breathing effort at a given sub maximum workload, decreases post endurance training in quadriplegic subjects (Loveridge 1989).

Despite the physiological limitations in spinal cord injured populations, upper limb performance improves with training, and this is probably due to peripheral adaptations (Glaser 1985, Taylor 1979, Shephard 1988a, Per A. Tesch 1983). Glaser (1985) suggested that most of the observed gains in performance for arm exercise are probably due to peripheral adaptations, particularly, improved muscle blood flow by capillarization and metabolic capability in terms of lactic acid threshold, of the upper body. He stated that the relatively small muscle mass of the upper body cannot increase the metabolism of the body sufficiently and for long enough duration, to argue for central training effects. Although endurance arm exercise is reported to increase aerobic fitness, as indicated by changes in $\dot{V}O_2$ values and heart rate responses, there is doubt about the effectiveness of arm training compared with leg exercise in promoting aerobic fitness (Shephard 1988). In spite of this finding, arm endurance training remains a major means of maximizing the cardiovascular training effects in SCI populations.

Hooker (1989), found that SCI subjects who trained with a moderate intensity wheelchair exercise program had significantly lower post training submaximal lactate and perceived exertion with no changes in the maximum $\dot{V}O_2$ or $\dot{V}_E$. He also found significantly increased high density lipoprotein cholesterol (HDL-C) and decreased triglycerides (TG), low density lipoprotein cholesterol (LDL-C) and total cholesterol/HDL-C ratio, in these subjects. Bauman (1992), investigated aspects of the development of coronary artery disease in paraplegics. He observed an inverse relationship between HDL cholesterol and coronary artery disease, and a positive relationship between higher activity levels and higher HDL cholesterol levels in these SCI persons. The findings of these studies are consistent with the possibility that endurance training may play an even more important preventative role in the development of coronary artery disease in the SCI population. Further, parameters such as heart rate and peak $\dot{V}O_2$, may not be sufficiently sensitive to assess the benefits of training in the cardiovascular system for the SCI population.

To date, few studies have focused on the role of upper limb strength in wheelchair endurance performance. Noreau and Shephard (1992), investigated the potential contribution of physical fitness of SCI subjects and their return to work after injury. They sent questionnaires to 95 traumatically SCI persons relating to personal, educational, vocational and medical characteristics. They also included the Modified Barthel Index assessing performance in activities of daily living, and a modified physical activity readiness questionnaire. The independent variables included anthropometric estimates of body composition, assessment of static and dynamic lung function, measurements of muscular strength, peak $\dot{V}O_2$ and peak power output, and measures of leisure time and physical activity. They observed that subjects who were gainfully employed had a significantly higher level of cardiorespiratory fitness and muscular strength than those who were not employed. They felt that "strong" arm muscles were vital to activities such as curb or ramp mounting and the negotiation of architectural barriers.

Several authors suggest that the gains in exercise performance in SCI are due to peripheral muscle adaptations and capillarization of the surrounding tissue (Glaser 1985, Simmons and Shephard 1971, Shephard 1988a, VanLoan 1987). Maximizing the muscle "bulk" available for this task becomes important. There is a need to both better evaluate the strength gains with various upper limb training regimens, and to develop training protocols which optimize both strength and endurance gains.

Wheelchair Propulsion

Wheelchair propulsion is a specific task involving balance, biomechanical adaptations, and for the quadriplegic, learning to sequence impaired upper limb function to perform the task. Improvement in upper limb muscle strength and overall exercise performance in wheeling appears to be dependant, at least in part, on the biomechanics of wheeling. Several authors have investigated wheelchair propulsion techniques at different speeds, wheelchair design and efficiency, and the kinematic features of wheelchair propulsion (Sanderson 1985, Veeger, 1989 and 1991, Engel 1974).

Peizer et al. (1964) looked at two different types of chairs (a conventional wheelchair and a "lightweight" chair which was conventional except in the sense that it was constructed from lightweight material such as aluminum and nylon). He found that although initial inertial energy requirements may be greater in the conventional standard chair, once the chair was in motion, the relative energy costs to continue propulsion were not different between chair designs. The light chair offered no advantages in average velocity attained, stroke efficiency or significant reduction in caloric cost in propulsion compared with the standard wheelchair. The energy costs were more related to the friction encountered at the tire-floor surface, within the tire material and at the axles.

Sanderson and Sommer (1985) looked at the kinematic features of wheelchair propulsion and used cinematography to observe the angular kinematics of the shoulder and elbow joints and the variation in trunk position of paraplegic subjects during different speeds on a treadmill. They found considerable differences in the styles of wheeling between subjects. Two subjects used a circular motion where the hand followed the pushrim, and one of the paraplegics used more of a "pump action" during the push-recovery sequence. They felt that the pump arm action would be more of a technique employed by quadriplegics to compensate for the loss of hand function. Their analysis of trunk movement led them to conclude that the position of the trunk, in terms of range of motion and relative amount of mean forward lean, related to the main axle, has a bearing on the mechanism of force application. The subject has to balance effective force application against the physiological factors controlling range of forward lean, mean forward lean and residual abdominal musculature. Choice of style in wheelchair propulsion appeared to be individual. However, they did argue in favour of the circular style motion rather than a pumping action since the circular pattern of motion may enable the participant to prolong the propulsive phase through gripping the rim, thus applying a greater impulse to the pushrim.

Veeger and van der Woude (1989), in their study of wheelchair propulsion techniques at various speeds, also found that there were considerable differences in propulsion style, describing stroke patterns as either "circular" or "pumping". Using markers and filming exercise tests on a wheelchair treadmill, they discovered that there were some general changes observed relative to speed. Timing parameters were estimated on the basis of the number of film frames and film speed. Cycle time decreased with speed as a result of shorter push time. Push angle (defined as the difference between the start angle and the end angle) remained constant and the movement ranges of the trunk and arms shifted with speed. They concluded that adaptation to speed changes occurred mainly by flexion of the trunk and arms. Quadriplegics have restricted ability to use the trunk flexion strategy and, therefore, would have limited options for adapting to speed changes.

Davis and Shephard (1990) investigated the effects of forearm ergometer training in sedentary adult males with spinal lesions. Their Cybex II, iso-velocity dynamometry measurements of peak power, average power and total work were used to assess muscular endurance for elbow flexion/extension, shoulder flexion/extension and shoulder abduction/adduction, at five different speeds, before and after 16 weeks of upper limb training. They found gains of average power in two of the muscle groups primarily involved in the ergometer task, shoulder extension and elbow flexion. The conclusion was that gains were largest with prolonged, high intensity activity at angular velocities approximating those adopted during training. They also felt there was a "specificity of training" in that the gains of average power were highest in the low velocities which approximated the training speeds on the ergometer. Glaser (1985) also indicated that an activity which more closely resembled wheelchair activity may be more advantageous to the wheelchair user, and wheelchair ergometer exercise training would probably be more effective in improving performance for actual wheelchair locomotion. Shephard (1988) stated, that the efficiency of wheelchair operation depends on design and mass, experience of the subject, knowledge of an appropriate pace and small variation of the ground surface. He recognized that the arm ergometer is attractive in standardizing the task, however, limitations include test learning, habituation and non-specificity. The main advantage of using wheelchair testing in experiments is realism, as far as the daily life of the patient is concerned.

Thus, there is strong argument for both testing and training the SCI population using wheelchair ergometry versus other methods. When considering the specificity of the task, biomechanical adaptations for wheeling with impaired upper limb function, and dealing with balance while performing the activity of wheeling, it seems appropriate to train and test quadriplegics in a setting similar to that of daily living, in particular, overground wheeling.

Strength

Strength is an important component of rehabilitation. It would appear from a review of the current research that this area of study continues to be a perplexing problem in the definition and quantification of the variable (Herzog 1988, Rothstein 1987). Indeed, many authors do not have consistent definitions of strength, and some do not define strength at all, although most articles refer to strength as the variable being studied.

Muscular strength can be defined as the maximum force or tension generated by a muscle, or muscle groups (DiNuble, 1991). However, this refers to the situation where a muscle is being tested out of the body, (in vitro) whereas in vivo, we must be concerned with the segmental rotation produced by the muscular forces. As such, the definition of strength must include the generation of a moment about an axis of rotation. Therefore, a more encompassing definition of muscle strength would be "the magnitude of the torque exerted by a muscle (or muscles) in a single maximal isometric contraction of unrestricted duration" (Atha 1981, Enoka 1988). However, muscle torque does not necessarily represent any single intrinsic property of muscle, but rather, is the consequence of neural (motor-unit recruitment and rate coding), mechanical (moment arm), and muscular (length and cross sectional area) simple joint system interactions (Howard, 1985). The preferred definition of strength is "the ability of the musculoskeletal system under volitional control to maintain a segmental angular position or produce segmental rotation. The joint moment/angle/angular velocity relationship best depicts strength for single segment motion" (Kriellaars, 1992). Parameters related to strength can be objectively measured in the following ways: tensiometry (force), one repetition maximum (load or weight), or dynamometry (moment or torque) with computer assisted force and work output devices (McCardle 1981). The use of iso-velocity dynamometers has proven to be a very effective "in vivo" method of quantifying strength (Burdett, 1987, Delitto, 1990, Gransberg, 1983).

Iso-velocity (constant angular velocity equal to the rate of change of the angular displacement), dynamometers are electromechanical or electrohydraulical instruments which contain speed controlling mechanisms that accelerate to a preset speed when any force is applied. The transducer within the dynamometer continuously monitors the immediate level of applied force or moment and feeds this information into the recorder, which in turn is processed to provide a readout of the moment generated in a given time. The dynamometer reports the moment with respect to time (isometric), in addition to moment with respect to angle at a constant velocity (iso-velocity). The moment/angle relationship which can be established for any velocity (concentric, eccentric or isometric) best depicts the strength of an individual.

The Kinetic Communicator, Kin-Com (Med-Ex Diagnostics of Canada Inc., Coquitlam, B.C.) provides an objective, reliable and reproducible measurement of strength. Farrell and Richards 1986, and Harding et al. 1988, have documented the reliability and validity of iso-velocity testing at the knee joint on the Kin-Com. Optimum testing velocities for the shoulder are still being sought, however, iso-velocity testing at both a slow speed for strength assessment, and a fast speed for power assessment is customary (Hageman 1989). Researchers investigating the shoulder during concentric activity have used speeds ranging from 60-300 degrees per second (Alderink 1986, Bonci 1986, Davis 1990, Hageman 1989). The most frequently reported speed is 60°/sec for rotation about the shoulder joint in able-bodied and athletic populations (Duncan et al.1989, Hageman 1989, MacDonald et al. 1988). Using the Kin-Com, Hageman (1989) investigated the effects of angular position and speed on peak torque values during both concentric and eccentric activity of the shoulder rotators. She found that concentric internal rotation moment decreased significantly, while eccentric external rotation moment increased significantly at the higher speeds. Other studies have indicated that there is a decrease in production of peak torque, concentrically, with an increase in test velocities higher than 60°/sec (Hageman et al. 1989, Worrell et al. 1989). Worrell investigated test velocities of 60, 180, and 240°/sec on the hamstring and quadriceps muscle groups. In addition to finding that the seated position, compared with testing in supine, elicited higher peak torques, the results also indicated that there was a decrease in production of peak torque with an increase in concentric test velocity for both muscle groups.

The literature most frequently has cited the movements of flexion, extension, abduction, adduction, internal rotation and external rotation as the test movements to assess the strength of the muscle spanning the shoulder joint (Bonci 1986, Ellenbecker 1988, MacDonald 1988). At the present time, there are no defined protocols for testing shoulder girdle movement, such as shoulder shrug, depression, protraction or retraction. This is a serious limitation in evaluating shoulder girdle strength particularly as it relates to wheeling. Wheelchair wheeling, utilizes musculature from the shoulder girdle, shoulder, elbow and wrist joints. In particular, quadriplegics do not have the available muscle mass necessary to perform the wheeling activity without a substantial contribution from shoulder elevation. Therefore, assessment of shoulder elevation and the shoulder movements are required to adequately determine changes in upper limb strength with quadriplegics. Pilot evaluation with a C6 level quadriplegic, prior to this project indicated that for shoulder shrug (elevation of the shoulder girdle and scapula), the T2 spinous process could be effectively used as the "joint axis" for the movement. As well, the speed of 60°/sec was too fast to achieve a reliable reading. Performance of shoulder shrug at a speed of 30°/sec provided reproducible results.

Alderink and Kuck (1986) concentrically tested the shoulder abductors/adductors, flexors/extensors, horizontal abductors/adductors and internal/external rotators at speeds of 90, 120, 210 and 300 degrees per second. They found that there were no consistent differences between dominant and nondominant arm strength in their study of shoulder strength of high school and college-aged pitchers. Although Ivey et al. (1985) found there was a consistent pattern of greater strength in the dominant shoulder, no statistical difference was found between dominant and non-dominant shoulders in 31 volunteers with no shoulder pathology. Therefore, it appears that unilateral strength testing would yield a result that could be generalized to the other upper limb.

Common testing protocols range from using 3 to 6 repetitions with rest intervals between contractions (Alderink 1986, Hageman 1989, Harding 1988, Richards 1981, Worrell 1989). Stratford et al.(1990) investigated the effects of an inter-trial rest interval on the assessment of isokinetic thigh muscle torque. The two testing protocols consisted of five trials of knee flexion and extension performed either with no rest or a 30 second rest between trials. He found that the rest protocol produced average torques which were 5% greater and had higher reliability coefficients than those values obtained in a no rest protocol. In addition, during our pilot testing, it was found that continuous contractions for the quadriplegic population were unrealistic, as some subjects did not have the strength or ability to return to the starting position. For example, C6 level quadriplegics were able to perform elbow flexion but lacked the capability to return to the start position with active elbow extension using triceps (C7 innervation).

Dynamometers are used to measure torque and the accompanying range of motion as a function of time. The term "isokinetic" is often utilized in the literature when reference is made to the iso-velocity dynamometer. "Kinetics" refers to the relationship between the forces acting on the body, the mass of the body, and the motion of the body (Beer, Dynamics 1977). "Iso" refers to equality or the same. Thus, the term "isokinetic" would mean that the forces acting on the body would have a constant relationship. This is a different connotation from that which is denoted when referring to the type of movement and moments generated when testing individuals on these devices. It appears that when authors are referring to the term "isokinetic" they mean the relationship of the dynamometer itself and the subject being tested, in that the movement is performed at a constant speed or velocity. A more appropriate term which describes exactly which parameters and the type of movement being studied would be "iso-velocity".

Table 1 defines the terms related to dynamometry and the assessment of strength.

Table 1

Definition of Terms Used in Iso-velocity Measurements

Concept	Definition
Force	Characterized by its point of application, its magnitude and its direction. Force is proportional to mass time acceleration. The unit of measure is the Newton (N). (Beer, Dynamics, 1977)
Torque or Moment	The tendency of a force to cause rotation about an axis. It is equal to the magnitude of the force multiplied by the perpendicular distance from the action line of the force to the axis of rotation. The unit of measure is the Newton-metre (Nm). (LeVeau, 1977)
Angular Work	A moment overcoming a resistance by rotating an object through an angle. (Beer, Dynamics, 1977)
Total Work	The area under the torque vs angular displacement curves in all the test repetitions. It is measured in joules. (Kannus, 1990)
Power	Power is rate of doing work. It is measured in Nm/s. (LeVeau, 1977)

Average Power	The total work of the contractions divided by the actual total contraction time. Average power is measured in Watts. (Kannus 1988)
Impulse	A linear impulse is reflected in the equation force x time. With respect to angular impulse, it is equal to the moment x angle, the sum of the angular impulses about the axis, and is equal to the change in angular momentum. (Beer, Statics and Dynamics, 1977)
Iso-velocity	Constant angular velocity (equal to the rate of change of the angular displacement), i.e. constant angular speed through a range of motion.
Isokinetic	The relationship between the forces acting on the body is constant.
Tensiometry	Measurement of the amount of force a muscle can generate using a cable and gauge apparatus. (LeVeau, 1977)
Dynamometry	A measurement of the analysis of a body, or body segment in motion. (Beer Statics and Dynamics, 1977)

Comparison of results in dynamometric assessment of muscle performance is difficult due to the variability in reporting of findings. This results in a lack of common nomenclature, and the use of varied definitions when relating to iso-velocity muscle testing. A standardization of terminology is needed to allow meaningful comparisons of data from the literature. (see Table 1)

The majority of the literature has focused on reporting peak torque as a measure of strength or muscle performance (Burdett 1987, Connelly 1989, Deutsch 1987, Gross 1990, Hageman 1989, Motzkin 1991, Nelson 1990). Other studies have reported average torque, average power, and work (Burdett 1987, Duncan 1989, Elert 1989, Knapik 1983, Knapik 1986, Rabin 1990). In several studies, peak torque was the most frequently used variable (Adeyanju 1983, Barton 1988, Gransberg 1983, Molnar 1979). This refers to the highest torque output about a joint produced by muscular contraction as the limb moves through the ranges of motion when concentric and eccentric type muscle contractions are being studied (Kannus 1988, Kannus 1990). During an isometric contraction, the peak torque would be the maximal voluntary contraction within the contraction period (Knapik 1983, Knapik 1986, Motzkin 1991). Gerdle et al. (1988) studied positioning of the shoulder in isometric shoulder flexion contractions and monitored the action of several muscles with EMG. In calculating the mean power frequency and the root mean square value for EMG, they concluded that the position of testing had a significant effect on these values for the deltoid and infraspinatus muscles. The trapezius and biceps brachia muscles did not show a change in mean power frequency as a result of the different testing positions (Gerdle 1988). Thus, it would appear that the position of the limb in the testing position would have an effect on the torque generated by the subject.

Since microprocessors have been interfaced with the iso-velocity dynamometers, the quantification of other parameters including total work, peak angular impulse, and average power has been more readily allowed.

Recent interest has surfaced in the relationship between peak torque and the total work. Kannus and Jarvinen (1990) demonstrated in a study of a population with lateral collateral insufficient and uninjured knees, that there was little additional information gained about thigh muscle function in the analysis of the peak angular impulse or the average power when compared with the peak torque analysis (Kannus 1988, Kannus 1990). In contrast, Davis (1990), felt that average power gave a better measure of overall muscle strength than peak moment or peak torque. Warner (1990), investigated isokinetic shoulder testing and found significant differences in internal/external rotation ratios for both peak torque and total work. They created ratios using internal and external rotation peak torque and average torque production to quantitatively report patterns of flexibility, laxity, and strength in asymptomatic and unstable shoulders. Assuming there is a relationship between the internal and external rotators of the shoulder, a strength ratio can used to compare between subjects.

Despite more elaborate computer software programs which enable the investigator to examine the average power and total work, to date the most commonly reported variable continues to be peak torque (Connelly 1989, Deutsch 1987, Greenfield 1990, Gross 1990, Nelson 1990). Some studies have indicated that they have found no additional information when they have compared the results of peak torque with the more elaborate calculations of average power and total work (Kannus 1988, Kannus 1990, Knapik, 1983, Knapik 1986). However, this is perhaps unique to their study population, in that they were mostly employing healthy individuals or athletic populations. While the correlation coefficients between peak torque and total work are significant, there would appear to be some interesting data not reported. In particular, where in the range of motion being tested does the peak torque occur? Does this differ after some intervention, for example, an exercise program? This is not clear in the current literature, and may be of clinical relevance.

As well, the joint most often evaluated was the knee, which has been documented to have much less movement about the axis of rotation than does the shoulder. Therefore, there is less apt to be errors in measurements at the knee, while trying to maintain alignment with the rigid axis of rotations within the iso-velocity testing devices (Barton 1988, Bonci 1986, Burdett 1987, Delitto 1990, Kannus 1988, Kannus 1990).

In contrast to the knee, systematic error in measurement could occur at the shoulder, due to the larger displacement of the moving axis of rotation within the shoulder, and the fixed axis of rotation of the iso-velocity testing devices (Bonci 1986, Delitto 1990, Elert 1989, Gerdle 1988). However, attention to positioning of the subject, coupled with consistent testing protocols, which include visual alignment, minimize the error, and ensure that any error which may occur would be systematic. In this way, the same procedure would be used with each measured contraction, with each repetition, for all subjects. Thus, the absolute error in an intra-subject design such as this study, would be systematic in nature, with no effect on the results.

Due to the complexity of assessing shoulder muscle performance as compared to the knee; the argument for a more comprehensive analysis of the torque profiles is strengthened. Assessment of peak torque alone may not provide enough data concerning the muscle action. While the knee lends itself to comparability between peak torque measurement and other parameters of strength such as work and average power, the shoulder is a joint in which the peak torque may not be representative of these same parameters, as may be the case with other less studied joints. Therefore, it is important to report not only the peak torque or the ratios, but also to extrapolate the raw data, and perform more sophisticated statistical analyses which would provide a more comprehensive profile of muscle performance. As well, variability between groups with quadriplegic and able-bodied subjects would further support the need for a more in depth analysis of muscle performance than peak torques may provide.

To summarize, endurance training is widely used in the rehabilitation of SCI persons to increase wheelchair performance. There are serious limitations regarding existing rehabilitation protocols when looking at the specificity of the task, the cardiovascular effects achieved, and the biomechanical factors involved in wheelchair wheeling with the quadriplegic population. This results in fragmented rehabilitation strategies. Cardiovascular training effects such as increases in peak $\dot{V}O_2$, are limited in quadriplegics, however, exercise performance does improve. Further investigation is needed to demonstrate more clearly the factors contributing to increased exercise performance. However, it is clear that due to specificity of training, wheeling is the ideal training modality. Also, the biomechanics of wheeling are specific to the individual. Therefore, for higher level SCI persons with limited options, training in their own chair is a relevant issue. Increasing the strength of the upper limb and shoulder girdle may be a critical factor in this process, and high intensity exercise training protocols for strength development would be ideal.

This study proposes to determine the relationship between upper limb strength and exercise performance in quadriplegics with the intervention of a high intensity, interval wheeling exercise program. Clinically, the results may be used to establish the most effective and optimum training program for increasing strength, exercise performance and tolerance for activities of daily living in this population.

METHODS

Population

Twelve subjects participated in the study; six (6) quadriplegics and six(6) able-bodied controls. The baseline characteristics of the subjects are outlined in Table 2. Two C6 and four C7 traumatic quadriplegics with complete motor loss below the level of the lesion were recruited from the outpatient department at the Spinal Cord Unit from the Rehabilitation Centre, 800 Sherbrook Street, Winnipeg, Manitoba. Criteria for establishing the lesion level were based on the ASIA (American Spinal Injury Association) Standards for Neurological Classification. All subjects were prescreened by a physician prior to entry into the study. The quadriplegic subjects were all at least 1 year post injury.

All subjects were free of any acute infections for at least 2 months prior to entry into the study. A screening 12 lead resting electrocardiogram was performed on the quadriplegic subject over age 35.

Six able-bodied subjects younger than age 35, and in apparently good health were recruited from the University of Manitoba, Health Sciences Centre campus.

Exclusion criteria for both groups included athletes participating in upper limb endurance or strength exercise training programs, any history of upper limb tendinitis, or cardiovascular dysfunction. All subjects completed the Par Q readiness Questionnaire (American College of Sport Medicine, 1986) and informed consent was obtained before entry into the study.

The subjects were instructed to maintain their present activity level throughout the duration of the study. Medications were monitored, but not changed. Subjects were paid an honorarium of $100.00 and parking/transportation costs were provided to facilitate participation in the study.

Table 2

Characteristics of Subjects

SUBJECT	SEX	LESION	AGE (years)	HEIGHT (cm)	MASS* (kg)	YEAR OF INJURY
Quadriplegics						
1	F	C7	24	168	75	1988
2	M	C7	27	174	93	1981
3	M	C6	41	188	105	1966
4	M	C7	32	172	84	1979
5	M	C7	30	179	94	1980
6	M	C6	18	180	65	1988
Able-bodied						
7	M		23	159	83	
8	F		21	160	78	
9	F		24	159	74	
10	F		20	157	75	
11	M		22	180	104	
12	M		33	162	87	

* The mass in kilograms includes the mass of the wheelchair. For able-bodied subjects the wheelchair used had a mass of 18 kg.

Baseline Testing

Baseline testing included the following:

1. Maximum Inspiratory Mouth Pressure (Pimax)
2. Maximum Exercise Test on a Wheelchair Roller
3. Iso-velocity Strength Testing

Outline of Training Regimen

	PRE-TRAINING	TRAINING	POST TRAINING
QUADRIPLEGICS	Pimax	4 weeks	Pimax
	Max. Ex. Test		Max. Ex. Test
	Iso-velocity Strength Testing	re-test	Iso-velocity Strength Testing
ABLE-BODIED	Pimax		Pimax
	Max. Ex. Test	4 weeks	Max. Ex. Test
	Iso-velocity Strength Testing		Iso-velocity Strength Testing

1. Maximum Inspiratory Mouth Pressure

All tests were performed in the seated position. Maximum inspiratory mouth pressure (Pimax) was determined using a comparable technique to that described by Black and Hyatt. (Black, 1971) A minimum of 6 maximum inspiratory efforts were recorded for each subject, with rest periods interspersed between each measurement. If these measurements were within 5% of each other, the Pimax. recorded was the average of the three highest measurements. Repeated measurements were made following a brief rest if the variability exceeded 5% for the three maximum measurements.

2. Maximum Exercise Testing on a Wheelchair Roller

Exercise Testing

All quadriplegic subjects were tested and trained seated in their own wheelchairs. The able-bodied subjects were tested and trained in light weight wheelchair. (Everest and Jennings, Lightweight, Camarillo, California, 93010)

Exercise Device

The wheelchair ergometer was a modified B.C. Telephone Shops (B.C. Chapter 53) wheelchair roller. (Figure 1) The original braking mechanism was replaced with a strap brake fitted with sensors to obtain repeatable and calibrated force measurements. (Figure 2) The wheelchair roller was instrumented with an optical tachometer to monitor the number of revolutions (REVS) and the revolution rate (RPM). These measurements allowed direct determination of workload and power. Two high contrast strips were located on the flywheel and the passage of the strips was detected by the reflective optical sensor. A single revolution had been completed after two stripes had been detected. The relationship between the radius of the wheelchair wheel and the roller allowed the derivation of RPM and REVS of the wheelchair.

The force sensor system monitored the difference between the tension at the ends of the belt during flywheel motion. A strain gauge transducer was used to obtain a voltage reading which was linearly related to the braking force. The force indicator was calibrated in Newtons (N).

Knowing the force, revolutions and the circumference of the flywheel, allowed the calculation of mechanical power and work performed by the individual.

MODIFIED PIONEER WHEELCHAIR ROLLER

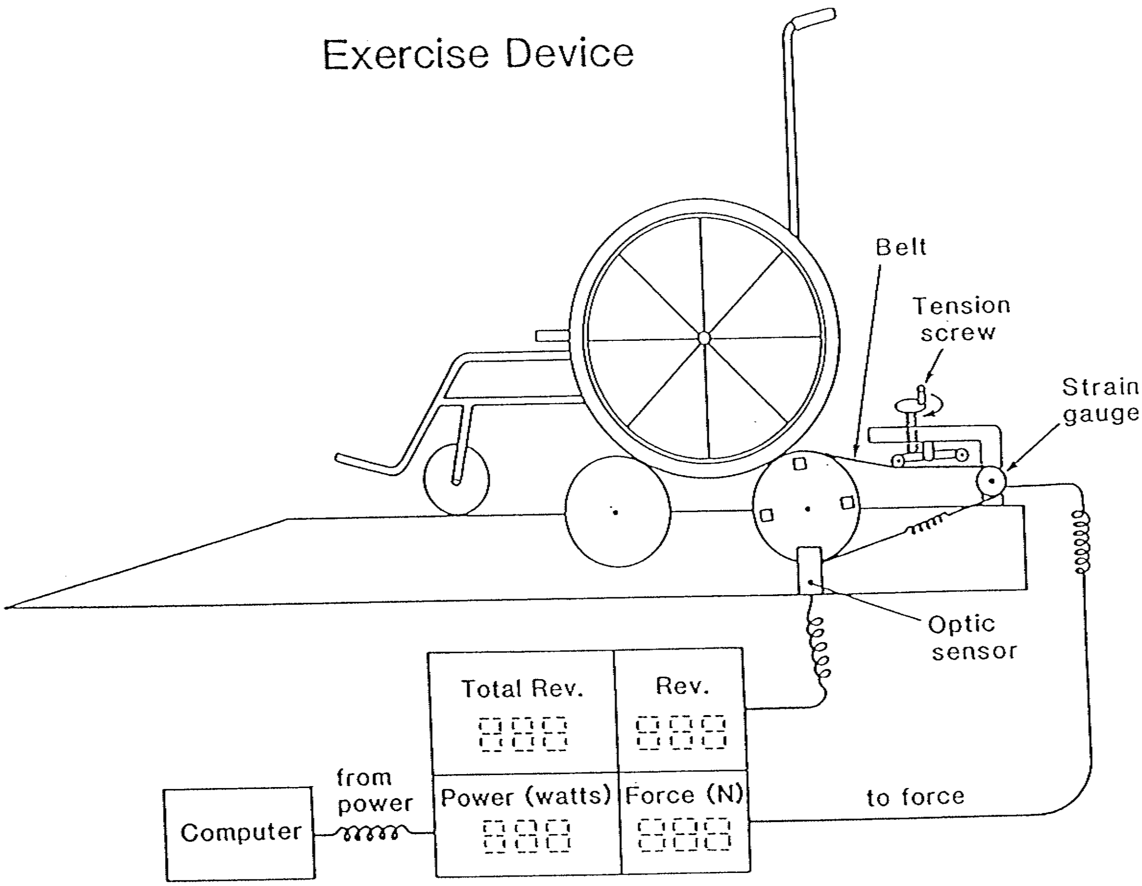


Figure 1 - Modified pioneer wheelchair roller

STRAP BRAKE MECHANISM

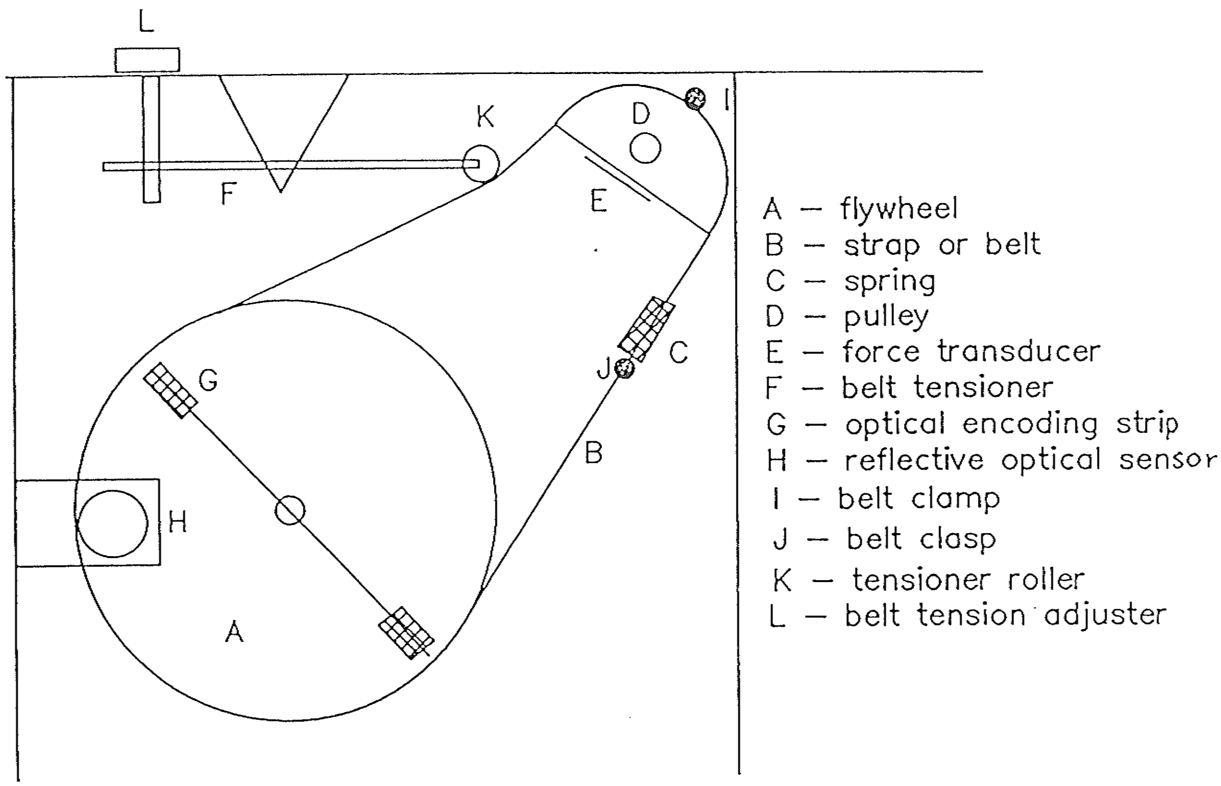


Figure 2 - Side view of the strap brake mechanism showing the key components. The flywheel (A) has a machine groove which accommodates the strap. The strap or belt is rigidly affixed to the pulley (D) which houses the force transducer (E). The initial tension of the belt can be adjusted by a clasp (J) connected to the spring (C). The spring serves to increase the travel of the belt tensioner adjuster, for finer control of the workload. The reflective sensor (H) monitors the passage of two high contrast stripes (G). The optical sensor (H) is fixed to the frame 2-5mm from the flywheel. (figure taken from Kriellaars, 1990)

Subjects were placed on a mouthpiece and wore noseclips. Expired gas was collected and analyzed with the aid of a Sensormedics 2900 Metabolic Cart. The metabolic cart consisted of a computerized system which included an online gas collection method with a mixing chamber and oxygen (O_2) and carbon dioxide (CO_2) analyzers. The subjects were also monitored with a single modified V5 lead electrocardiogram throughout the exercise test. External analog inputs for power in Watts from the wheelchair roller and heart rate were interfaced through an IBM compatible microprocessor. On line computation and comparison of ventilatory, cardiovascular and work output variables was provided. The metabolic cart provided a 20 second average of workload, heart rate, tidal volume, frequency, minute ventilation, oxygen uptake ($\dot{V}O_2$) and CO_2 output to be recorded throughout the exercise test. Two minutes of resting breathing were collected prior to commencement of the exercise test.

In a preliminary trial, subjects pre-selected a comfortable wheeling speed, and this speed was used for the exercise testing. Due to physical limitations, particularly poor trunk control, we determined that quadriplegics performed better by increasing the braking resistance rather than the speed of propulsion. The revolutions per minute (RPM) were monitored and controlled with the use of a metronome. Subjects also had visual feedback from the display monitor to assist in maintaining a constant speed. Braking resistance was increased in increments of 2.0 Newtons every 2 minutes to maximum. During the last 30 seconds of each workload, the subjects identified their rate of perceived exertion separately for both arm effort and breathing effort. Borg's Scale of perceived exertion was used to assess these efforts as it has been utilized in other studies (Dunbar 1992, Ceci 1991, Klesges 1990, Robertson 1990). Borg's scale (Table 3) was held within the subjects vision and they were asked "How do your arms feel?". The subject nodded when the appropriate number on the scale was read to them. The perceived effort for breathing was then determined by asking "How does your breathing feel?" and the appropriate level indicated was noted (Borg 1982).

At the end of the exercise test, the subject remained on the mouthpiece until ventilation and $\dot{V}O_2$ returned to the pre-exercise state.

Subjects repeated the exercise test at the four week interval to re-establish their training workload, and again at the end of the 8 week study period.

Table 3

Borg's Perceived Exertion Scale

0...............Nothing at All

1............. Very Light

2...............Light

3...............Moderate

4...............Somewhat Heavy

5...............Heavy

6

7...............Very Heavy

8

9

10.............Very, Very Heavy

3. Iso-velocity Strength Testing

Kinetic Communicator (Kin-Com) Strength Dynamometer

The Kin-Com (Med-Ex Diagnostics of Canada Inc., Coquitlam, B.C.) iso-velocity dynamometer was chosen to evaluate strength changes because it has been established as a reliable and valid method of testing strength about the knee joint (Farrell and Richards 1986, Burdett 1987). In addition, the current literature for able-bodied subjects aids in establishing the testing protocols, test speeds and positioning of subjects and methods of comparison of results (Griffin 1987, MacDonald 1988, Osternig 1977, Weltman 1988). These positions and protocols were then modified to the specific study population. The Kin-Com was also chosen because of its availability and accessibility to the study. This system is a computer controlled hydraulic device which has "isokinetic", isometric, isotonic or passive test modes.

Subjects exerted a force with the isolated limb against the Kin-Com and the parameters of force, arm angular velocity, and angular displacement were sampled and recorded on the Kin-Com and stored on disk. No handgrips were required for any of the movements tested. The pad used for all tests was the small knee pad which is standard equipment in the Kin-Com apparatus.

In the "isokinetic" mode (iso-velocity), the dynamometer arm angular velocity remained constant, regardless of the force applied by the subject. In the passive mode, the exercise arm moved at a pre-selected velocity through the range whether force was applied or not.

Testing Positions

Some of the testing positions were adapted from those cited in previous studies (MacDonald 1988, Griffen 1987, Osternig 1977). All tests were conducted with the subject seated in a wheelchair.

Pilot testing was carried out with one quadriplegic subject who did not participate in the study, to establish the optimum position for reproducible testing with quadriplegics. It was established that a platform was necessary to raise the level of the wheelchair to accommodate the height of the subjects in their wheelchairs to the Kin-Com. The platform devised by the Engineering Department of St. Boniface Hospital, Winnipeg Manitoba, measured 6 feet by 4 feet and was 5 inches in height. There was a non-slip surface to aid in stabilization of the wheelchair. In addition the wheels were sandbagged to avoid unwanted movement of the wheelchair wheels. Repeated assessments and movement testing were performed with this volunteer quadriplegic to ensure accuracy and reproduction of each movement.

All movements were performed with the right arm only during concentric contraction. If the subject had such limited motor function that active contraction was not possible, for example a C6 quadriplegic being unable to actively extend the elbow, the passive mode on the Kin-Com was utilized. The right arm only was tested since wheeling is a bilateral activity, and it was assumed that similar strength gains would be observed with both arms (Alderink 1986, Hageman 1988). Four maximum contractions with one minute rest intervals between repetitions were performed. Two sub-maximal contractions were performed to serve as a warm-up and familiarize the subject with the testing procedure. No verbal encouragement was provided after the initial explanation of the testing procedure. An angular velocity of 60 degrees per second was used for testing of shoulder flexion and abduction, elbow flexion and extension and wrist extension. This is a commonly reported testing speed for the shoulder in the literature (Brumbac 1992, Cahalan 1991, MacDonald 1988, Davis 1990). A velocity of 30 degrees per second was used to assess the movement of shoulder shrug. It was established in the pilot testing that 60 degrees per second was too fast to achieve reproducible results, whereas, reproducible results were achieved for this movement at 30 degrees per second. The testing was repeated in the same manner after the wheelchair training program.

Movements tested were as follows:

elbow flexion

elbow extension

wrist extension

shoulder abduction

shoulder shrug

shoulder flexion

Table 4 outlines the movements tested, the muscles performing the action and the nerve root supply to these muscle.

Table 4

Movements Tested and the Muscle Performing the Action

MOVEMENT	MUSCLE	NERVE SUPPLY	ROOT
elbow flexion	1.brachialis 2.biceps brachia 3.brachioradialis 4.pronator teres 5.flexor carpi ulnaris	musculocutaneous musculocutaneous radial median ulnar	C5,C6,C7 C5,C6 C5,C6,C7 C6,C7 C7,C8
elbow extension	1.triceps 2.anconeus	radial radial	C6,C7,C8 C7,C8,T1
wrist extension	1.extensor carpi radialis longus 2.extensor carpi radialis brevis 3.extensor carpi ulnaris	radial posterior interosseous posterior interosseous	C6,C7 C7,C8 C7,C8
shoulder abduction	1.deltoid 2.supraspinatus 3.infraspinatus 4.subscapularis 5.teres minor	circumflex suprascapular suprascapular subscapular circumflex	C6,C7 C5,C6 C5,C6 C5,C6 C5,C6
shoulder shrug elevation	1.trapezius (upper fibres) 2.levator scapulae 3.rhomboid major 4.rhomboid minor	accessory C3,C4 n.roots C3,C4 n.roots dorsal scapular dorsal scapular dorsal scapular	cranial nerve XI C3,C4 C5 C4,C5 C4,C5
shoulder flexion	1.deltoid (anterior fibres) 2.pectoralis major (clavicular) 3.coracobrachialis 4.biceps	circumflex (axillary) lateral pectoral musculocutaneous musculocutaneous	C5,C6 post C5,C6 lat cord C5,C6,C7 C5,C6,C7

Figure 3 represents a schematic diagram of the Kin-Com and the position of the subject tested seated in the wheelchair.

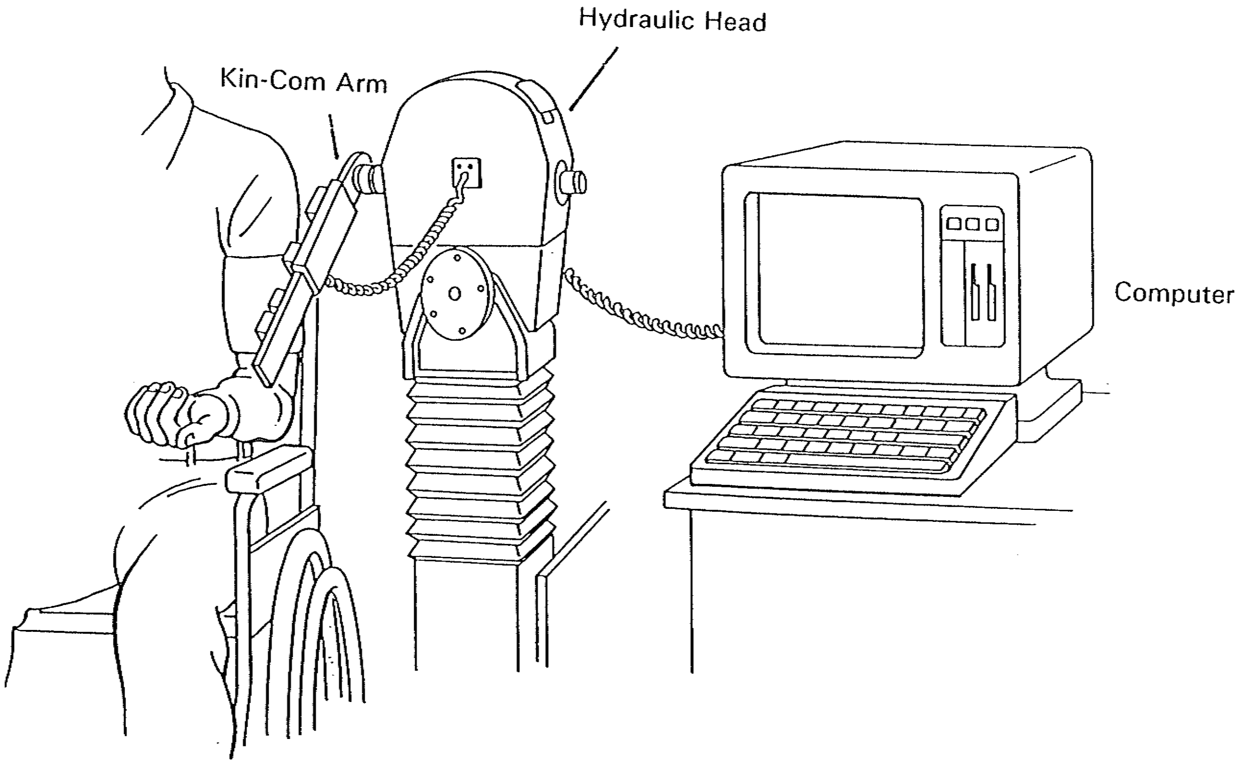


Figure 3 - representation of the Kin-Com Iso-velocity Dynamometer and position of the subjects during testing.

Description of the pad placement, axis of movement of the dynamometer in relation to the axis of movement of each joint being tested are detailed as follows:

1. Elbow flexion

i. subject was seated in the wheelchair on the platform facing the bench of the Kin-Com. The platform table was adjusted in height to allow the subject's upper arm to rest horizontally on the table. The axis of rotation of the machine was aligned with the axis of rotation of the elbow located just anterior to the lateral epicondyle (Kaltenborn 1980, Kapandji 1974). The forearm was positioned in mid-prone.

ii. the lever arm of the Kin-Com was adjusted so that the pad was proximal to the wrist resting on the radius.

iii. a velcro strap fixed the pad in place around the forearm. No additional stabilization was necessary other than verbal instruction to only flex the elbow.

iv. the start angle for the limb was 0 degrees flexion and the return angle was set at 110 degrees flexion making the range of motion tested 110 degrees. (Figure 4)

v. the angular velocity was set for 60 degrees per second for the test repetitions.

2. Elbow extension

i. subject was seated in the wheelchair on the platform facing the bench of the Kin-Com. The platform table was adjusted in height to allow the subject's upper arm to rest horizontally on the table. The axis of the machine was aligned with the axis of rotation of the elbow located just anterior to the lateral epicondyle (Kaltenborn 1980, Kapandji 1974). The forearm was positioned in mid-prone.

ii. the lever arm of the Kin-Com was adjusted so that the pad was proximal to the wrist with the ulna resting on the pad.

iii. a strap fixed the pad in place around the forearm. No additional stabilization was necessary other than verbal instruction to only extend the elbow. In subjects who were not able to actively extend the elbow (the two C6 quadriplegics) the passive mode on the Kin-Com was utilized.

iv. the start angle of the limb was 110 degrees of flexion and the return angle was 0 degrees of flexion making the range of motion tested 110 degrees. (Figure 5)

v. the angular velocity was set for 60 degrees per second for the test repetitions.

3. Wrist extension

i. subject was seated in the wheelchair on the platform facing the bench of the Kin-Com. The platform table was adjusted in height to allow the subject's upper arm and forearm to rest horizontally on the table with the wrist overhanging the platform table. The axis of the machine was aligned with the axis of rotation of the wrist located at the level of the ulnar styloid process (Kaltenborn 1980, Kapandji 1974). The forearm was positioned in pronation.

ii. the lever arm of the Kin-Com was adjusted so that the pad rested on the metacarpals, distal to the dorsal wrist crease.

iii. the strap was placed around the metacarpals through the first web space leaving the thumb free of restraint. No other stabilization was required.

iv. the start angle for the limb was 0 degrees of extension and the return angle was set for 50 degrees of extension making the range of motion 50 degrees. (Figure 6)

v. the angular velocity was set for 60 degrees per second for the test repetitions.

4. Shoulder abduction

i. the platform was removed and the subject sat in his wheelchair with his back facing the Kin-Com machine and the non-tested left arm hanging over the edge of the chair for stabilization during the movement. The axis of the Kin-Com was aligned with the axis of rotation of the glenohumeral joint, approximately 4 cm. medial to the tip of the acromion on the posterior aspect of the shoulder (Kaltenborn 1980, Kapandji 1974).

ii. the pad was placed on the lateral lower 1/3 of the humerus proximal to the elbow.

iii. no attempt was made to check lateral trunk flexion with stabilization straps, except for verbal instruction to avoid lateral trunk flexion during the movement.

iv. the elbow was placed in a position of 90 degrees of flexion and the start position was 10 degrees of abduction with the return angle set at 90 degrees of abduction (range of motion was 80 degrees). (Figure 7)

v. the angular velocity was set for 60 degrees per second for the test repetitions.

5. Shoulder shrug

i. the platform was removed and the subject sat in his wheelchair with his back facing the Kin-Com machine and the non-tested left arm resting comfortably in his lap. The axis of the Kin-Com was aligned with an axis of rotation approximately located at the level of T2 spinous process.

ii. the pad was placed on the mid section of the upper fibres of trapezius.

iii. no stabilization straps were required except for verbal instruction to avoid trunk movement during the test.

iv. the scapula was placed in a position of 0 degrees of elevation for the start position with the return angle set at 25 degrees of elevation (range of motion was 25 degrees). (Figure 8)

v. the angular velocity was set at 30 degrees per second for the test repetitions.

6. Shoulder flexion

i. subject was moved to the other side of the Kin-Com, seated in his wheelchair. The axis of the machine was aligned with the axis of rotation of the glenohumeral joint approximately 1 1/2 inches inferior to the tip of the acromion process on the lateral aspect of the humerus (Kaltenborn 1980, Kapandji 1974).

ii. the lever arm of the Kin-Com was adjusted so that the pad was proximal to the elbow 1/2 way down the shaft of the anterior humerus.

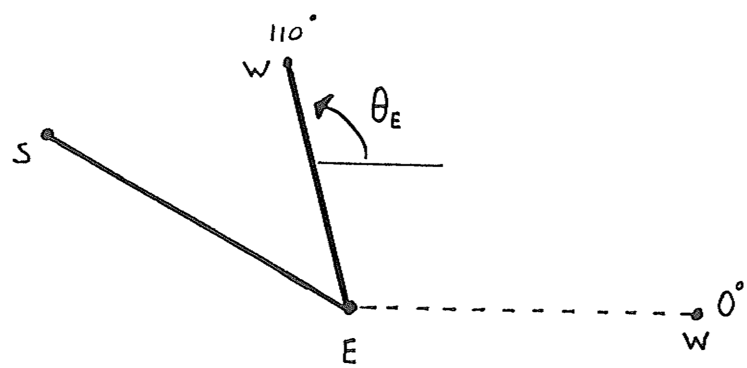
iii. no other stabilization straps were required, except for verbal instruction to move only the right arm.

iv. the elbow was placed in approximately 90 degrees of flexion, the start angle of the limb was 0 degrees shoulder flexion and the return angle was set at 110 degrees of shoulder flexion (range of motion measured was 110 degrees). (Figure 9)

v. the angular velocity was set for 60 degrees per second for the test repetitions.

The following figures 4-9 are diagrammatic representations of the movements tested and the range of motion during the excursion. Elbow flexion, elbow extension, wrist extension, shoulder abduction, shoulder shrug and shoulder flexion follow respectively.

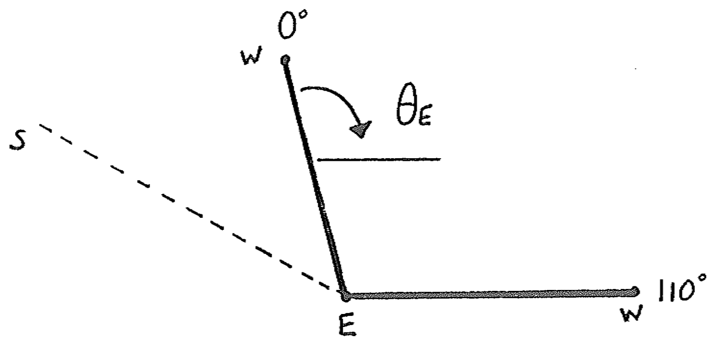
ELBOW FLEXION



S = shoulder joint
E = elbow joint
W = wrist joint
θ_E = elbow angle

Figure 4 - Elbow flexion. The axis of rotation for movement was at the elbow joint. Gravitational direction (g) is indicated by the arrow.

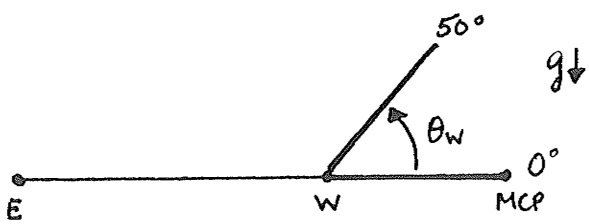
ELBOW EXTENSION



S = shoulder joint
E = elbow joint
W = wrist joint
θ_E = elbow angle

Figure 5 - Elbow extension. The axis of rotation for movement was at the elbow joint

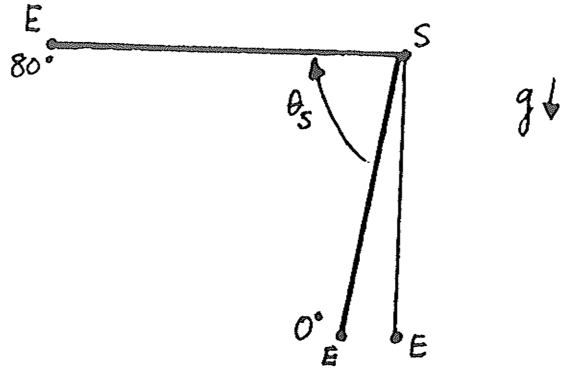
WRIST EXTENSION



E = elbow joint
W = wrist joint
MCP = metacarpal phalangeal joint
θ_W = wrist angle

Figure 6 - Wrist extension. The axis of rotation for movement was at the wrist joint.

SHOULDER ABDUCTION

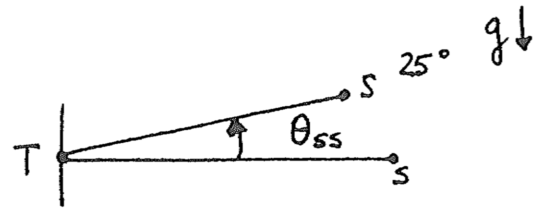


S = shoulder joint
E = elbow joint
θ_S = shoulder angle

Figure 7 - Shoulder abduction. The axis of rotation for movement was at the glenohumeral joint.

SHOULDER SHRUG

posterior view

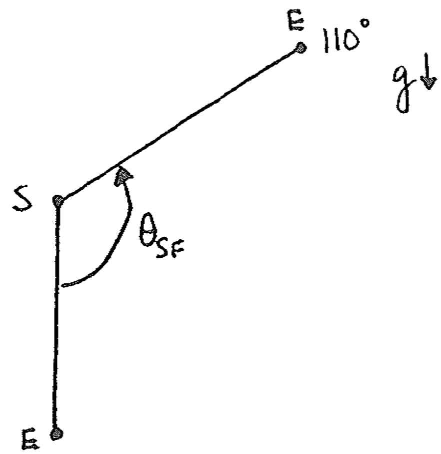


T = T_2 spinous process
S = shoulder joint
θ_{SS} = shoulder shrug angle

Figure 8 - Shoulder shrug. The axis of rotation for the Kin-Com was aligned with the T2 spinous process.

SHOULDER FLEXION

side view



S = shoulder joint
E = elbow joint
θ_{SF} = shoulder flexion angle

Figure 9 - Shoulder flexion. The axis of rotation of movement was at the glenohumeral joint.

Exercise Training Protocol

Each subject attended the lab for exercise training sessions 5 days per week for a period of 8 weeks. The exercise training protocol is outlined in Table 6. Since the comfortable wheeling speed of each subject differed widely, particularly between quads and controls, the protocol of the training program had a variable speed of wheeling between subjects, and a fixed resistance for each subject based on the results of their most recent exercise test. Subjects maintained the same wheeling speed as during the exercise tests. The braking resistance was adjusted in small increments (2N) to the maximum workload. Rest periods of 2 minute intervals were interspersed between 5 minute intervals of wheeling exercise.

Table 5 indicates the wheeling speed of the wheelchair ergometer during the exercise tests. (RPM)

Table 5

Revolutions per Minute in Final Exercise Test

QUADRIPLEGICS		ABLE-BODIED	
1	100	7	130
2	90	8	120
3	50	9	130
4	50	10	130
5	115	11	120
6	80	12	150

Table 6

Exercise Protocol

WEEK	TOTAL EXERCISE TIME (minutes)	RESISTANCE (Newtons)
1	20	5 mins @ 40% max.workload 15 mins @ 60% max.workload
2	30	5 mins @ 40% max.workload 25 mins @ 60% max.workload
3	30	5 mins @ 40% max.workload 15 mins @ 60% max.workload 10 mins @ 80% max.workload
4	30	5 mins @ 40% max.workload 15 mins @ 60% max.workload 10 mins @ 80% max.workload

Exercise Test Repeated

Note: The workload is based on the braking resistance achieved during the maximum exercise test.

During the second week of training, the total exercise time was increased to 30 minutes; 5 minutes at 40% max workload, and 5 intervals of 5 minutes each at 60% max workload. By the third week of training the subjects were wheeling for 30 minutes; 5 minutes at 40%, 3-5 minute intervals at 60% and 2-5 minute intervals at 80% of maximum workload.

After the fourth week, subjects were retested and their training workload was adjusted to reflect the updated maximum workload achieved in the most recent max. exercise test. The same training protocol as outlined in Table 5 was followed for Weeks 4 - 8.

RESULTS

Overall participation in the study and attendance was very high. All of the subjects appeared highly motivated and did not miss their training sessions with only one exception. In one case, where a quadriplegic suffered a bladder infection during the training period he had to stop training for 2 days. He made up the days lost from training on subsequent weekends.

The results for Pimax for both quadriplegic and able-bodied subjects are included in Table 7. There were significant increases in Pimax following the wheelchair endurance training program for both groups. (Figure 10) Pimax increased from -77.67 $\pm$ 12.69 to -89.67 $\pm$ 11.47 cmH_2O in the quadriplegic group ($p < 0.004$), using a Paired T-Test. This represents a 17% increase in Pimax. The able-bodied subjects increased their Pimax from a mean of -111.5 $\pm$ 9.376 to -127.3 $\pm$ 8.9 cmH_2O ($p < 0.009$) indicating a 13.5% increase post exercise training.

TABLE 7

Pimax ($-cm\ H_2O$) for Quadriplegic and Able-bodied Subjects Pre and Post Exercise Training

Pimax		
	PRE	POST
QUADS		
1	96	100
2	82	98
3	47	68
4	32	44
5	102	110
6	107	118
$\bar{X}$	77.67	89.67
S.E.	12.69	11.47
p	.004	
ABLE BODIED		
7	138	149
8	108	113
9	71	90
10	117	135
11	138	149
12	108	140
$\bar{X}$	111.5	127.3
S.E.	9.376	8.9
p	.009	

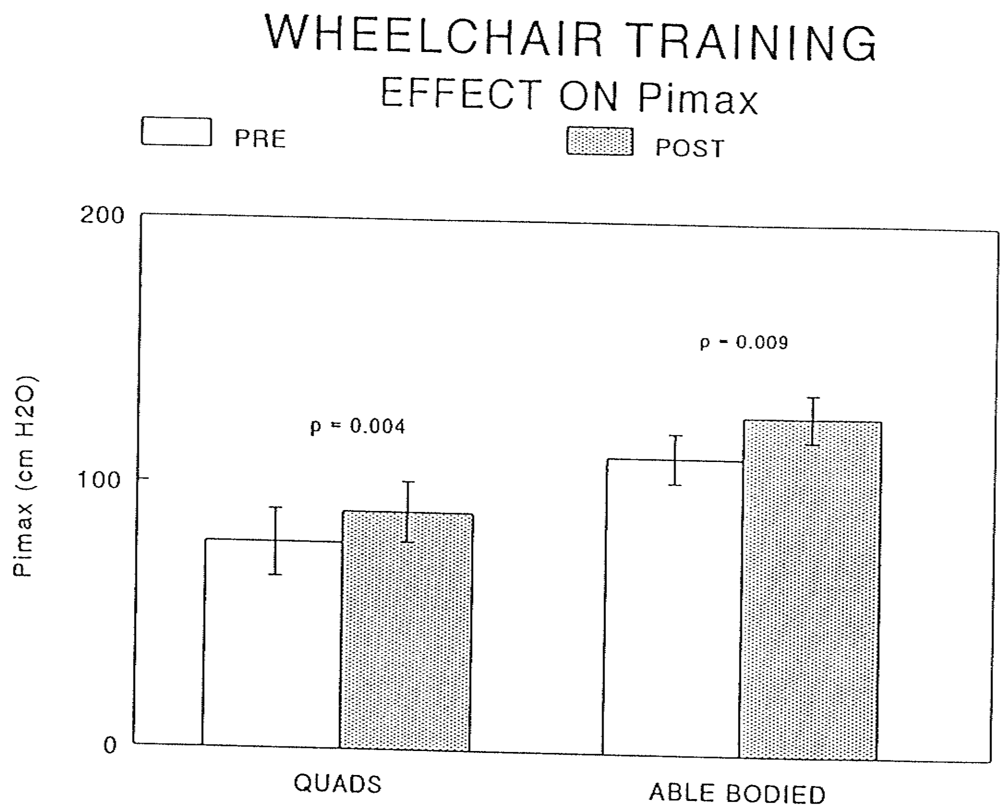


Figure 10 - Effect of the wheelchair exercise training program on Pimax in both Quadriplegic and Able-Bodied Subjects.

Table 8 and Figure 11 indicate the results for Peak $\dot{V}O_2$ (ml) for both quadriplegic and able-bodied subjects. Significant increases in Peak $\dot{V}O_2$, were observed in both groups after the endurance exercise program. The quadriplegic group increased mean Peak $\dot{V}O_2$ from 739.0 ± 99.30 ml. to 840.33 ± 119.43 ml. ($p < 0.025$), using a Paired T-Test. This represents a 14% change post exercise training. The able-bodied group increased their mean Peak $\dot{V}O_2$ from 1934.3 ± 267.8 ml. to 2465.0 ± 264.3 ml. ($p < 0.0025$) indicating more than a 50% change after training.

TABLE 8

Peak VO_2 (ml) for Quadriplegic and Able-bodied Subjects Pre and Post Exercise Training

VO_2		
	PRE	POST
QUADS		
1	840	1021
2	844	899
3	473	603
4	421	434
5	1053	1253
6	803	832
$\bar{X}$	739.0	840.33
S.E.	99.30	119.43
p	.027	
ABLE BODIED		
7	1741	2641
8	2860	3488
9	1134	1861
10	1044	1896
11	1586	2047
12	1441	2858
$\bar{X}$	1634.3	2465.0
S.E.	267.8	264.3
p	.0025	

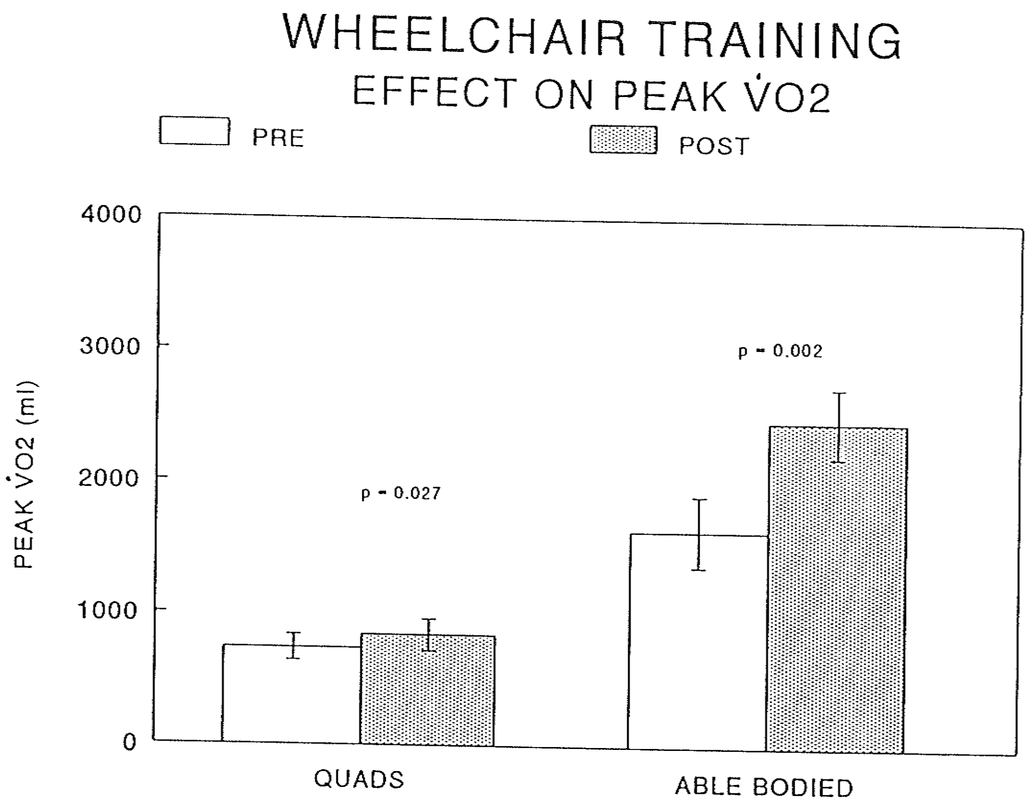


Figure 11 - Effect of wheelchair training program on Peak $\dot{V}O_2$ in quadriplegic and able-bodied subjects.

Table 9 indicates the results for maximum exercise tidal volume (Vt litres) for both quadriplegic and able-bodied subjects. Significant increases in max.Vt were observed in both groups following the exercise program. The quadriplegic group increased max. Vt from .637 $\pm$ .062 to .780 $\pm$ .105 litres ($p < .025$), using a Paired T-Test, a 22.4% increase. Vt during maximum exercise for the able bodied group increased from a mean of 1.21 $\pm$ 0.14 to 1.91 $\pm$ 0.26 litres ($p < .0025$), a 50.8% increase post exercise training.

TABLE 9

Maximum Exercise Tidal Volume (litres) for Quadriplegic and Able-bodied Subjects Pre and Post Exercise Training

TIDAL VOLUME		
	PRE	POST
QUADS		
1	0.63	0.95
2	0.74	0.92
3	0.47	0.50
4	0.51	0.52
5	0.88	1.13
6	0.59	0.66
$\bar{X}$	.637	.780
S.E.	.062	.105
p	.025	
ABLE BODIED		
7	1.2	2.08
8	1.88	3.10
9	0.91	1.33
10	0.98	1.69
11	1.02	1.79
12	1.26	1.48
$\bar{X}$	1.21	1.91
S.E.	0.14	0.26
p	.0025	

Table 10 includes the perceived exertion ratings for both breathing effort and arm effort for all subjects during matched submaximum workloads. To obtain matched submaximum workloads, a midrange workload was noted during the initial exercise test and the perceived exertion ratings at that workload were recorded. This same workload was used to assess perceived exertion during the final exercise test, after the intervention of the wheelchair exercise program. The range of matched submaximum workload for the quadriplegic subjects was from 6 to 32 Watts. The workload in the able-bodied group ranged from 22 to 40 Watts. Both quadriplegic and able-bodied subjects reported significantly decreased arm and breathing effort for a given submaximum workload post exercise training.

Figure 12 graphically illustrates the perceived exertion ratings for breathlessness for both quadriplegic and able-bodied subjects. The submaximal workload was matched for each subject within a range of 24-30 watts for the quadriplegic group and 26-36 watts for the able-bodied group. The ratings of perceived exertion decreased significantly for the quads from 2.5 $\pm$ .85 before the exercise program to 0.83 $\pm$ .31. The able-bodied subjects reported decreased exertion ratings for breathing effort from 3.83 $\pm$ .48 before the training program to 0.83 $\pm$ .167 after the exercise training program.

Figure 13 graphically illustrates the significant decrease in perceived exertion for arm effort during a given submaximal exercise workload. The ratings of perceived exertion for arm effort decreased significantly for the quadriplegic group from a mean of 4.92 $\pm$ 1.33 before the exercise training to 1.17 $\pm$ 0.31 after the exercise training. The able bodied group reported decreased exertion ratings for arm effort from 6.17 $\pm$ .65 before training and 1.0 $\pm$ .258 after the exercise program.

Table 10

Perceived Exertion Ratings During Matched Submaximum Exercise for Arm Effort and Breathing Effort for all Subjects Pre and Post Exercise Training

PERCEIVED EXERTION									
QUADS					ABLE BODIED				
	PERCEIVED EXERTION ARMS		PERCEIVED EXERTION BREATHING			PERCEIVED EXERTION ARMS		PERCEIVED EXERTION BREATHING	
SUBJECT	PRE	POST	PRE	POST	SUBJECT	PRE	POST	PRE	POST
1	3	0	4	1	7	7	1	5	1
2	0	1	0	0	8	3	1	2	1
3	9.5	2	5	1	9	7	1	5	1
4	7	2	1	2	10	6	2	3	1
5	5	1	4	1	11	7	0	4	1
6	5	1	1	0	12	7	1	4	0
MEAN	4.92	1.17	2.5	0.83	MEAN	6.17	1.0	3.83	0.83
S.E.	1.33	0.31	0.85	0.31	S.E.	0.65	0.258	0.48	0.167
p	0.05		0.05		p	0.01		0.005	

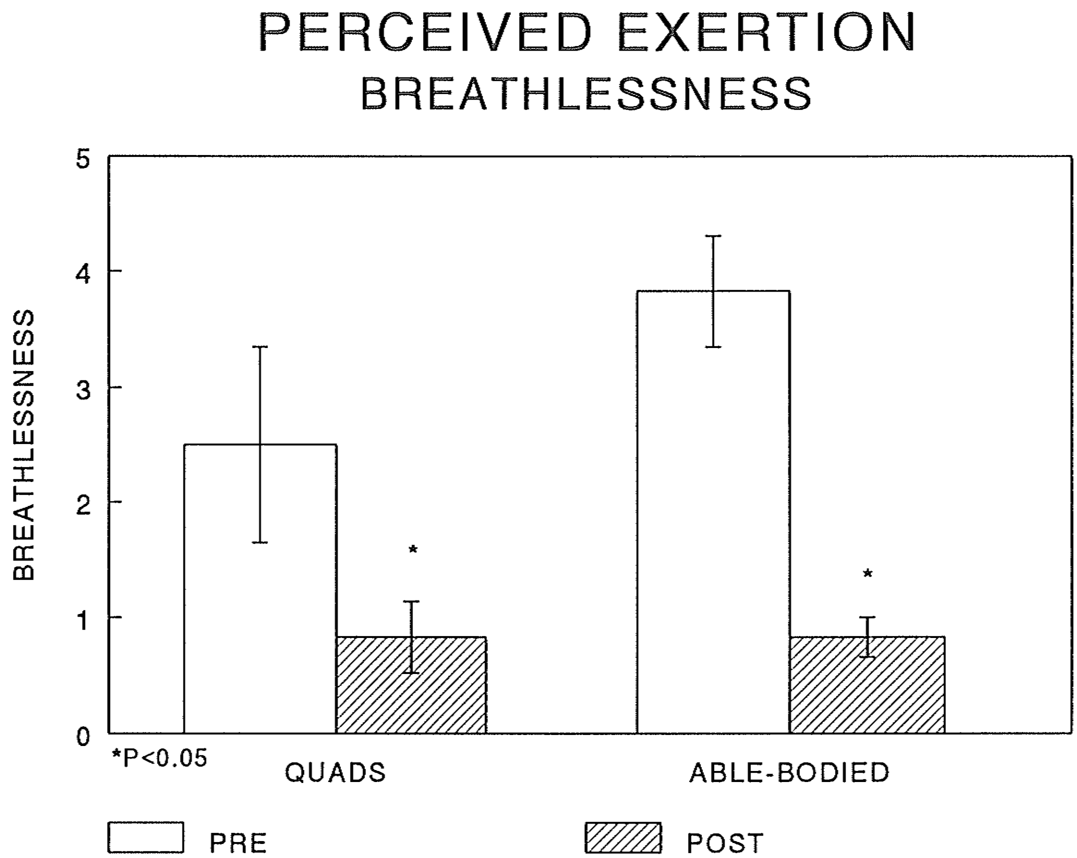


Figure 12 - Perceived Exertion for breathlessness for a given submaximal exercise workload.

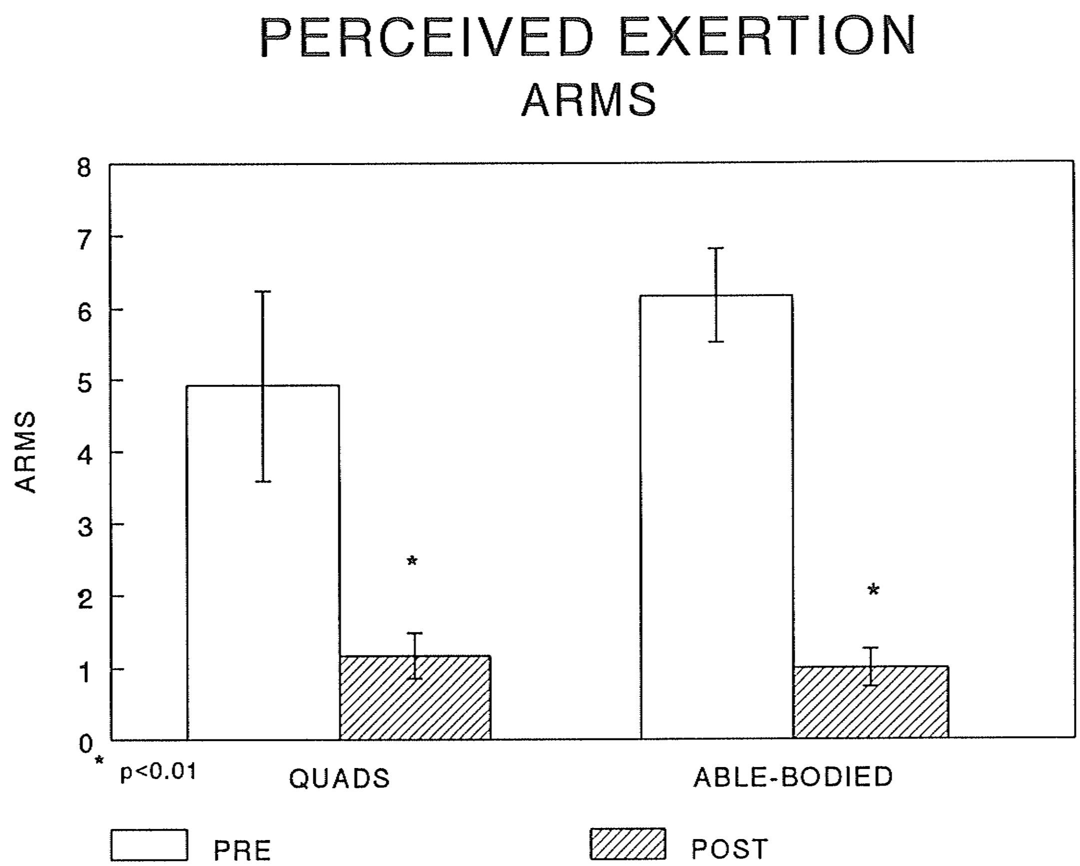


Figure 13 - Perceived Exertion for arm fatigue for a given submaximal exercise workload.

Table 11 and Figure 14 indicate the maximum power output (watts) for all subjects. Both groups showed significant increases in maximum power output after the exercise training program. The quadriplegic subjects increased the maximum power output from a mean of 20 $\pm$ 4.5 to 27.3 $\pm$ 4.6 watts ($p < .025$). The able-bodied group increased maximum power output from 31 $\pm$ 3.67 to 55 $\pm$ 3.04 watts ($p < .0005$).

Table 11

Maximum Power Output (Watts) on Exercise Tests for all Subjects

Pre and Post Exercise Training

MAXIMUM POWER OUTPUT (WATTS)					
QUADS			ABLE BODIED		
SUBJECT	PRE	POST	SUBJECT	PRE	POST
1	28	32	7	36	60
2	30	30	8	46	64
3	6	16	9	24	44
4	6	12	10	22	54
5	26	42	11	26	50
6	24	32	12	32	60
MEAN	20	27.3	MEAN	31	55
S.E.	4.5	4.6	S.E.	3.67	3.04
p	0.025		p	0.001	

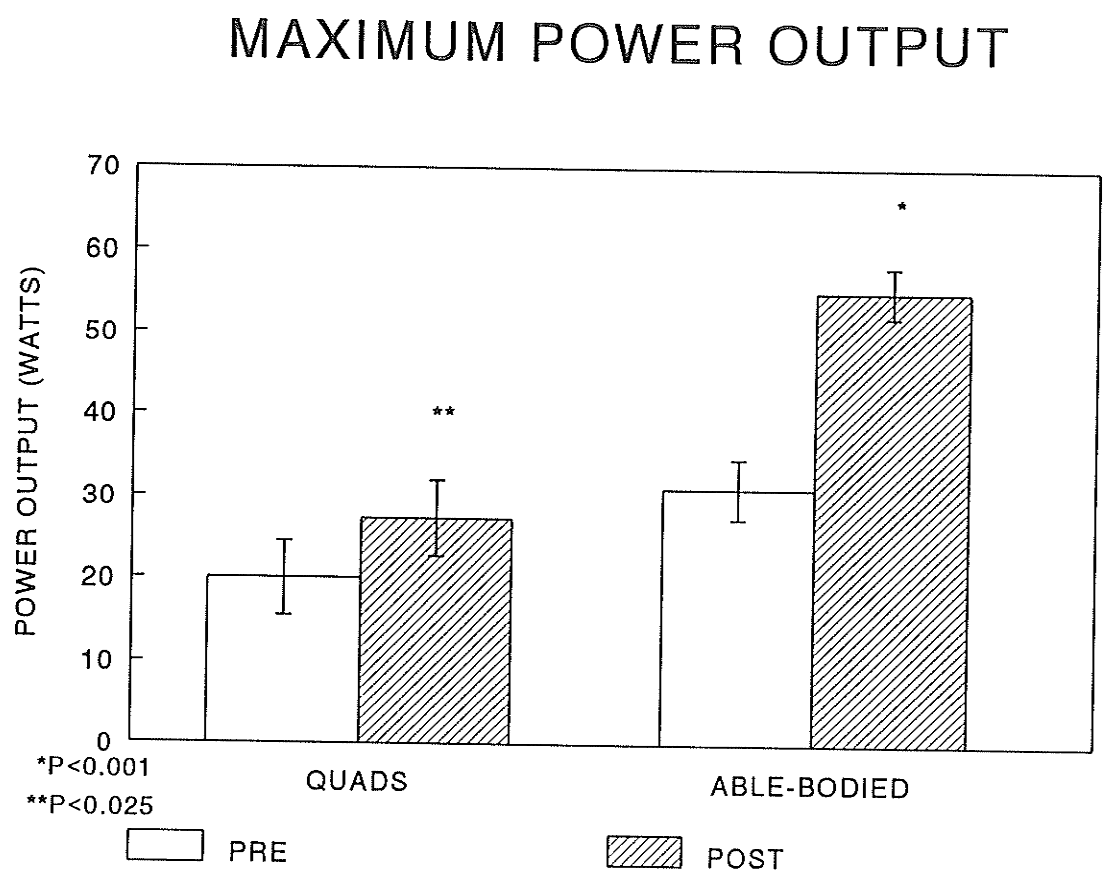


Figure 14 - Maximum Power Output (Watts) during exercise test.

Analysis of the Iso-velocity Testing Measures

The computer software with the Kin-Com provided adequate recordings of the measurement of moment. The raw data was transferred to a AT & T personal computer for additional analysis. This additional analysis allowed the deletion of the periods of angular acceleration (i.e. constant velocity was achieved) and therefore, the torque could be measured exclusively in the range of constant velocity. This was necessary as the quadriplegic population was much weaker than the able-bodied control subjects. Data for the periods of constant velocity were used in this study to compare the results between the quadriplegic and able bodied subjects.

The best performance for each movement was determined by the highest peak torque achieved in that movement. However, the values for all repetitions were included in the repeated measures ANOVA.

Although peak torque has been widely used in the literature to demonstrate changes in strength, the preliminary analysis indicated that the results would be misleading if the study was limited to analysis of peak torque alone. The area under the torque angle curve related to the amount of work performed, was felt to be a more encompassing measurement of the overall strength performance, since although the actual peak torque may not have changed, the angle at which it occurred in the range may have changed, or the length of time the torque was maintained over the range of motion may also have changed with the intervention of the exercise program.

Performance in this test, as well as in the max. exercise test is effort dependent. During the preliminary data analysis, it was noted that in some individual trials, there was an inconsistent effort. The torque angle curve for one repetition was observed occasionally to differ from that of the other three curves. One of the limitations of the Kin-Com software included the inability to preview each trial during the testing procedure. Therefore, variations in the repetitions would not be detected until post test review of the complete file. For this reason, the least representative of the four trials was deleted from each file prior to the statistical analysis of the data. Having established that there was no difference between the remaining three repetitions, these 3 repetitions for each test have been averaged, and the average value is included for both peak torque and the area under the torque angle curve for graphical purposes. The angles at which the peak torque was observed is also included. Table 12 includes the accumulated raw data for the quadriplegic subjects, and Table 13 includes the raw data for the able-bodied group.

Figures 15 - 24 are the pre and post training torque angle curves for representative subjects from both the quadriplegic and able bodied groups for elbow flexion, wrist extension, shoulder abduction, shoulder shrug and shoulder flexion respectively. The individual repetitions were not significantly different with respect to the peak torque. The graphs have been scaled to show comparisons between pre and post exercise training and performance on the Kin-Com.

TABLE 12

Peak Torque, Area Under the Torque Curve and the Angle Values for Quadriplegic Subjects Pre and Post Exercise Training

QUADRIPLEGICS

PRE PEAK TORQUE	ANGLE	AREA	**POST** PEAK TORQUE	ANGLE	AREA	%CHANGE	SUBJECT
ELBOW FLEXION							
29.3	63	2050.1	35.8	25	2552.6	25.5	1
40.1	27	2389.1	42.4	30	2838.2	18.3	2
33.7	48	2415.0	36.6	19	2640.7	9.3	3
12.2	44	852.3	12.1	45	802.9	5.8	4
17.4	38	1225.2	17.4	68	1315.0	7.3	5
34.2	29	2325.7	41.4	49	2869.0	23.4	6
ELBOW EXTENSION							
4.8	75	165.7	2.2	71	120.9	27	1
11.4	89	641.6	4.8	7	289.7	55	2
8.6	88	539.6	6.6	81	405.3	25	3
1.7	14	47.1	0.8	31	29.4	37.6	4
4.3	13	199.4	3.7	90	199.4	0	5
11.7	88	832.2	10.6	26	752.2	9.9	6
WRIST EXTENSION							
3.6	24	71.5	3.7	20	74.0	3.5	1
7.7	20	152.0	11.3	23	232.1	52.7	2
6.0	20	110.4	7.2	14	140.0	26.8	3
0.2	27	1.3	0.5	13	2.6	100	4
2.8	20	53.9	3.8	17	73.5	36.4	5
5.7	10	116.1	6.2	22	126.1	8.6	6

TABLE 12 CONTINUED

Peak Torque, Area Under the Torque Curve and the Angle Values for Quadriplegic Subjects Pre and Post Exercise Training

QUADRIPLEGICS

PRE PEAK TORQUE	ANGLE	AREA	**POST** PEAK TORQUE	ANGLE	AREA	% CHANGE	SUBJECT
SHOULDER ABDUCTION							
17.8	12	592.4	27.9	15	618.5	4.4	1
18.2	15	643.5	20.1	23	753.4	17.1	2
27.7	18	860.0	34.1	21	1150.7	33.7	3
9.3	14	267.2	8.9	15	264.1	1.2	4
16.3	24	631.8	17.6	14	686.1	8.6	5
12.6	15	463.6	28.3	18	1049.5	126.4	6
SHOULDER SHRUG							
24.0	7	299.2	28.9	6	332.8	11.2	1
22.5	9	307.9	40.4	10	538.2	74.8	2
40.5	6	456.0	16.6	10	167.3	63.3	3
10.0	5	108.6	10.6	5	119.0	9.6	4
25.5	5	266.5	27.7	5	331.8	24.5	5
16.6	19	238.7	34.8	18	491.6	105.9	6
SHOULDER FLEXION							
32.7	11	1254.3	39.1	17	1341.2	6.9	1
27.4	28	1042.2	29.9	21	1058.0	1.5	2
24.6	10	816.6	30.2	10	1131.8	38.6	3
8.3	22	236.5	11.9	25	475.0	100.8	4
15.2	21	585.2	17.0	37	652.0	11.4	5
18.6	46	735.9	30.4	41	1278.9	73.8	6

TABLE 13

Peak Torque, Area Under the Torque Curve and Angle Values for the Able-bodied Subjects Pre and Post Exercise Training

ABLE BODIED

PRE PEAK TORQUE	ANGLE	AREA	**POST** PEAK TORQUE	ANGLE	AREA	% CHANGE	SUBJECT
ELBOW FLEXION							
37.8	67	2742.5	39.9	63	3103.0	13.1	7
30.9	16	2288.8	51.4	50	3730.6	62.9	8
40.7	35	2800.6	45.1	10	3351.2	19.6	9
27.2	65	1941.4	26.7	32	1971.7	1.6	10
33.6	57	2401.0	31.1	63	2282.9	4.9	11
32.1	78	2285.5	34.9	62	2430.4	6.3	12
ELBOW EXTENSION							
26.0	71	1735.3	23.4	82	1382.5	20.3	7
21.6	50	1584.8	34.1	55	2537.8	60.1	8
37.7	25	2415.2	35.7	69	2575.8	6.6	9
17.9	42	1276.6	20.5	47	1476.0	15.6	10
25.2	80	1640.8	20.4	77	1386.0	15.5	11
26.6	73	1968.4	21.8	75	1677.1	14.8	12
WRIST EXTENSION							
10.8	44	184.4	12.0	17	241.2	30.8	7
11.5	24	230.3	15.7	23	306.0	32.8	8
12.6	23	252.3	14.9	15	287.9	14.1	9
7.3	14	140.8	7.8	19	156.3	11.0	10
7.3	38	113.1	8.9	26	180.8	59.8	11
8.1	9	157.5	8.2	14	159.8	1.5	12

TABLE 13 CONTINUED

Peak Torque, Area Under the Torque Curve and Angle Values for the Able-bodied Subjects Pre and Post Exercise Training

ABLE BODIED

PRE PEAK TORQUE	ANGLE	AREA	POST PEAK TORQUE	ANGLE	AREA	%CHANGE	SUBJECT
SHOULDER ABDUCTION							
41.9	12	1740.1	36.9	19	1498.2	13.9	7
21.4	12	915.0	35.4	18	1571.0	65.8	8
42.1	13	1739.4	37.5	15	1600.3	7.9	9
23.5	12	974.9	23.9	16	1054.6	8.2	10
29.7	14	1194.8	27.1	13	1101.2	7.8	11
39.8	12	1570.5	37.2	5	1455.7	7.3	12
SHOULDER SHRUG							
40.6	8	588.9	63.6	11	939.2	59.5	7
59.2	10	880.8	71.1	10	1077.3	22.3	8
79.3	5	946.7	104.7	6	1551.0	63.8	9
31.3	6	453.2	32.3	14	489.8	8.1	10
55.6	9	794.3	43.0	13	630.0	20.7	11
48.7	8	581.5	64.2	7	850.7	46.3	12
SHOULDER FLEXION							
30.0	16	1241.3	53.4	7	2224.9	79.2	7
67.4	13	2619.3	65.9	16	2635.3	0.6	8
63.0	16	2666.9	62.6	15	2640.7	1.0	9
35.6	10	1506.1	29.0	60	1282.0	14.9	10
34.6	22	1476.3	42.6	13	1805.4	22.3	11
43.0	23	1854.3	42.5	34	1845.1	0.5	12

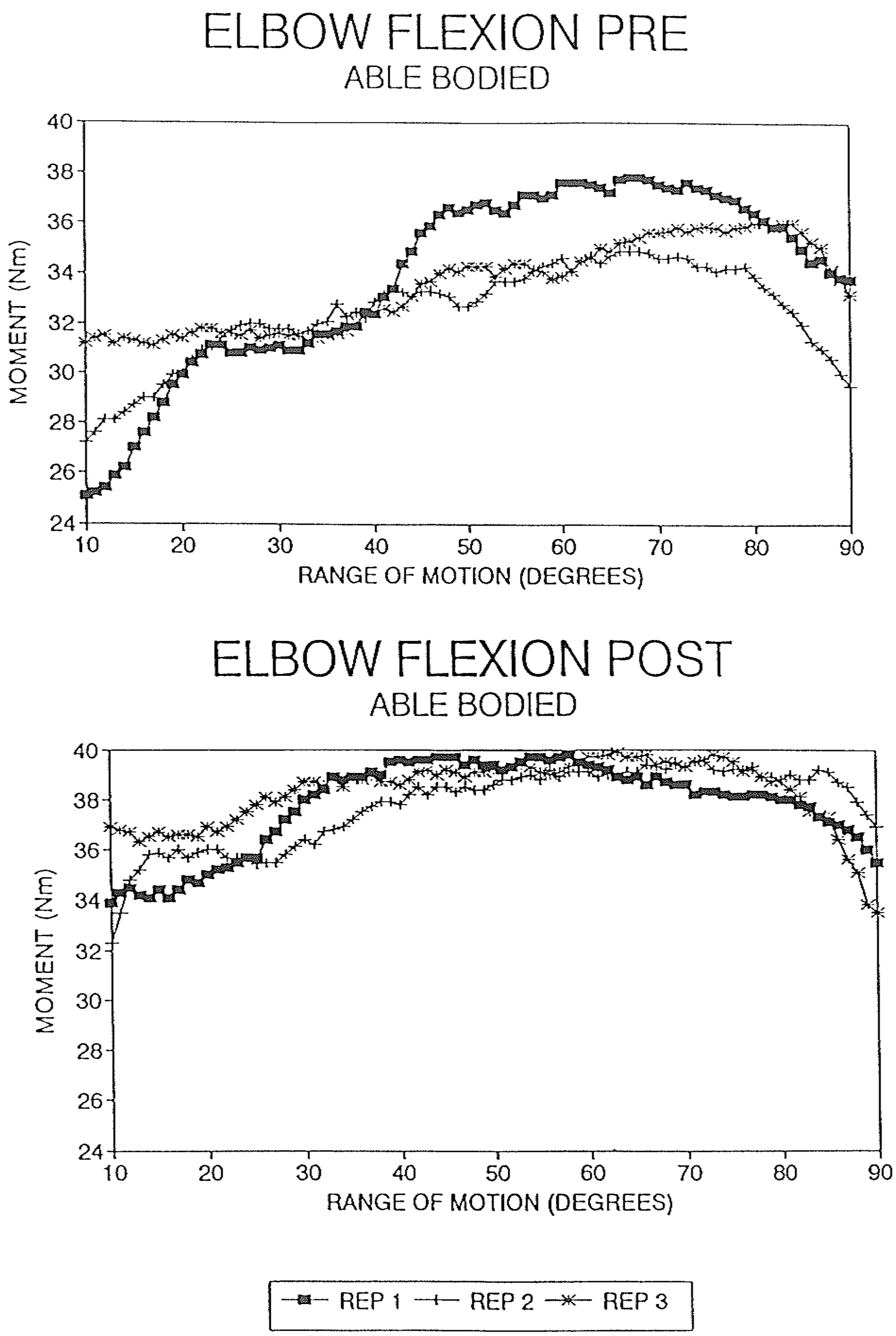


Figure 15 - Elbow flexion movement for a representative able-bodied subject. The graph includes the 3 repetitions and the range of motion represents the elbow joint angle.

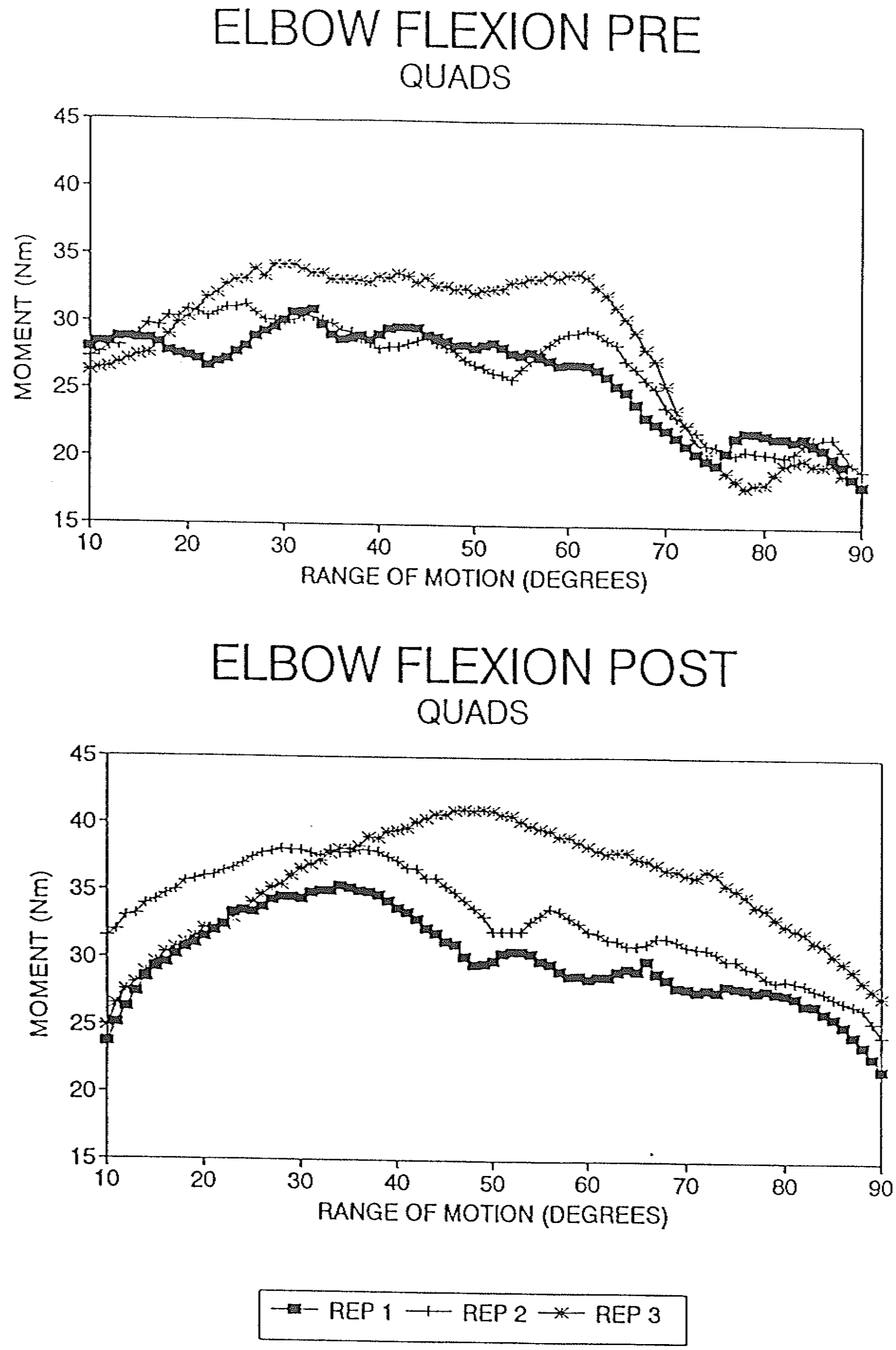


Figure 16 - Elbow flexion movement for a representative quadriplegic subject. The graph includes the 3 repetitions and the range of motion represents the elbow joint angle.

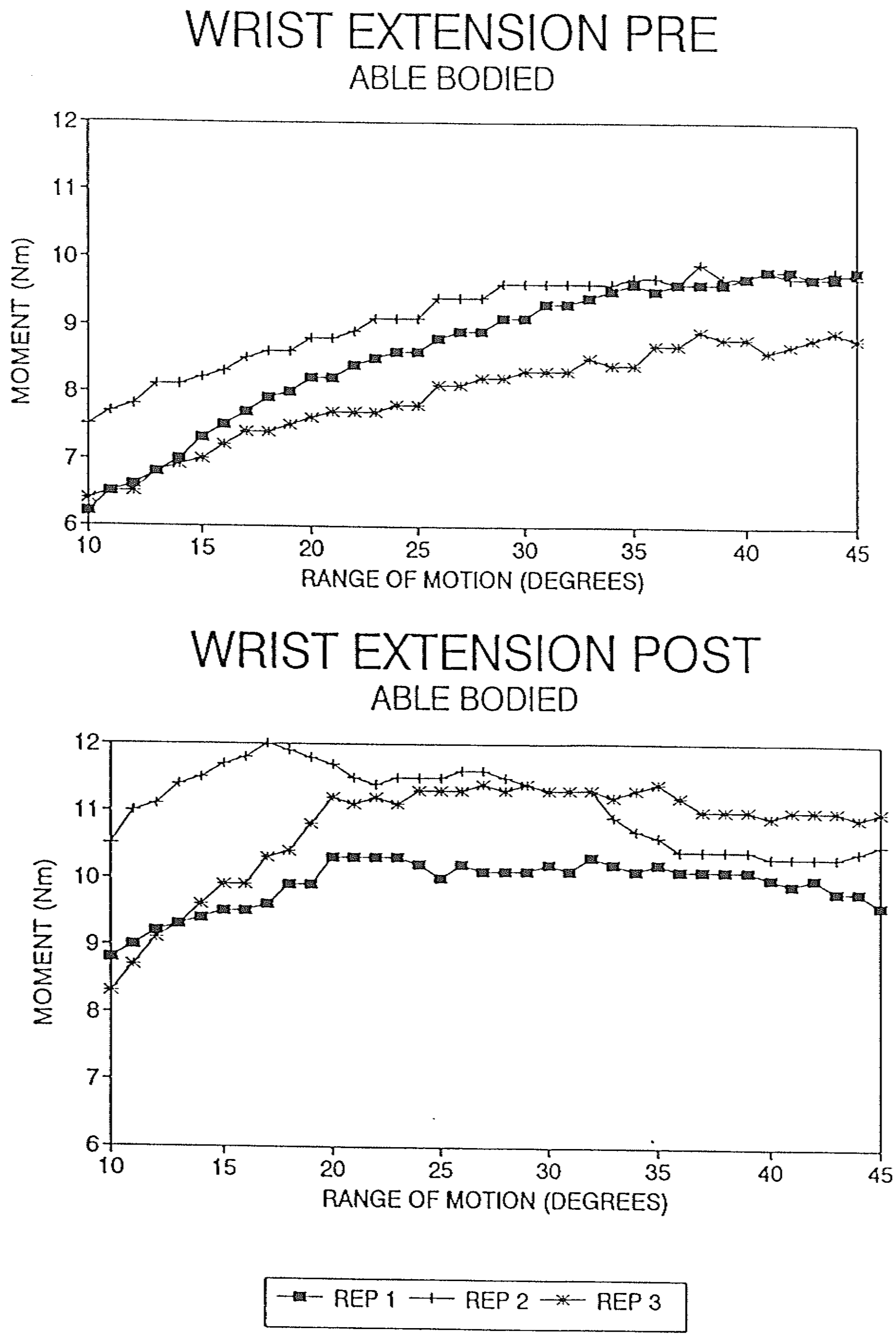


Figure 17 - Wrist extension movement for a representative able-bodied subjects. The graph includes the 3 repetitions and the range of motion represents the wrist joint angle.

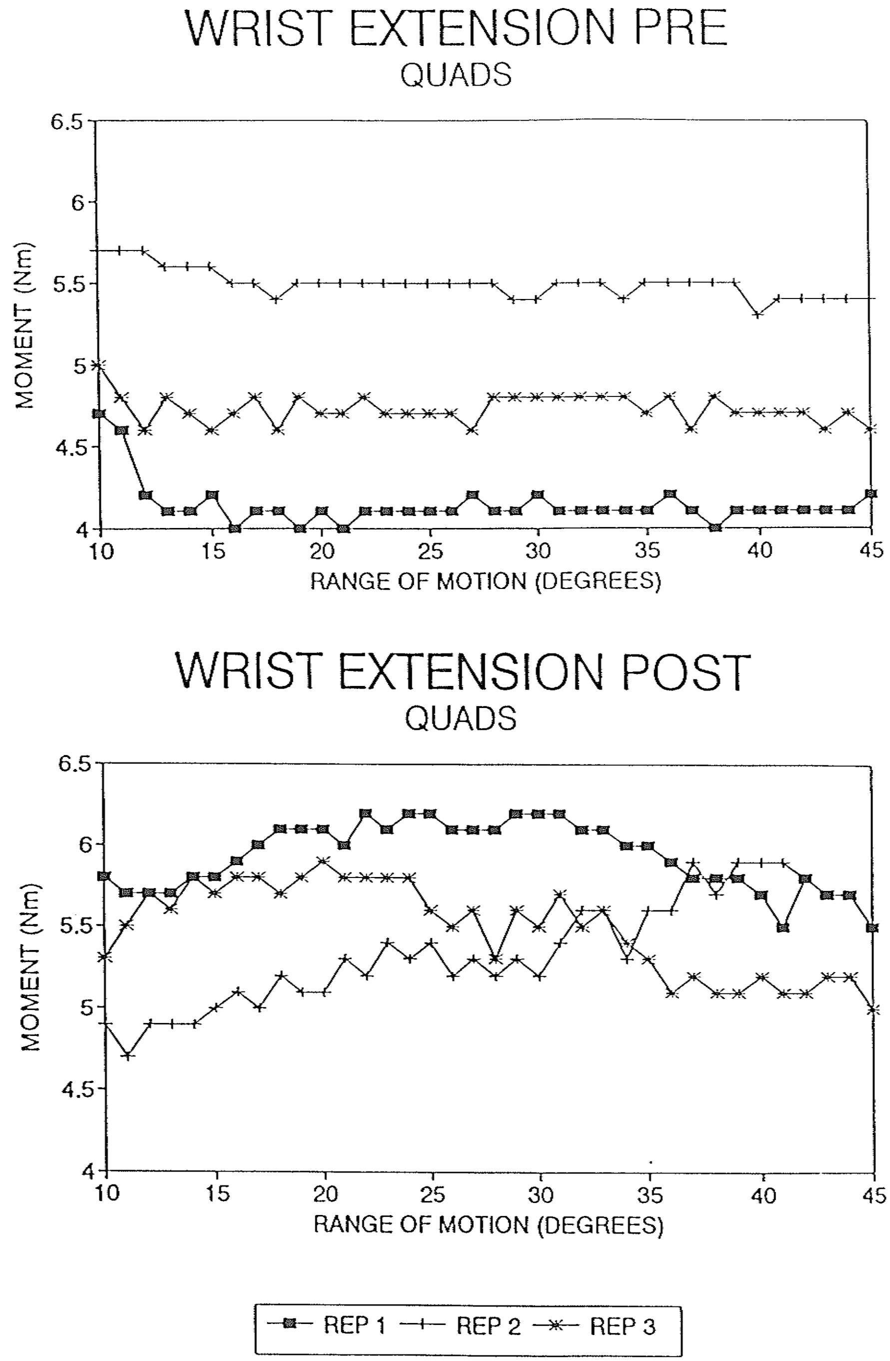


Figure 18 - Wrist extension movement for a representative quadriplegic subject. The graph includes the 3 repetitions and the range of motion represents the wrist joint angle.

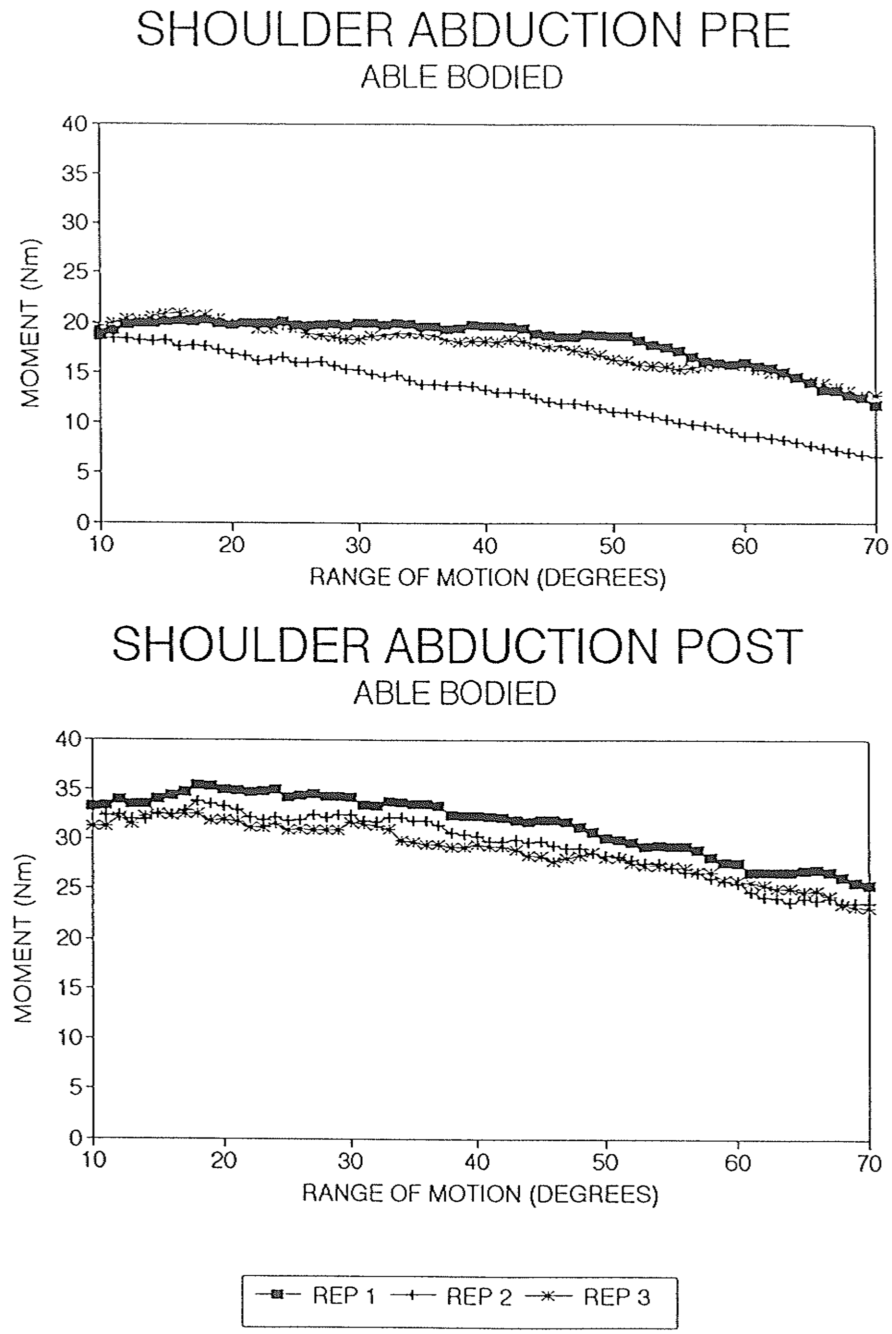


Figure 19 - Shoulder abduction movement for a representative able-bodied subject. The graph includes the 3 repetitions and the range of motion represents the shoulder joint angle.

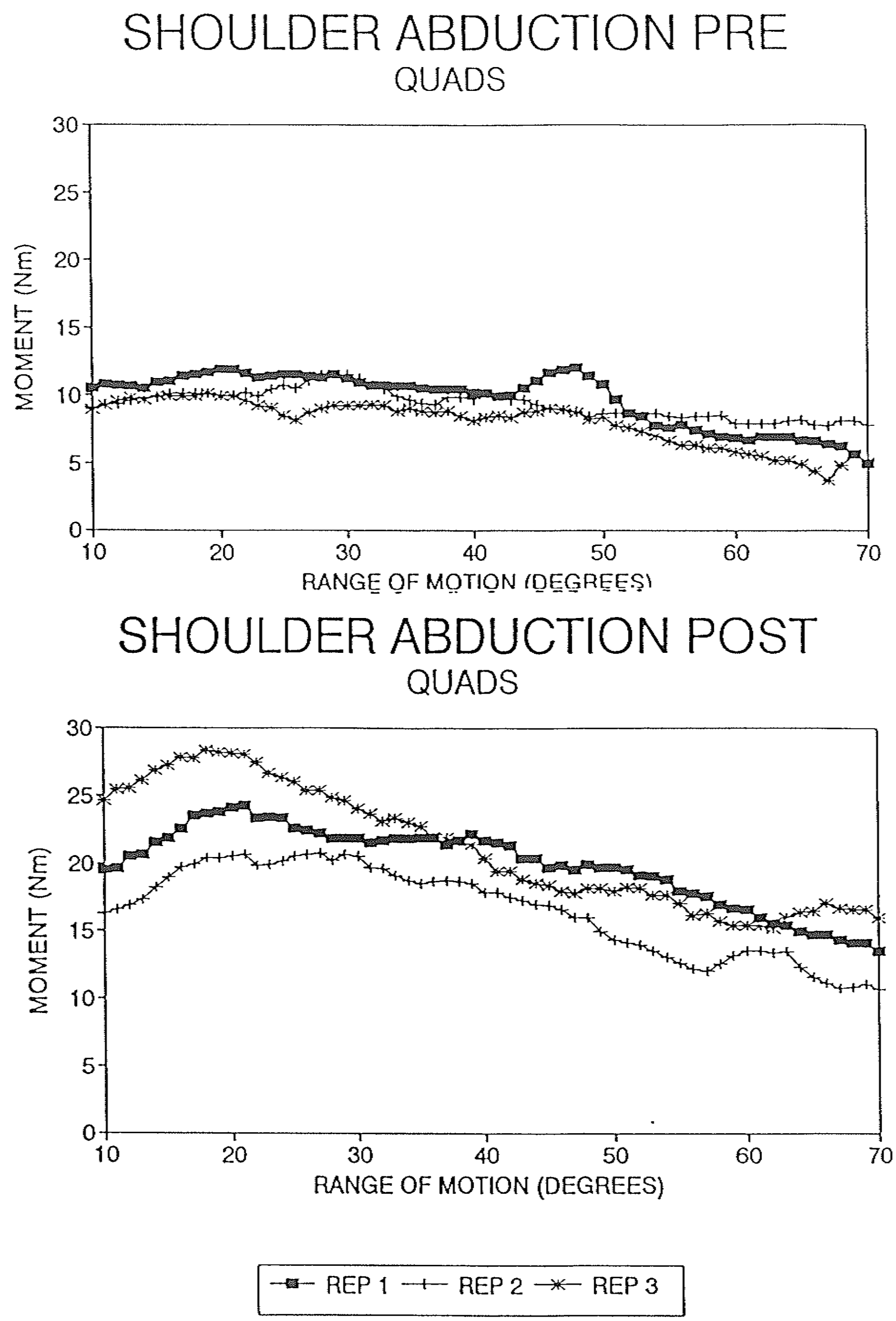


Figure 20 - Shoulder abduction movement for a representative quadriplegic subject. The graph includes the 3 repetitions and the range of motion represents the shoulder joint angle.

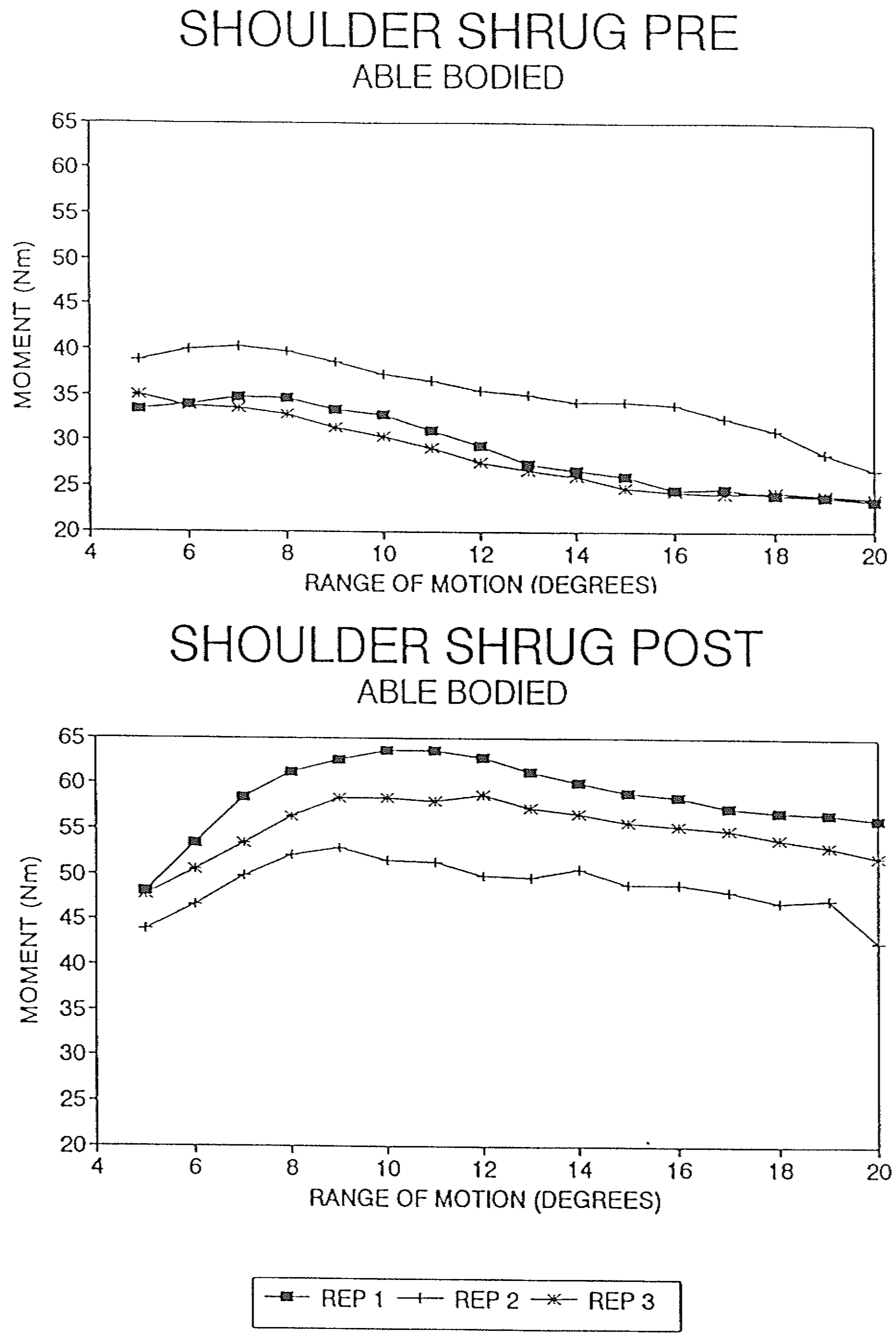
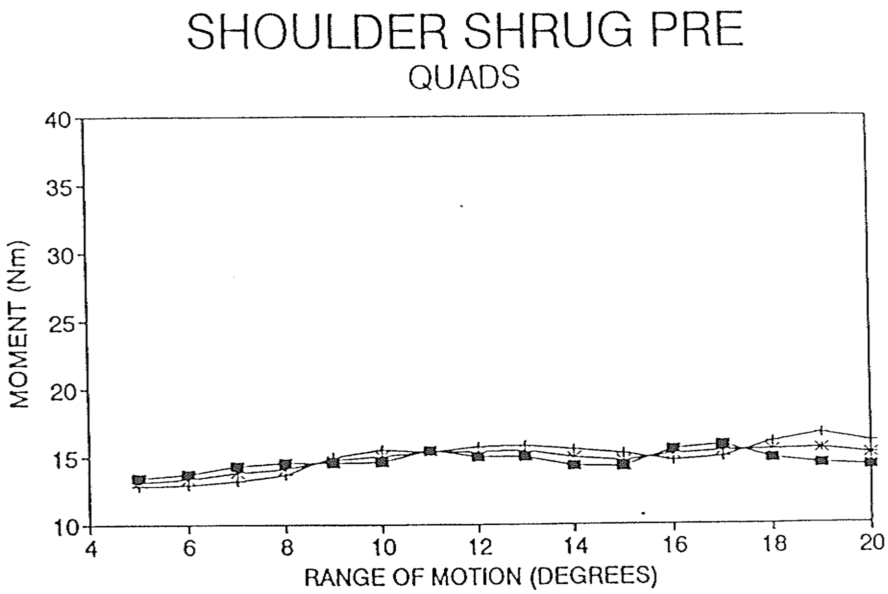


Figure 21 - Shoulder shrug movement for a representative able-bodied subject. The graph includes the 3 repetitions and the range of motion represents the shoulder joint angle.



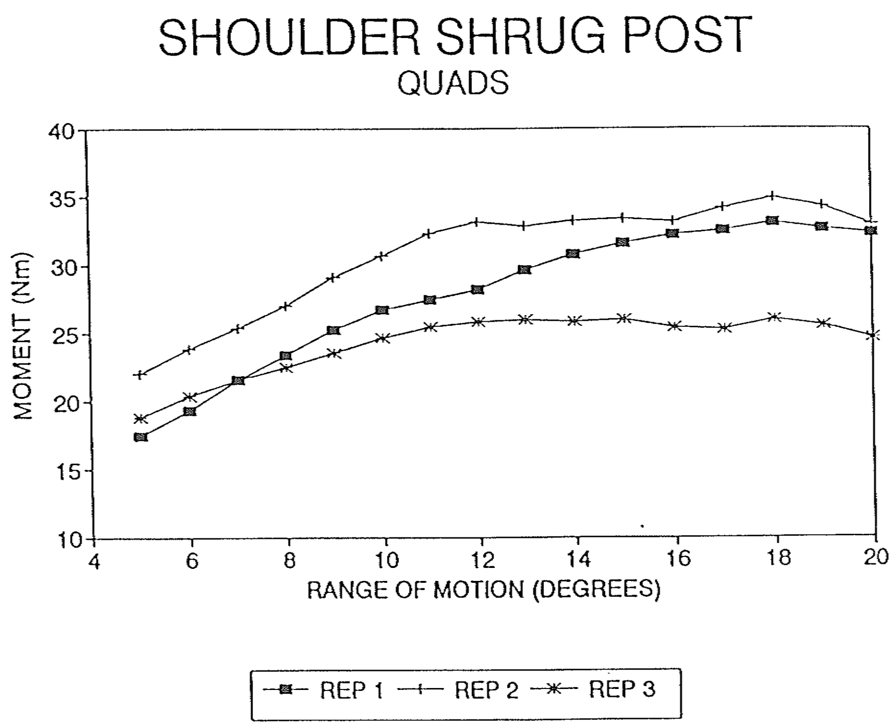


Figure 22 - Shoulder shrug movement for a representative quadriplegic subject. The graph includes the 3 repetitions and the range of motion represents the shoulder joint angle.

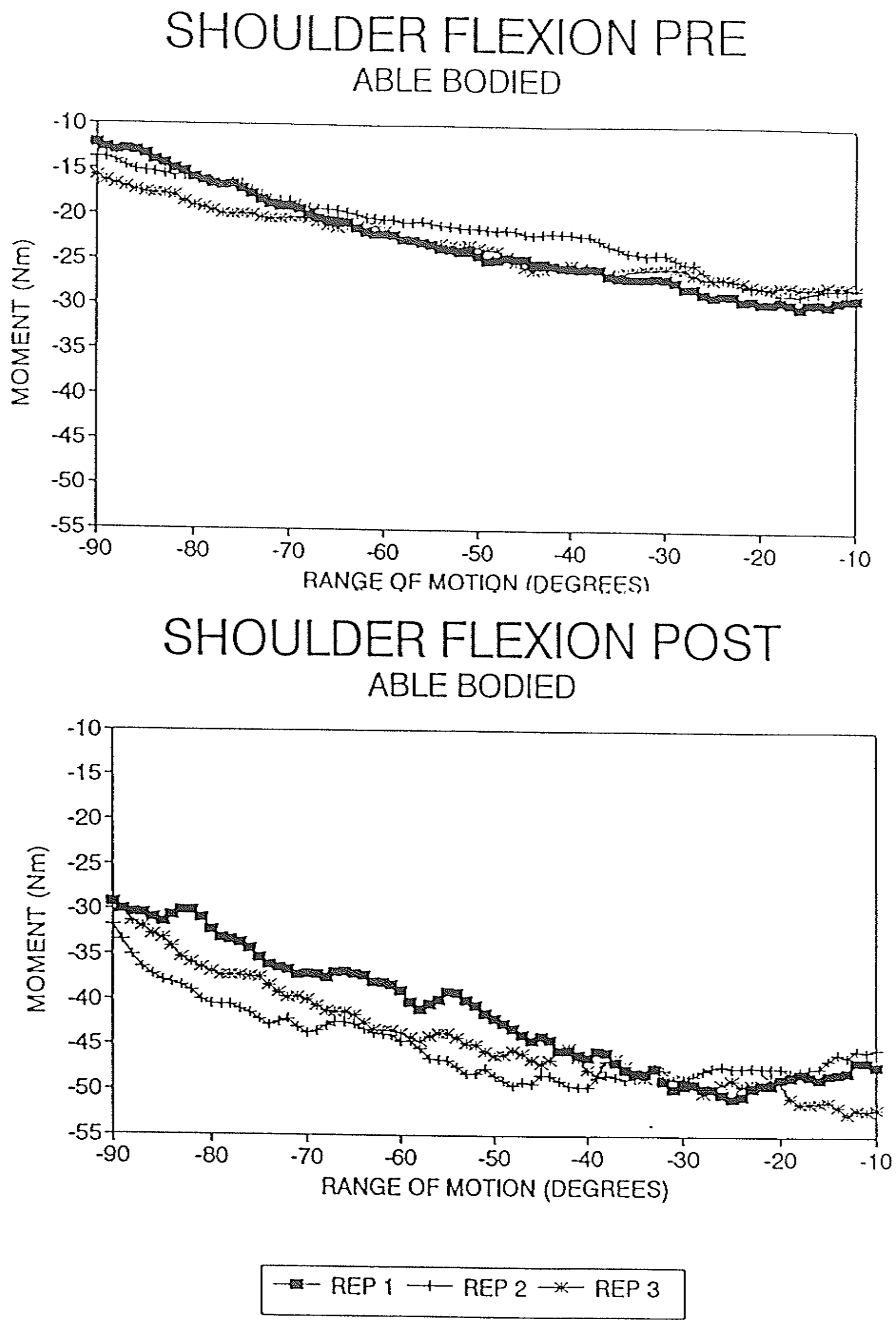


Figure 23 - Shoulder flexion movement for a representative able-bodied subject. The graph includes the 3 repetitions and the range of motion represents the shoulder joint angle.

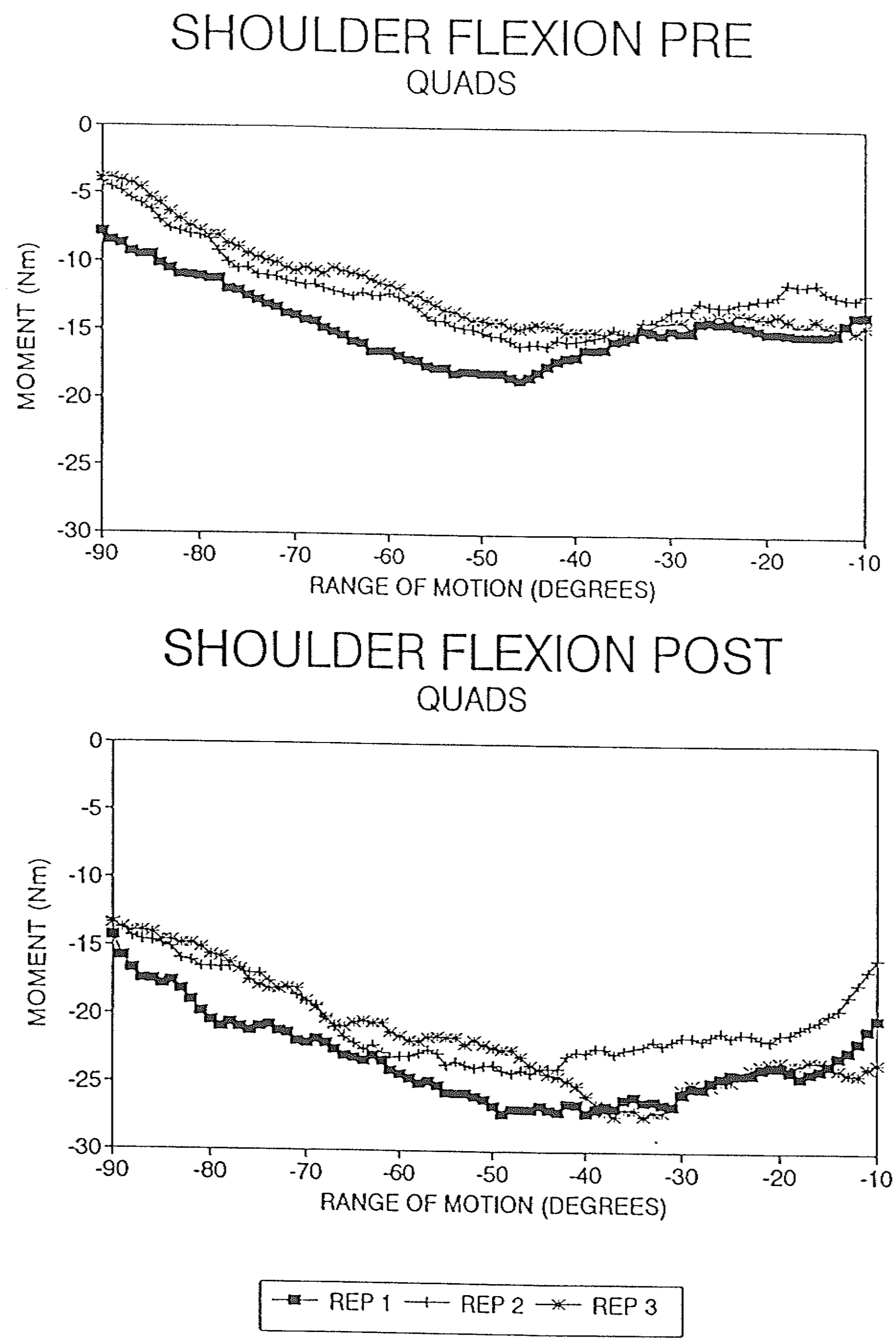


Figure 24 - Shoulder flexion movement for a representative quadriplegic subject. The graph includes the 3 repetitions and the range of motion represents the shoulder joint angle.

Elbow Extension

The population of subjects in the study included three C6 quadriplegics. These subjects were unable to exert the minimum 20 Nm of force required by the dynamometer to produce the movement of elbow extension. They were tested in the passive mode on the Kin-Com which measures the resistance offered while the machine passively moves through the set range of motion. It is not possible to compare these results in the quadriplegic population with those obtained while in the iso-velocity mode, therefore, analysis of this movement was excluded from the study. Furthermore, although no statistical analyses were performed on this movement, there appeared to be no increase or trend toward increase in moment generated after the training program intervention in either the three C7 quadriplegic subjects or the able-bodied subjects.

Shoulder Shrug

The movement of shoulder shrug was thought to be an important movement to assess in this population. As stated previously, quadriplegics have a reduced available muscle mass for functional activity, primarily wheelchair wheeling. Therefore, in the wheeling activity, the group of muscles participating in shoulder shrug may be highly utilized. There has been no protocol documented on the iso-velocity measurement of this movement, most probably due to the absence of a landmark from which to align the axis of rotation of the iso-velocity device. In these subjects, as is outlined in the position for testing (Figure 6), the axis of rotation of the Kin-Com was aligned with the T_2 spinous process, and there was confidence that the protocol was strictly adhered to in the alignment and performance of the movement to be tested. Since a controversy may exist over a true "joint" axis, the results have not been included in the general data that was analyzed. The pre and post exercise training results for the shoulder shrug movement are shown in Figure 25. The quadriplegic group generated a peak torque value of 15 Nm in the pre training test, compared with 29 Nm (93.3% change) after the exercise program. The able bodied group's pre training peak torque production value of 37 Nm increased to 58 Nm (nearly 60% change) post exercise training. Also of note, is that the peak torque in the quadriplegic group was recorded later in the range of motion, that is, after 18 degrees into the movement. Conversely, the able-bodied group generated their peak torque early in the movement, before 10 degrees into the range of motion.

Although there appears to be a trend for increased performance after the wheelchair training program, the results for shoulder shrug have not been assessed for statistical significance. This is due to the fact that the validity of the chosen methodology for recording this movement is unproven to date.

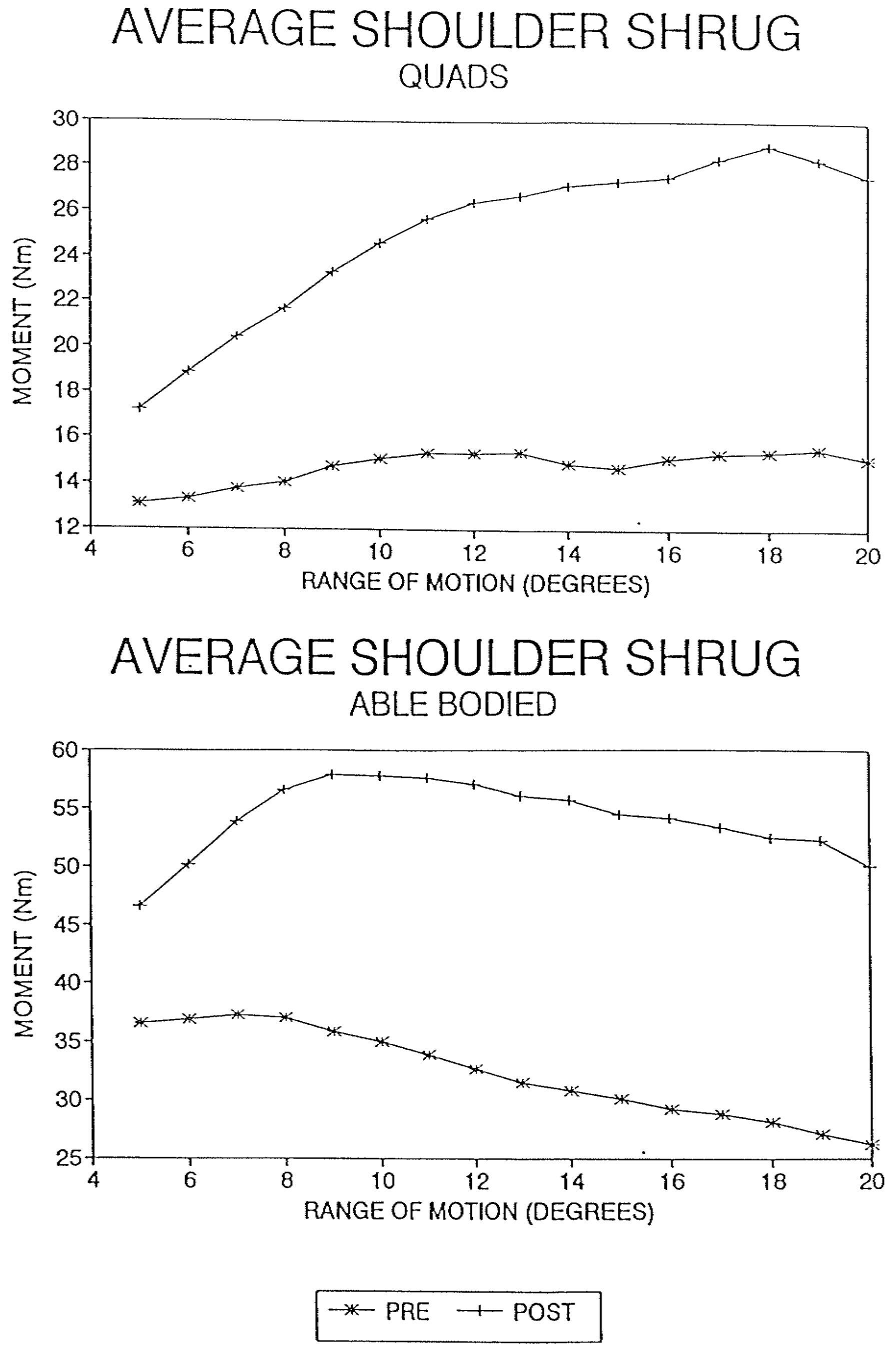


Figure 25 - Strength trends for the movement shoulder shrug. Includes the average torque over the range of motion of all the subjects in the able-bodied and quadriplegic groups pre and post exercise training.

Increases in Upper Limb Strength

Shoulder abduction, shoulder flexion, wrist extension and elbow flexion were used in calculating a repeated measures ANOVA. Wrist extension, $p < .001$ and elbow flexion, $p < .027$, showed significant increases in strength in the able-bodied group. (Figure 26) All movements showed significant strength changes post exercise training in the quadriplegic group, $p < .007$. (Figure 27)

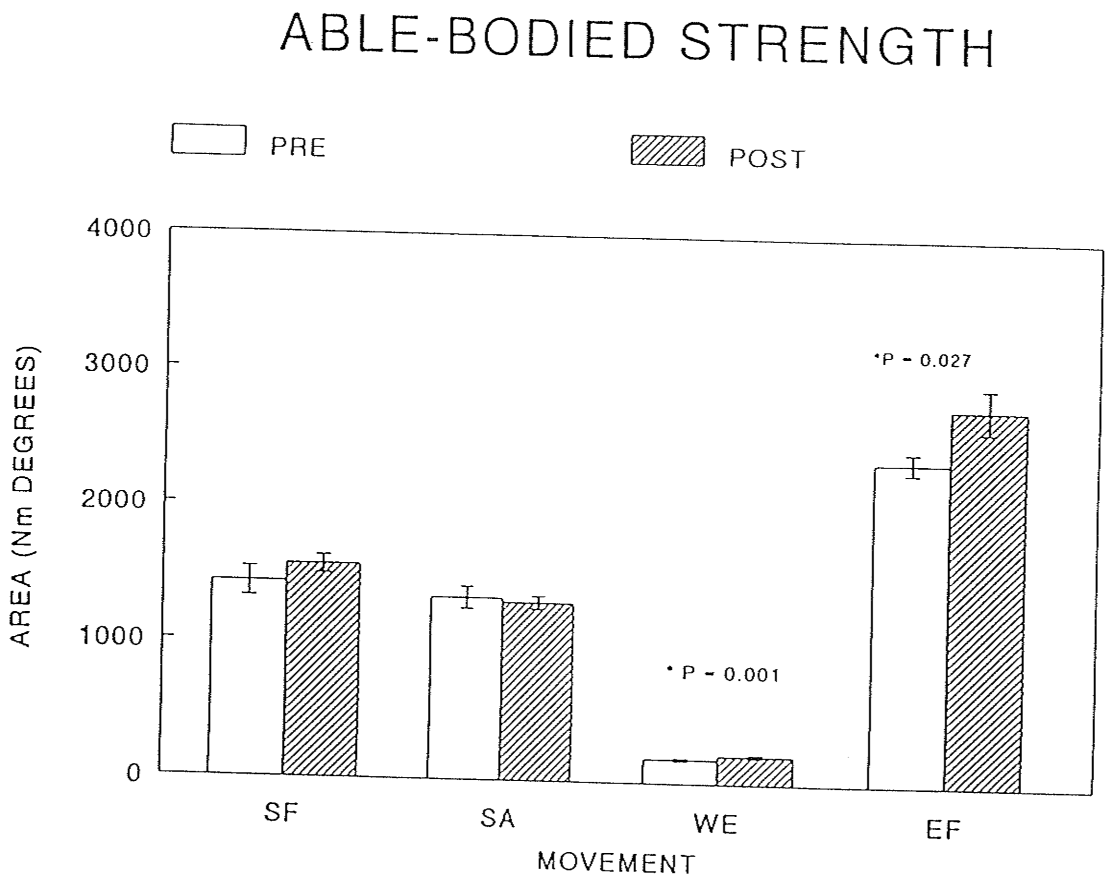


Figure 26 - Strength increases as assessed by the area under the torque/angle curve of the able-bodied subjects for the movements, shoulder flexion (SF), shoulder abduction (SA), wrist extension (WE), and elbow flexion (EF). The mean differences for the subjects are significant at the levels indicated.

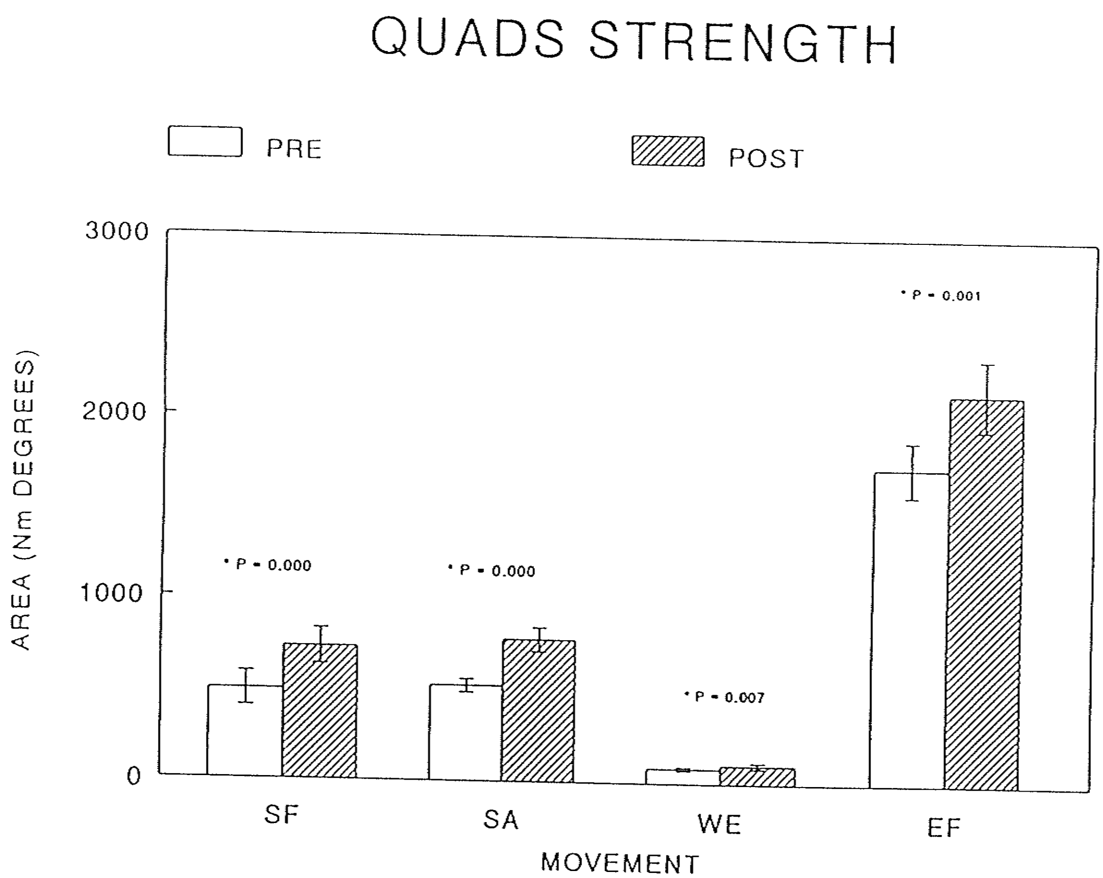


Figure 27 - Strength increases as assessed by the area under the torque/angle curve of the quadriplegic subjects for the movements, shoulder flexion (SF), shoulder abduction (SA), wrist extension (WE), and elbow flexion (EF). The mean differences for the subjects are significant at the levels indicated.

Correlations

For quadriplegics at this level of injury, the functional shoulder girdle would be expected to play a key role in the strength of the upper limb. A composite score for shoulder girdle strength was derived in the following manner. The raw score values for area were averaged over the three repetitions for each subject for each movement of the shoulder girdle. The movements included shoulder flexion, abduction and shoulder shrug. The means were added and this composite score for each subject was compared with the exercise performance values. Table 14 indicates the values used for the quadriplegic group in the comparison.

Pearson product moment correlation was used to compare increases in $\dot{V}O_2$ peak, Max Vt, Pimax and workload with this composite score reflecting strength changes post exercise training.

TABLE 14

COMPOSITE STRENGTH SCORES

QUADRIPLEGICS

	PRE				POST			
SUBJECT	SA	SS	SF	COMP	SA	SS	SF	COMP
1	645.7	390.9	624.06	1660.66	1087.9	149.4	1006.0	2243.3
2	513.1	297.1	1270.4	2080.6	882.8	333.6	1408.5	2624.9
3	625.2	296.1	303.0	1224.3	690.3	333.6	417.4	1441.3
4	162.1	94.1	71.9	427.1	287.1	97.1	258.8	643.0
5	468.6	236.1	424.9	1129.6	1013.9	440.4	850.1	2304.4
6	610.7	296.2	315.3	1222.2	700.1	516.6	439.36	1556.06

Table 14 - Illustration of the mean area (Nm degrees), for each subject in the quadriplegic group for the movements shoulder abduction (SA), shoulder shrug (SS), and shoulder flexion (SF). These are summed to form a composite (COMP) strength score for the shoulder girdle. Pre and post exercise values are included.

Pimax. values for the quadriplegic group were compared with the composite strength score for the shoulder girdle. A weak positive relationship was found, R = .5299 (NS).

There was a non-significant relationship between peak $\dot{V}O_2$ and the composite strength score, R = .529 (NS). However, when the strength scores were added to those including elbow flexion and wrist extension the relationship becomes much stronger. Pre exercise training R = .878, $p < .025$ and post exercise training R = .934, $p < 0.01$.

The comparison between max. exercise tidal volume and shoulder girdle strength was non-significant, R = .387 (NS).

There was a strong positive correlation between the maximum power output and the composite shoulder girdle strength score, R = .808, $p < 0.05$.

Summary of Results

Ventilatory Parameters

1) Pimax. increased significantly post exercise training in both quadriplegic, 17% increase, ($p < .004$) and able bodied groups, 13.5% increase, ($p < .009$)

2) Peak $\dot{V}O_2$ increased significantly post exercise training in both quadriplegic, 14% increase, ($p < .025$) and able bodied groups, 50% increase, ($p < .0025$). The absolute increase in peak $\dot{V}O_2$ in the quadriplegics was much lower (840.33 ± 119.43 ml) than in the able-bodied subjects (2465.0 ± 264.3).

3) Max. exercise tidal volume increased significantly post exercise training in both quadriplegic, 22.4% increase, ($p < .025$) and able bodied groups, 50.8% increase, ($p < .0025$)

Max. Exercise Test

1) Perceived exertion for arm effort decreased significantly during matched submax. exercise loads for both quads and able bodied subjects.

2) Perceived exertion for breathing decreased significantly during matched submax. exercise loads for both quads and able bodied subjects.

3) The max. power output on exercise tests increased significantly in both quads ($p < .025$) and able bodied subjects ($p < .0005$) post exercise training.

Strength

1) Able bodied subjects showed significantly increased strength in wrist extension ($p < .001$) and elbow flexion ($p < .027$) movements after the training program.

2) Quadriplegic subjects showed significantly increased strength in all movements analyzed, shoulder abduction, shoulder flexion, wrist extension and elbow flexion.

Correlations

1) A non-significant relationship existed between Pimax and strength of the shoulder girdle.

2) Significant correlations were observed between the change in peak $\dot{V}O_2$ and strength of the upper limb, when all movements were included in analysis.

3) A non-significant relationship existed between max. exercise Vt and composite shoulder girdle strength scores.

4) A significant correlation was observed between the maximum power output and composite strength scores.

DISCUSSION

The purpose of the study was to demonstrate that improvement in exercise performance with quadriplegics following high intensity, interval training was primarily due to increased strength of the upper limb musculature.

Both the quadriplegic and able-bodied groups were able to increase their maximum power output after the wheelchair training program. The quadriplegic subjects in this study improved their maximum exercise power output by 36.5%, from a mean of 20 Watts to 27.3 Watts post exercise training. The able-bodied group increased their maximum power output by 77.4%, from a mean of 31 Watts to 55 Watts post exercise training. Walker (1987 and 1989), found similar gains in power output. Maximum exercise power output rose from a mean of 17.4 Watts to a mean of 28.6 Watts in their study of chronic quadriplegics participating in a program of pulmonary therapy and resistance exercise for 7 to 12 weeks.

In contrast, the able-bodied subjects showed the normal, large increments in peak $\dot{V}O_2$ following an endurance exercise training program. While peak $\dot{V}O_2$ increased significantly, the gains were very modest in the quadriplegic group and other factors must have contributed to the increased exercise performance. Gains in exercise performance in the quadriplegic subjects were more likely due to peripheral adaptations, that is increased blood flow and/ or metabolic capability, than due to both central and peripheral adaptations which are commonly observed in able-bodied subjects. Therefore, it was not surprising that the magnitude of the increased peak $\dot{V}O_2$ was substantially smaller in quadriplegics as compared to able-bodied subjects, considering also the available muscle mass to perform the work was of less magnitude in the quadriplegic subjects.

The results from this study are consistent with other researchers who demonstrated that spinal cord injured (SCI) subjects were able to increase their $\dot{V}O_2$ and work capacity with wheelchair training or arm ergometry (Elkblom and Lundberg 1968, Glaser 1980, Nilsson 1975). The increased peak $\dot{V}O_2$ observed in this study is consistent with the small increases observed in quadriplegics in other studies. Other studies with SCI used paraplegic subjects which exhibited normal or close to normal cardiovascular responses to exercise training. The able-bodied subjects in this study increased their peak $\dot{V}O_2$, dramatically when compared with the smaller although significant increase in the quadriplegic subjects. The able-bodied subjects increased their peak $\dot{V}O_2$ from a mean of 1.63 to 2.46 l/min, an increase of over 50%. The quadriplegic subjects increased their peak $\dot{V}O_2$ from a mean of 0.739 to 0.840 l/min, an increase of 14%. The range of $\dot{V}O_2$ in the quadriplegic subjects was very wide, from 0.43 to 1.25 l/min (0.82 l/min range) post exercise training. These quadriplegic subjects were not involved in an active training program but 4 out of 6 were active in the community, while the 2 subjects with the lowest Peak $\dot{V}O_2$ led extremely sedentary lifestyles that involved minimal independent wheeling. The increases in peak $\dot{V}O_2$ were similar to the results found by Gass et al. (1980), who imposed a wheelchair treadmill exercise program on chronic institutionalized patients with SCI and demonstrated an increase in $\dot{V}O_2$ max. as well as increased maximum wheelchair treadmill time. Wicks (1983), investigated arm cranking and wheelchair ergometry in spinal cord injured elite athletes. He found that the peak $\dot{V}O_2$ in quadriplegic athletes with lesions at C6 was 1.00 $\pm$ 0.35 l/min for males and 0.75 l/min for the one quadriplegic female athlete studied. This is comparable to results regarding peak $\dot{V}O_2$, in other studies (Gass 1979, Gass 1980, Loveridge 1989, Wicks 1983). Gass and Camp (1979) measured $\dot{V}O_2$ max. in highly physically trained paraplegic and quadriplegic subjects to be 2.04 $\pm$ 0.64 l/min. Their study population consisted primarily of paraplegics and the one C6-C7 quadriplegic subject had a $\dot{V}O_2$ of 1.06 l/min. Likewise, Eriksson (1988), reported $\dot{V}O_2$ during maximal wheelchair exercise to be 0.88 $\pm$ 0.16 l/min in untrained quadriplegic subjects and 1.11 $\pm$ 0.34 l/min in trained quadriplegic subjects. Additionally, Eriksson (1988), has shown that during maximal wheelchair exercise, the peak $\dot{V}O_2$, pulmonary ventilation and blood lactate concentrations were higher in subjects with lower levels of spinal cord lesions. Moreover, he found that trained SCI subjects reached higher peak $\dot{V}O_2$ than untrained subjects at corresponding lesion levels. Further support for these results are found in Hjeltnes' (1986) study of cardiorespiratory capacity in quadriplegics shortly after injury. He found that mean peak $\dot{V}O_2$ was found to be as low as 0.74 l/min in males with complete quadriplegia and 1.9 l/min in patients with conus and cauda lesions. Therefore, with the exception of the two sedentary quadriplegics in this study, the peak $\dot{V}O_2$ observed are consistent with those reported in the literature.

The fact that the able-bodied subjects increased their mean peak $\dot{V}O_2$ more than 50% indicates that the high intensity interval wheeling protocol utilized was an effective tool for enhancing cardiovascular and muscular endurance. The inability to improve mean peak $\dot{V}O_2$ in quadriplegics by a similar degree indicates the magnitude of the limitation to enhance oxygen uptake in this population. The increases in peak $\dot{V}O_2$ found in the present study are probably reflective of the relatively sedentary lifestyles of the subjects as well as the limitations in cardiac output and decreased available muscle mass, imposed by the level of the lesion. With exercise training their peak $\dot{V}O_2$ improved. However, when comparing even well-trained quadriplegics with able bodied subjects, there are great differences in attainable maximum oxygen uptakes (Figoni 1984, Gass 1979, VanLoan 1987, Wicks 1983). The higher the level of injury, the greater reduction in functional mass and strength available for use in exercise tests. In quadriplegics, their impaired sympathetic cardiac stimulation also contributes to the reduced work capacity and oxygen transport. This reduced cardiac sympathetic stimulation may be due to decreased neuronal and circulating catecholamines as well as neurogenic, humoral and temperature factors (Burkett 1990, Shephard 1988, VanLoan 1987).

The quadriplegic subjects in the present study appear to be comparable to untrained quadriplegics in other studies (Eriksson 1988, Hjeltnes 1986). Their response to the exercise program would be related not only to the initial level of fitness, but also to the training protocol of the program itself. This was a high intensity interval program. Subjects exercised 5 days a week for 30 minutes at 60-80% of the maximum workload achieved in the exercise tests. Other wheelchair training protocols where no improvement in peak $\dot{V}O_2$ was found may not have been as intense, and were performed 3 days a week (Davis 1990, Glaser 1981, Hooker 1988, Shephard 1988). Hooker (1989), investigated the effects of low and moderate intensity training in quadriplegics and paraplegics. Both protocols involved wheelchair ergometer training for 20 minutes three times per week. The moderate intensity group trained at 70-80% of their maximal heart rate and the low intensity group trained at 50-60% of their maximal heart rate. The less intense protocols may account for the minimal changes observed in peak $\dot{V}O_2$.

It is difficult to make valid comparisons of results from different studies because of alternate methods for testing and training protocols, initial levels of fitness and variable lesion levels of the subjects. In addition, the sample sizes in all studies tend to be small making the variance much greater.

In spite of a mean increased peak $\dot{V}O_2$ of only 14%, the quadriplegic group increased their power output by 37%. While the increase in peak VO_2 could explain a considerably greater degree of the improvement in performance observed in the able-bodied subjects, clearly, factors other than improved peak $\dot{V}O_2$ must have contributed to the increased performance in the quadriplegic subjects. Recent evidence suggests that increased muscle strength and endurance may play an important role in improving exercise performance independent of changes in peak $\dot{V}O_2$ (Marcinik 1991).

The quadriplegic group showed significantly improved strength performance in all movements analyzed, that is, elbow flexion, wrist extension, shoulder abduction and shoulder flexion. Mean percent change increases were 15% for elbow flexion, 38% for wrist extension, 32% for shoulder abduction, 48% for shoulder shrug and 39% for shoulder flexion. It is interesting to note that the able-bodied comparison group significantly increased their strength in elbow flexion and wrist extension, but not shoulder abduction and shoulder flexion. One explanation for these observed differences may be variations in wheelchair propulsion techniques. Able-bodied subjects probably use different muscle groups to perform the activity of wheelchair wheeling than do the quadriplegics. Shoulder girdle movements may be more important for the quadriplegic group whereas, the able-bodied subjects have the ability to utilize abdominal and leg musculature for stabilization of the trunk and forward flexion at the hips. These strategies are not available to quadriplegics. Therefore, the large increase in strength in the movement shoulder shrug may reflect the limitation in options for the quadriplegics. In addition to increasing upper limb strength, the able-bodied subjects may have increased the strength of their trunk musculature which was not evaluated in this study.

Veeger (1989), noted two styles of wheelchair propulsion in his study of well trained subjects confined to wheelchairs. With the circular style of propulsion, the subject releases the wheels at the end of his push, and continues to move the arms in a circular motion so that they follow the path of the wheels. With the "pump style" arm action type of propulsion, the arm follows a more abrupt course during the push recovery sequence. In terms of mechanical efficiency, the circular push style is superior to the push "pumping" technique (Sanderson 1985). In the absence of trunk stabilization, quadriplegics would utilize shoulder shrug to assist in providing greater force in pushing the wheelchair. Veeger (1989), noted that cycle time decreased with speed. A cycle is divided into 1) the push or contact phase and, 2) the recovery phase where the arms are brought back to the start position. They also found that adaptations to speed changes occurred mainly by flexion of the trunk and arms. Indeed, this was observed in the able-bodied population in this study. As the resistance increments were advanced, in order to maintain the revolutions per minute (RPM), the able- bodied subjects tended to lean further forward and exhibit more trunk and arm flexion. Due to limited trunk motor control, the quadriplegic subjects were unable to utilize this strategy in their wheeling efforts. Trunk movement and forward lean are marginal options for quadriplegics. Instead, the quadriplegics tended toward increasing the shoulder shrug movement and increasing the speed of the propulsion phase, to maintain the RPM at higher workloads. In this study, although not videotaped, it was noted that the quadriplegic subjects generally used the pump action style of propulsion, relying somewhat on the friction between their gloves and the pushrim. What was also evident in observing the quadriplegic as well as the able-bodied subjects in this study, both in the training sessions and their exercise tests, was the shoulder shrug movement that accompanied propulsion of the chair.

The shoulder shrug movement may be of paramount importance in the wheeling strategy of most of the quadriplegics, as well as the able-bodied subjects. We observed a large increase in shoulder shrug strength ranging from 10-105 % change (mean of 48.2%) after the wheelchair exercise training program in the quadriplegics. Able-bodied subjects increased strength by a mean of 36.8% in the movement shoulder shrug post exercise training. Evaluation of this movement is probably one of the most relevant in the analysis of shoulder girdle strength in wheeling, and yet is the most problematic. The axis of joint motion with the movement shoulder shrug, in which to align the axis of the Kin-Com or any other dynamometer must be related to a specific landmark. This movement is not readily assessed, according to the standard protocols. There are as yet, no studies describing protocols for accurate assessment of shoulder elevation or other complex shoulder girdle movements.

However, in the absence of a defined, validated protocol to assess shoulder shrug, we chose to develop a protocol which employed the T2 spinous process as the axis of movement. The spinous process of T2 is stationary and easily located. In pilot testing prior to the commencement of the study, consistent measures of iso-velocity strength were obtained for the shoulder shrug movement with the use of T2 as the axis of movement. Further trials need to be performed to establish and validate this particular testing protocol, and to provide a more comprehensive evaluation of shoulder movement involving the shoulder girdle as well as the glenohumeral joint.

Although there is little emphasis on the relationship between strength and increased endurance performance in the literature, for groups with as limited a functional muscle mass as quadriplegics, this becomes an important consideration. A recent study by Marcinik et al. (1991) supports the importance of strength training in endurance performance. In his study of 18 healthy untrained normal males, Marcinik found no significant changes in treadmill $\dot{V}O_2$ max. or cycle peak $\dot{V}O_2$. A 33% increase in cycling time was observed in the subjects who participated in a lower limb strengthening program. The subjects trained on exercise machines three times per week for 12 weeks. The exercises included bench press, hip flexor, knee extension, knee flexion, push-ups, leg press, lat-pulldown, arm curl, parallel squat and bent knee sit-ups. The training program resulted in significant increases in strength assessed by measurement of peak torque in knee flexion and extension using the Cybex II dynamometer. Post training, on retesting, the subjects performed significantly longer with respect to cycle endurance time despite no changes in $\dot{V}O_2$ max. or peak $\dot{V}O_2$. He suggested that strength training can enhance cycle performance independently of increases in $\dot{V}O_2$ max. and that the improvement is related to increases in lower limb strength and endurance (Marcinik 1991).

In our study, there were strong correlations between the maximum power output and upper limb strength ($R = .808$, $p < .05$), as well as between peak $\dot{V}O_2$ and upper limb strength ($R = .934$, $p < .01$) post exercise training. These results support the premise that both increased peak $\dot{V}O_2$ and increased upper limb strength contribute to the increased performance observed.

Furthermore, it is likely that the increase in upper limb strength contributed to a greater degree than did the peak $\dot{V}O_2$ in the quadriplegic group.

There was no significant correlation between the increased Pimax and the increased strength of the upper limb, in either the quadriplegic or able-bodied group. This is surprising because Pimax is considered a clinical index of inspiratory muscle strength, and one would have expected that at least part of the increase in Pimax would have been due to increased accessory muscle strength. The sample size was small (6 subjects in each group) and this may have contributed to the insignificance of this relationship. As well, a more detailed assessment of the shoulder girdle muscles, including accessory muscles of respiration may have provided a stronger relationship. The inability to assess the shoulder girdle in detail may in fact account for the lack of correlation observed between Pimax and upper limb strength. Furthermore, pre training Pimax for some of the quadriplegic subjects was within the range found in able-bodied subjects. Pre-training Pimax for the quadriplegics was -77.67 $\pm$ 12.69 cm H_2O (range from -32 to -107 cm H_2O) and this increased to -89.67 $\pm$ 11.47 cm H_2O (range from -44 to -118 cm H_2O) following wheelchair training. The able-bodied group Pimax ranged from -71 to -138 cm H_2O. Also when compared with other quadriplegics it is evident that these subjects have quite high initial values for Pimax and yet they still increased Pimax further following the wheelchair training program. Loveridge et al.(1990), examined the resting breathing pattern in chronic quadriplegics. They found a mean of -75 $\pm$ 20 cm H_2O in quadriplegics with comparable lesion levels. In our study, the increases in Pimax were greater in the subjects with the lower Pimax to start,which is not surprising. However, the data does suggest that for deconditioned SCI clients with low initial Pimax, high intensity and sustained upper limb training may have a beneficial effect on the ventilatory system.

Another important observation in this study was the significantly decreased perceived exertion for both arm effort and breathing effort at submaximal workloads reported by both quadriplegic and able-bodied subjects post training. During submaximal work, for a given load, quadriplegic subjects rated arm effort as heavy (4.92) pre training and very light (1.17) post exercise training. They rated breathing effort as moderate (2.5) pre training and very light (0.83) post exercise training. The able-bodied group rated arm exertion as heavy (6.17) pre training and very light (1.0) post exercise training. Breathing effort was rated as somewhat heavy (3.83) pre training and very light (0.83) post exercise training. Other researchers have found that ratings of perceived exertion correlate with exercise intensity in studies with able-bodied populations (Ceci 1991, Dunbar 1992, Robertson 1990). Loveridge et al. (1989) found this same decrease in perceived exertion for arm and breathing effort after the intervention of upper limb endurance training in SCI clients.

Killian and Campbell (1983), contended that dyspnea was related to the effort necessary to generate the force of the inspiratory muscles. The intensity of effort required to produce a given pressure increases when the muscle is weak, (LeBlanc 1986), or conversely, as the muscle strength increases, the intensity of effort decreases. Therefore, it is likely that the decreased ratings in perceived exertion observed are due at least in part to increased strength in the upper limbs.

In addition to the objective increases in strength, exercise performance, and Pimax, the quadriplegic group also reported subjective improvement in functional activities. They related an increased ability to wheel on uneven surfaces, carpeted surfaces were easier to negotiate and they reported less fatigue with their activities of daily living since completing the 8 week training program. Subjective improvement has also been reported in other studies on exercise training in SCI. Nilsson (1975) examined the physical work capacity and effects of training on SCI subjects. After the 7 week intensive training which included arm exercise, arm crank ergometry and weight training, he reported increased $\dot{V}O_2$, work performance and mean dynamic strength. In addition to these observations, the subjects reported positive subjective effects from the training. They reported increased confidence in coping with daily problems and an increased sense of well-being. Glaser (1981) found that during wheelchair locomotion, variables such as gross energy cost, net locomotive energy cost, pulmonary ventilation and heart rate all increased significantly on the carpet surface compared with the tiled surface. The quadriplegic subjects in the present study reported that they found it easier and less strenuous to negotiate different surfaces with their wheelchairs and participate in their normal activities of daily living after the exercise program, which translates to an expression of the increases in peak VO_2 and upper limb strength. Most of the subjects expressed interest in continuing with training once the study had terminated.

CONCLUSIONS

The high intensity, interval wheelchair training protocol applied in this study resulted in significant increases in maximum power output, peak $\dot{V}O_2$, upper limb strength and Pimax in both quadriplegic and able-bodied subjects.

This study has demonstrated that wheelchair ergometry is an effective means of increasing upper limb strength. As well, peak $\dot{V}O_2$, a measure of exercise endurance performance, increased significantly which further promotes the efficacy of a high intensity interval training protocol. The increased upper limb strength, coupled with a small but significant increase in peak $\dot{V}O_2$, probably accounts for the improved exercise performance that was observed in the quadriplegic group. The increases observed in peak $\dot{V}O_2$ alone, however, are insufficient to support the increased exercise performance noted. Therefore, increased upper limb strength, particularly in the quadriplegic group, is an important contributor to improved exercise performance.

While the significant increases in Pimax and strength did not correlate, this may be more reflective of a limitation in ability to more thoroughly assess shoulder girdle function and a problem of small sample size. It is clear that upper limb training increases Pimax. The most logical mechanism for this increase is an increase in available accessory muscle mass. Measurement and strength testing of the accessory muscles for quadriplegics with low Pimax is required to better determine if a relationship between upper limb strength and Pimax exists.

Ventilation is limited in SCI individuals and ventilatory insufficiency is more common in quadriplegics. The value of upper limb training in enhancing ventilation should be considered as relevant as the cardiovascular and skeletal muscle alterations that occur as a result of training.

The Kin-Com iso-velocity dynamometer was an effective tool for assessing strength of some of the upper limb motion in the quadriplegic population. It provided a consistent and reliable measurement of torque generation. However, there were limitations encountered when applying dynamometry to quadriplegics. It is important to consider the motor control of the muscles that contribute to the movements of interest. In quadriplegics, the available muscle mass is considerably smaller and the moments that they are able to generate are much lower than in an able-bodied population. In very weak movements such as elbow extension in some C6 and C7 subjects the moment generated was not be able to be detected by the iso-velocity dynamometer. This is because detection of the moment produced must be a minimum amount (20N).

There are no existing protocols to functionally evaluate the movements of the shoulder girdle. This is due to the non-existence of a typical "joint axis" with which to align the dynamometer. The movement of shoulder shrug can be accurately assessed for changes in torque production even though there is no established axis of joint rotation by aligning the iso-velocity device axis of rotation with the T2 spinous process. As long as this is kept consistent the results can be reliable. Further testing on reliability and validity of shoulder girdle movement needs to be addressed.

The increased upper limb strength probably contributed to the decreased perceived exertion for both breathing and arm effort at sub-maximal exercise workloads, in both quadriplegic and able-bodied subjects. This provides a very important functional relationship between strength and perceived exertion.

High intensity wheelchair exercise as a means of increasing strength, improving endurance, and enhancing ventilation is a directly applicable and training specific exercise for quadriplegics. The strong correlation between maximum power output and composite shoulder girdle strength leads to the conclusion that the improvement in exercise performance is primarily due to increased strength of the upper limb musculature. High intensity, interval wheelchair exercise, therefore, should be considered a necessary and integral part of rehabilitation programs for wheelchair bound individuals.

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