

# Chapter One

## The Physiology of Exercise

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### INTRODUCTION

Knowledge of exercise physiology is essential for implementing strategies to develop optimal physical performance among individuals with lower limb paralysis due to spinal cord injury (SCI). Since there can be marked neuromuscular changes, it is necessary to take into consideration specific deficits in neuromuscular, cardiovascular, and respiratory function. Indeed, physiologic responses to arm exercise performed by individuals with SCI can be quite different from those for either arm or leg exercise by individuals who are nondisabled, and exercise activities need to be designed to reflect these differences.

Individuals with lower limb paralysis due to SCI typically use their arms for wheelchair locomotion and other activities of daily living (ADL), as well as for exercise training and sports activities. However, several physiologic factors, including the relatively small muscle mass that is under voluntary control, deficient cardiovascular reflex responses, as well as inactivity of the skeletal muscle pump of the legs (potentially resulting in a slowing down of circulation), can

markedly reduce the capacity for arm activity (1–3). Muscular weakness and the early onset of fatigue can discourage an active lifestyle, since activities of daily living become relatively more stressful to perform and limit the development of cardiopulmonary (aerobic) fitness. A sedentary lifestyle aggravates this situation, since muscle strength and cardiopulmonary fitness progressively decrease, leading to a debilitating cycle that can be difficult to arrest or reverse (1,2,4). In addition, a number of secondary medical complications that can cause much suffering and greatly increase the cost of medical care, tend to become more prevalent (5,6). However, studies on wheelchair users with SCI indicated that those who maintain a more active lifestyle by regularly participating in exercise and sports programs can increase their muscle strength, cardiopulmonary fitness, and physical performance to levels well above those of their inactive peers (2,4,7–10). In addition to fitness gains, habitual physical activity may also elicit improvements in health, psychosocial status, rehabilitation potential, functional independence, and quality of life (10–13). Therefore, a major focus of our VA-supported research effort has been to apply exercise physiology principles to develop specialized exercise testing and training techniques for individuals with SCI, and to gain a better understanding of how their

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muscular, metabolic, and cardiopulmonary responses to various exercise modes differ from those elicited from individuals who are nondisabled. This information may help clarify how physical performance of individuals with paraplegia and quadriplegia can be improved, and how risks for secondary medical complications can be reduced.

Arm exercise modes have traditionally been used for the testing and training of wheelchair users. However, physiologic responses to arm exercise performed by individuals with SCI can be quite different from those for either arm or leg exercise by nondisabled peers. Our research is related to physical capability and physiologic responses to exercise of wheelchair users with SCI, the use of the arm exercise techniques for physical fitness testing and training, and the use of recently developed training techniques that incorporate functional electrical stimulation (FES)-induced exercise of paralyzed leg muscles. Although most of the subjects who participated in the described research had SCI, many of the techniques and data presented may also be applicable to wheelchair users with other neuromuscular disorders (e.g., head trauma, stroke, multiple sclerosis).

### Causes of SCI

SCI is a disorder that can cause paraplegia or quadriplegia (tetraplegia) due to lesions that interrupt the transmission of nerve signals (i.e., action potentials) between the brain and periphery. Major causes are motor vehicle accidents (over 38 percent), accidents that occur during sports or physical activities, falls, and trauma during violent crimes (14). It has been estimated that there are more than 200,000 individuals with SCI (48 percent paraplegia, 52 percent quadriplegia) in the United States, and there are approximately 8,000 new cases of SCI each year that survive to join this population (14,15). Prior to World War II, 80 percent of victims with SCI died within 3 years of the injury (16), primarily due to kidney and pulmonary infections (17). However, with the advent of antibiotic drugs and advances in surgical techniques, individuals with paraplegia can have a near normal life expectancy, whereas those with quadriplegia tend to have a life expectancy that is about 10 percent lower than nondisabled individuals (17). Generally, the higher the age at the time of SCI, the higher the lesion level, and the greater the extent of the lesion, the lower will be the life expectancy (18,19). Currently, the prevalent causes of death with long-term SCI appear to be related to a

variety of cardiovascular and respiratory disorders (14,20–22).

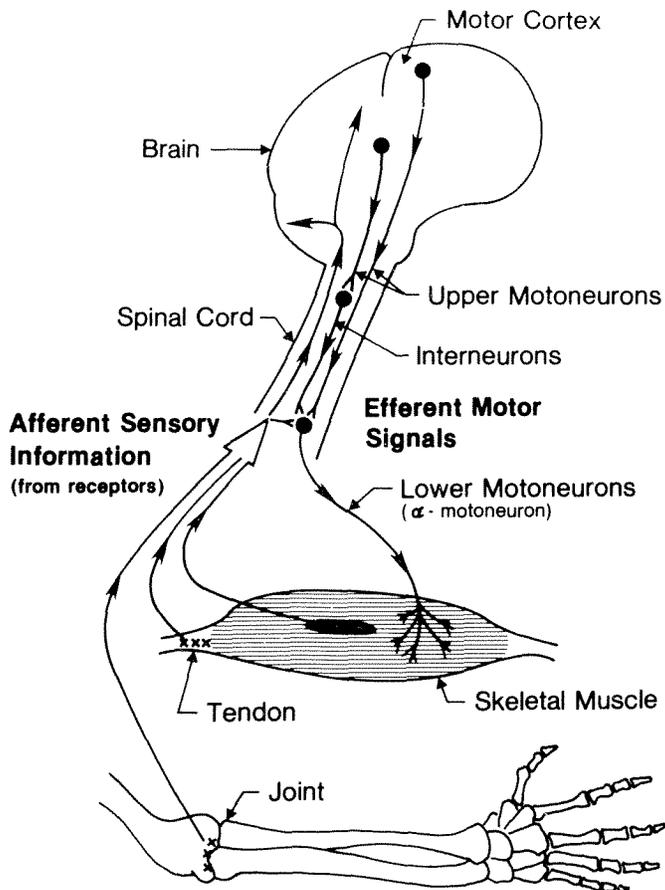
### Pathophysiology of SCI and Exercise Limitations

This section provides a brief overview of how skeletal muscles are controlled by the central nervous system (CNS; brain and spinal cord) and how SCI impairs this control and limits exercise capability. **Figure 1** is a diagram illustrating efferent (i.e., motor) and afferent (i.e., sensory) pathways which normally permit precise control of skeletal muscle contractions (1). To initiate skeletal muscle contractions voluntarily, action potentials arise in the motor cortex of the brain and are propagated down the spinal cord along upper motoneurons that eventually synapse onto the lower motoneurons ( $\alpha$  motoneurons). Axons of the lower motoneurons leave the CNS and provide motor signals to particular groups of skeletal muscle fibers via neuromuscular junctions. Lower motoneurons and the particular muscle fibers they innervate are called motor units, of which there are about one-half million in the body. Of course, an interruption of the efferent motor pathway would lead to paralysis of the particular skeletal muscle fibers involved. In addition to inducing contractions, the CNS normally monitors performance of the muscles. For this, sensory receptors located in muscles, tendons, and joints (in conjunction with afferent neurons), send feedback information, such as action potentials, to the CNS concerning muscle length, limb position, rate of movement, and contraction tension. This permits stimulation to the muscles to be continuously and appropriately modified so that the actual performance closely matches the intended performance, and motor learning can take place. Of course, an interruption of this afferent sensory pathway can result in a loss of kinesthetic sense, as well as skin sensations below the lesion level.

**Figure 2** diagrammatically illustrates the CNS with outflow levels of the somatic nervous system, which innervates skeletal muscles, and the autonomic nervous system, which innervates internal organs (1). The higher the level and more extensive the spinal cord lesion, the more widespread will be the loss of somatic and autonomic nervous system function.

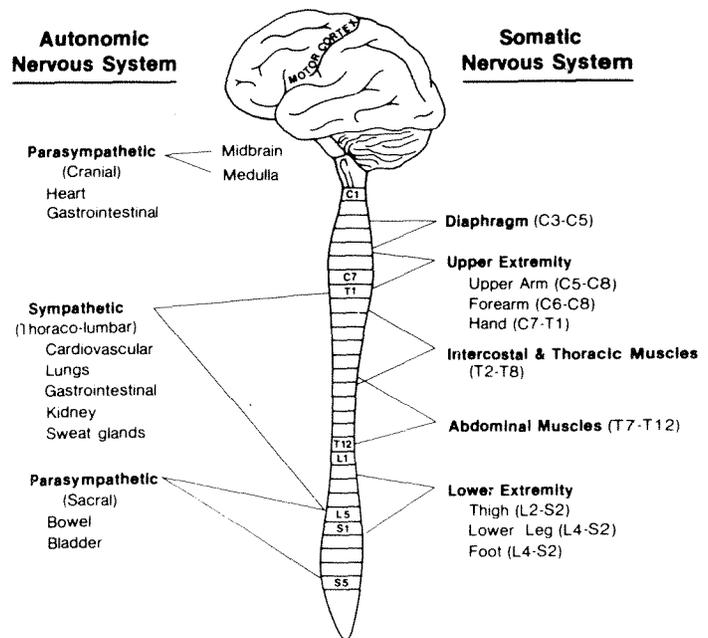
### *Somatic Nervous System Dysfunction*

With respect to somatic function, lesions in the thoracic and lumbar regions typically result in paraplegia with lower limb and partial trunk muscle involve-



**Figure 1.** Diagram of the central nervous system with efferent (motor) and afferent (sensory) pathways for controlling skeletal muscle contractions (1).

ment. Lesions in the cervical region typically result in quadriplegia with lower limb, trunk, and upper limb muscle involvement. Usually, the greater the skeletal muscle mass that is paralyzed, the lower will be the voluntary exercise capability and functional independence, and the lower will be the absolute cardiopulmonary (aerobic) fitness level that may be achieved through exercise training. The extent of the paralysis can also be directly related to the incidence of secondary medical complications. Paralysis commonly results in marked disuse, atrophy (weakening or wasting away) of the muscles involved, and osteoporosis (brittleness) of the bones. Inactivity of the skeletal muscle pump of the lower limbs can precipitate venous stasis, blood pooling and edema (swelling), and reduce venous return. This may increase the risk for deep venous thrombosis and subsequent pulmonary embolism



**Figure 2.** Diagram of the central nervous system, and the neural outflows from the somatic nervous system (innervating skeletal muscles) and autonomic nervous system (innervating internal organs). General innervations from each spinal cord level are indicated.

(blood clot in the lung). Decubitus ulcers (pressure sores on the skin) frequently occur due to prolonged pressure on supporting tissues and inadequate local circulation. In individuals with higher level SCI, paralysis of intercostal (chest) and abdominal muscles can severely limit pulmonary ventilation, which can further reduce aerobic exercise capability and lead to pulmonary (lung) complications due to diminished ability to cough.

### *Sympathetic Nervous System Dysfunction*

In addition to skeletal muscle paralysis, aerobic exercise capability of individuals with SCI can be limited by diminished sympathetic outflow (**Figure 2**), since sympathetic stimulation is required for normal cardiovascular reflex responses to exercise. These reflexes normally augment blood flow to metabolically active skeletal muscles to provide more oxygen and fuel substrates, while increasing the rate of metabolic end-product removal. Such responses include: vasoconstriction in relatively inactive tissues (e.g., gut, kidneys, skin); vasodilation of skeletal muscle arterioles; venoconstriction (which facilitates venous return); and increases in heart rate, myocardial contrac-

tility, stroke volume, and cardiac output (1,2,23–25). Although these reflexes are absent to varying degrees in most individuals with SCI, those with lesions above T1 would have interruption of all sympathetic nerves that innervate the heart (from T1 to T4), which would markedly limit cardioacceleration, myocardial contractility, stroke volume, and cardiac output (26). With this condition, any cardioacceleration that occurs with exercise may be primarily due to withdrawal of vagal parasympathetic tone to the S-A node. As a result, persons with complete quadriplegia usually have a peak exercise heart rate (e.g., 100–125 beats/min) that is well below the age-predicted maximal. In addition, the combination of reduced venous return and deficient myocardial contractility decreases the stroke work (i.e., stroke volume  $\times$  mean arterial blood pressure) of the heart, which can ultimately lead to loss of left ventricular muscle mass. This is especially prevalent in quadriplegia (27). It is also likely that reduced sympathetic outflow with SCI will impair thermoregulatory capacity due to inappropriate blood flow distribution and insufficient sweating response below the lesion level (28).

### *Exercise Consequences*

The loss of functional skeletal muscle mass with SCI and inactivity of the skeletal muscle pump in the lower limbs are compounded with diminished or nonexistent cardiovascular reflexes during exercise. This can cause high fatigability of active arm muscles due to their relatively small mass, inadequate blood flow due to hypokinetic circulation, and limited aerobic energy supply, as well as a greater component of anaerobiosis (living in an oxygen-free atmosphere) and the accumulation of metabolites in the muscles (1–3,29). High fatigability of arm muscles during wheelchair locomotion and exercise training can discourage many wheelchair users from leading active lives. Unfortunately, a sedentary lifestyle can lead to a further decrement of physical fitness and an even greater reduction of physical capability. Aging further decreases cardiovascular, pulmonary, and muscular function, which can eventually lead to a loss of independence and an increase in medical complications (19). An active lifestyle, which incorporates specific exercise training and/or sports programs, is needed to break this debilitating cycle of sedentary lifestyle/loss of fitness and to enhance one's functional independence and quality of life (1,2,4).

### **Exercise Precautions and Considerations for Persons with SCI**

Individuals with SCI who perform strenuous exercise are exposed to the usual risks known for nondisabled individuals, as well as additional risks due to their CNS damage and the resulting motor, sensory, and autonomic dysfunction. Generally, exercise guidelines recommended by the American College of Sports Medicine should be followed (30). In addition, since there can be numerous health risks, it is prudent for wheelchair users to have a thorough medical examination (including an EKG) prior to beginning a strenuous exercise program. This is especially true for older individuals who have been sedentary for many years. Unique risks that should be anticipated for individuals with SCI during exercise include trunk instability, exercise hypotension, orthostatic hypotension, autonomic dysreflexia, pressure sores, muscle spasms, and thermoregulatory problems (31–36). Therefore, it is recommended that individuals with SCI, health care professionals, and athletic trainers, be aware of known exercise risks and take appropriate precautions to derive optimal benefits in a safe manner such as:

*Appropriate Body Support.* Where necessary, a security belt should be placed around the individual's upper trunk during arm exercise to prevent malalignment and falls due to trunk instability and poor sitting balance. In addition, it is absolutely essential that measures be taken to minimize pressure on weight-bearing tissues to prevent decubitus ulcers. Therefore, it is important to place effective cushions under the ischial tuberosities and other weight-bearing areas, as well as to perform periodic pressure relief (i.e., raising the body off the cushion every 20–30 minutes for 30–60 sec—pushups).

*Blood Pressure Responses.* Exercise may elicit blood pressure (BP) responses from individuals with SCI that can be quite different and inconsistent in comparison to those from nondisabled individuals. This is particularly true for persons with high-level SCI who can exhibit a paradoxical drop in blood pressure as exercise progresses (29,34,35,37). This so-called exercise hypotension is apparently due to a lowering of total peripheral resistance, as blood vessels in active muscles dilate in response to hypoxia and increased concentrations of local metabolites (e.g., CO<sub>2</sub>, lactic acid, heat), without a corresponding increase in cardiac output. As indicated above, cardiac output can be limited by inadequate venous return due to inactivity of the skeletal muscle pump and deficient sympathetically

mediated redistribution of blood. Exercise in the upright posture can exacerbate this situation, since it can result in blood pooling in the lower body and orthostatic hypotension due to gravitational effects. The combined effects of exercise hypotension and orthostatic hypotension concurrent with reductions in cardiac output and cerebral blood flow can cause nausea/vomiting, dizziness, or possible loss of consciousness. If symptoms occur either during or following exercise, the individual should be immediately placed in a reclining position to facilitate venous return to elevate cardiac output and blood pressure. Hypotension risk may be reduced by elevating the legs during exercise, regular orthostatic training (e.g., head-up tilt, standing via tilt table, orthotic ambulation), proper hydration, compression stockings, abdominal binder, and physical conditioning.

Occasionally, some individuals with high-level SCI may exhibit a sudden and inappropriate episode of extremely high blood pressure (hypertension) due to autonomic dysreflexia (hyperreflexia). This is caused by loss of central control (i.e., inhibition) of spinal reflexes causing exaggeration of some sympathetic responses (increase in noradrenaline) to noxious afferent stimuli such as skin tissue trauma, bladder overdistension, and bowel impaction (31,38). Autonomic dysreflexia can be quite hazardous and possibly lead to fatality if it is not corrected immediately (39–41). To help avoid this condition, it is important that the individual follow proper health practices to eliminate noxious stimuli, and seek medical treatment where appropriate. It is, therefore, recommended that the bladder be emptied just prior to exercise and during prolonged exercise bouts, and that blood pressure be monitored at regular intervals—at least during initial exercise sessions (32). Of course, if extreme hypertension occurs, exercise should be immediately discontinued, and an upright posture should be maintained until the blood pressure returns to normal.

*Muscle Spasms.* Many individuals with SCI experience occasional spasms in the paralyzed lower limb muscles, ranging from mild to severe in intensity. This is due to a loss of inhibitory drive to motor neurons which makes them hyperexcitable to sensory input. Care must be taken to avoid damage to the lower limbs in the event of strong spasms and rapid limb movements. Pharmacotherapy is often employed to help control for muscle spasms. This treatment may involve the use of oral antispasmodic and muscle relaxant drugs. However, these drugs may further limit exercise capability by not only reducing excitability of the paralyzed muscles, but

also of the non-paralyzed muscles. In addition, there can be detrimental side effects including dizziness, ataxia (irregularity of muscular action), and depression (17).

*Thermal Stress.* Careful consideration should also be given to ambient temperature, relative humidity, type of clothing worn, exercise intensity, and duration in order to prevent hyperthermia or hypothermia. Since many individuals with SCI have limited thermoregulatory capacity due to inadequate secretion by sweat glands and inappropriate distribution of blood due to impaired cardiovascular system control, it is possible that overheating can occur more easily in this population than for nondisabled individuals (28,42–44). This is especially true in a hot, humid environment where prolonged strenuous exercise can cause severe dehydration, dangerously elevated body temperature, and possibly heat stroke and circulatory collapse. Under these conditions, frequent and adequate fluid replacement is essential. Exercise in cold environments may result in excessive heat loss from the body, also exacerbated by impaired cardiovascular system control. Therefore, if there are symptoms of hyperthermia or hypothermia, exercise should be discontinued, and clothing and environmental conditions should be appropriately adjusted.

### **Role of Exercise and Wheelchair Sports in SCI Rehabilitation**

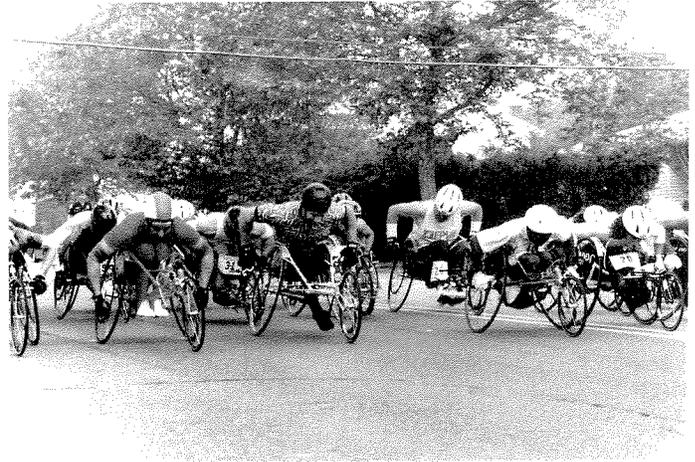
Trauma-induced SCI usually results in sudden and drastic changes in lifestyle where there is a marked decrease in physical activity. It has been found that physical activity in individuals with SCI tended to be lower with higher chronological age and shorter time since injury (45). These variables were also related to a less rewarding life and a decline in psychological adjustments. Sedentary lifestyle can be a major factor leading to consequential degenerative changes in the cardiovascular system (2,46,47). This may help explain the 228 percent higher death rate reported for an experimental group with SCI compared to the age- and gender-matched nondisabled control group in the same study (21). Higher coronary heart disease risk for sedentary individuals with SCI had been indicated by findings of significantly lower blood high-density lipoprotein-cholesterol (HDL-C) concentrations in comparison to athletes with SCI, as well as sedentary and active nondisabled individuals (46–48). Furthermore, reduced basal metabolic rate due to skeletal muscle wasting and lower daily energy expenditure (49) due to physical inactivity may lead to weight gain. Excessive body weight, which can also contribute to cardiovascu-

lar risks, as well as making activities of daily living more stressful (50), may be counteracted by increased physical activity. Thus, there is evidence to support that habitual arm exercise training by individuals with SCI may improve their health status and reduce cardiovascular risks in a similar manner as leg exercise training benefits nondisabled individuals (23,48).

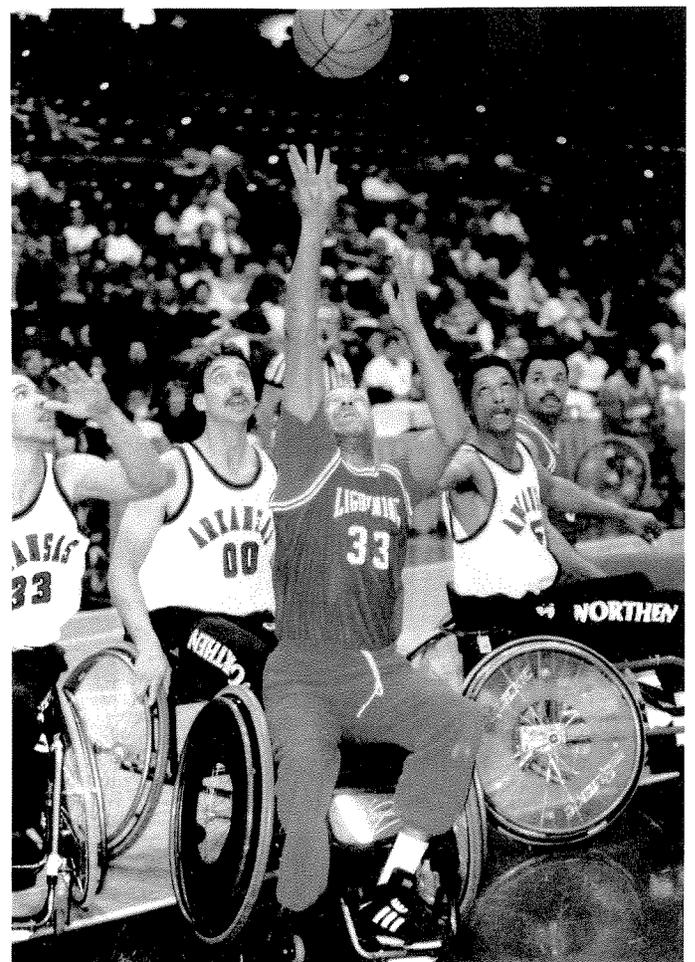
Participation in exercise and wheelchair sports programs can have a profound impact on rehabilitation outcome. Such practices can challenge individuals with SCI to overcome physical obstacles and expand functional independence. Indeed, sports competition provides many opportunities for the pursuit of excellence from the novice to the Olympic levels depending upon the particular needs and abilities of the person. **Figures 3 and 4** illustrate well-trained wheelchair athletes participating in road racing and basketball, respectively. Regardless of one's motivation to begin exercise training and participation in wheelchair sports, clinicians should consider prescribing such programs early in the post-traumatic rehabilitation process to optimize outcome.

Regardless of age, gender, and medical history, most wheelchair users can derive benefits from appropriately designed exercise programs. Well-established principles of "specificity" and "overload" should be followed to obtain the desired results in an efficient manner (1,2). Thus, specific exercise regimens (i.e., modes and protocols) are used for muscle strength versus endurance training, as well as for cardiopulmonary (i.e., aerobic) training. It has been clearly documented that exercise training has resulted in significant improvements in fitness, which can lead to greater physical capability and functional independence, and reduced relative stresses for performing given activities of daily living (1,2,4,50–54). There is also evidence that appropriate exercise training can potentially lower the risk for occurrence of secondary medical complications associated with wheelchair confinement and sedentary lifestyles. These include muscle atrophy, osteoporosis, decubitus ulcers, and a host of cardiopulmonary disorders.

If exercise and sports participation can enhance health and fitness, as well as societal interactions for wheelchair users, it seems reasonable to assume that there would be psychological benefits in terms of self-esteem and body image. Indeed, several studies have indicated that wheelchair users who engaged in sports and recreation programs experienced significant increases in skill performance, self-concept and self-



**Figure 3.**  
Wheelchair road racers in action.



**Figure 4.**  
Wheelchair basketball players.

acceptance. However, these results are most likely influenced by inherent differences of exercise habits, attitudes, beliefs, and personality prior to SCI. It is also apparent that psychosocial outcome of individuals with disabilities is highly influenced by societal attitudes. In this regard, wheelchair sports can have a positive effect upon reducing stigmatization, stereotyping and discrimination, and acceptance of those with disabilities as fully functioning members of society.

### PHYSIOLOGIC RESPONSES TO ARM VERSUS LEG EXERCISE

Wheelchair users are required to employ their relatively small and weak upper body musculature for locomotion and most other activities of daily living. This places them at a marked disadvantage due to the limited maximal power output (PO) capability and peak oxygen uptake for arm exercise, which has been reported to be approximately two-thirds of leg exercise values for nondisabled individuals who are not arm exercise trained (55–58). Arm exercise capability may be further reduced due to factors related to the SCI (as indicated above), as well as diminished muscular and cardiopulmonary fitness resulting from sedentary lifestyle and aging. Furthermore, studies have shown that arm exercise is rather inefficient (energy wasteful), and stressful to the muscles involved, as well as to the cardiovascular and pulmonary systems in comparison to the same intensities of leg exercise (56,59,60). Indeed, compared to walking at the same velocities and leg cycling at the same POs, handrim wheelchair propulsion generally elicited greater magnitudes of physiologic responses (61–63). These differences tended to be more pronounced at the greater exercise intensities that occurred at higher locomotive velocities and when negotiating architectural barriers, such as carpeting and upward grades.

When comparing arm crank and wheelchair ergometry to leg cycle ergometry at matched submaximal PO levels in nondisabled subjects, the arm exercise modes elicited greater metabolic stress, as indicated by the higher oxygen uptake and blood lactate (LA) values; heavier cardiac load, as indicated by higher heart rate (HR), peripheral vascular resistance, intra-arterial blood pressure, and stroke work; and greater demand on the pulmonary system, as indicated by higher pulmonary ventilation. Arm exercise also tends to elicit lower cardiac output (Q) and ventricular

stroke volume (SV) (56,59,64–67). Lower cardiac output and stroke volume may be due to a greater afterload on the heart because of the higher peripheral vascular resistance, and a lower end diastolic volume due to attenuated venous return of blood to the heart. During arm exercise by individuals with SCI, it is feasible that venous return is restricted by inactivity of the skeletal muscle pump in the paralyzed legs (1,2,23). Furthermore, elevated intrathoracic pressure during handrim stroking might decrease thoracic pump effectiveness. These combined factors may reduce the effective blood volume during wheelchair activity and limit maximal PO and peak oxygen uptake. Therefore, wheelchair locomotion, even at low PO levels, can represent relatively high exercise loads that can lead to the rapid onset of fatigue. Excessive cardiovascular and pulmonary stresses that may be elicited can hinder rehabilitative efforts and impose risks upon certain patients, such as those with cardiovascular or pulmonary impairments and the elderly (1,2). As indicated above, individuals with higher level and more extensive spinal cord lesions will be placed at greater disadvantage when performing given activities. This can be especially obvious during sporting events where competitors have a wide range of physical capabilities. Therefore, classification systems based upon anatomical, physiological, and functional considerations have been devised for wheelchair sports competitors in an attempt to better group them according to physical capability, and to improve the fairness of competition.

### ASSESSMENT OF PHYSIOLOGIC RESPONSES TO ARM EXERCISE STRESS

#### Limiting Factors for Leg Versus Arm Exercise

Exercise stress testing is important since it enables exercise capacity and metabolic and cardiopulmonary responses to be ascertained. By repeating this testing periodically, fitness changes over a period of time can be objectively tracked. To assess physiologic responses to exercise in nondisabled individuals, leg exercise modes such as treadmill walking/running, bench stepping, and leg cycle ergometry are typically used. Here, a large muscle mass is rhythmically contracted, which can stimulate maximal metabolic, cardiovascular, and pulmonary responses for valid functional evaluation of these systems. Many exercise physiologists suggest that the primary factor limiting maximal PO and oxygen uptake during these tests is central circulatory in nature,

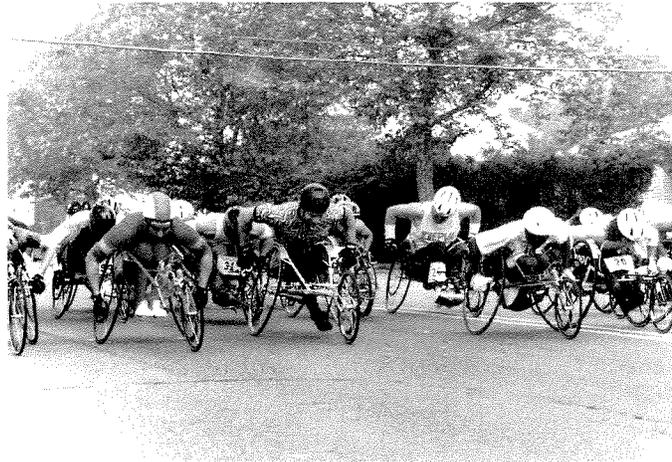
ill as making activities of daily living (50), may be counteracted by increased . Thus, there is evidence to support that exercise training by individuals with SCI their health status and reduce cardiovascular in a similar manner as leg exercise training inabled individuals (23,48).

on in exercise and wheelchair sports have a profound impact on rehabilitation practices can challenge individuals with the physical obstacles and expand func- tence. Indeed, sports competition pro- vides opportunities for the pursuit of excellence to the Olympic levels depending upon needs and abilities of the person. **Figures** illustrate well-trained wheelchair athletes in road racing and basketball, respectively.

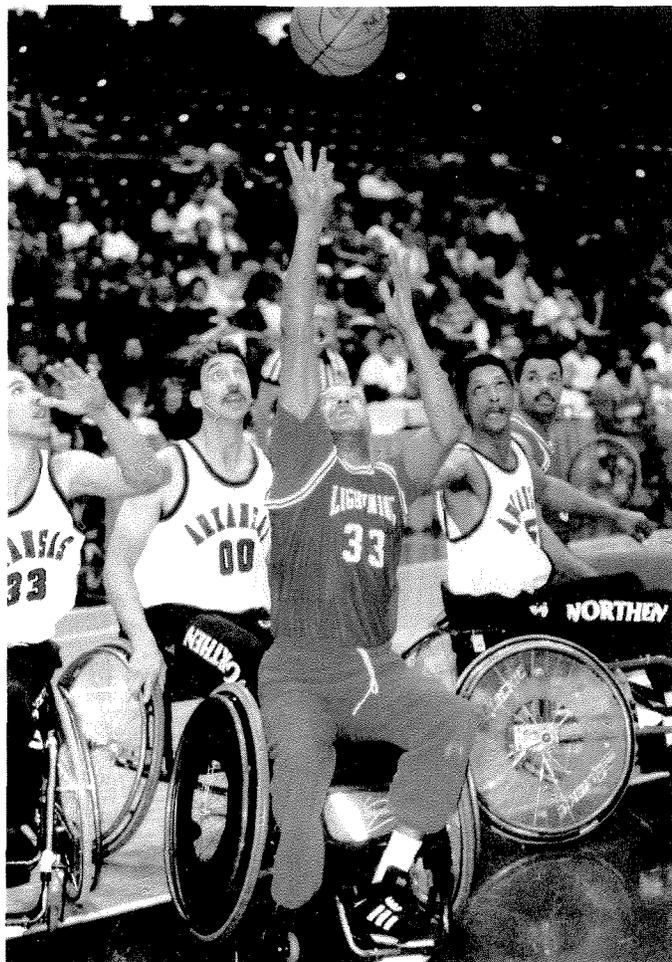
one's motivation to begin exercise participation in wheelchair sports, clinicians consider prescribing such programs early in the rehabilitation process to optimize

of age, gender, and medical history, for users can derive benefits from approved exercise programs. Well-established "specificity" and "overload" should be obtained to achieve the desired results in an efficient manner. Thus, specific exercise regimens (i.e., protocols) are used for muscle strength training, as well as for cardio- (aerobic) training. It has been clearly demonstrated that exercise training has resulted in improvements in fitness, which can lead to increased capability and functional independence, and reduced relative stresses for performing given activities of daily living (1,2,4,50-54). There is also evidence that appropriate exercise training can potentially reduce the risk for occurrence of secondary complications associated with wheelchair dependent lifestyles. These include muscle atrophy, osteoporosis, decubitus ulcers, and a host of other disorders.

and sports participation can enhance independence, as well as societal interactions for individuals. Therefore, it seems reasonable to assume that wheelchair users can derive psychological benefits in terms of improved self-image. Indeed, several studies have demonstrated that wheelchair users who engaged in rehabilitation programs experienced significant improvements in skill performance, self-concept and self-



**Figure 3.** Wheelchair road racers in action.



**Figure 4.** Wheelchair basketball players.

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Wheelchair mounted device being collected.



**Figure 6.**  
Wheelchair aerobic fitness trainer (WAFT).

### **Wheelchair Aerobic Fitness Trainer (WAFT)**

A new wheelchair ergometer called the Wheelchair Aerobic Fitness Trainer (WAFT) is another wheelchair exercise mode that can be used for rehabilitation and stress training (**Figure 6**). The device was developed under the sponsorship of the Department of Veterans Affairs, Rehabilitation Research and Development Service, Baltimore, Maryland, John W. Goldschmidt, M.D., Director. It was clinically tested at the Rehabilitation Research and Development Center, Edward Hines, Jr. VA Hospital, Hines, Illinois, and is currently being tested in six VA Medical Center cardiopulmonary exercise testing and rehabilitation programs. Mandates for its design include evaluation, rehabilitation, and development of cardiorespiratory fitness in persons whose primary mode of mobility is the manually operated wheelchair. For this particular mode, the WAFT is a wheelchair exercise device designed to accommodate the user's own wheelchair, provide a form of exercise that requires the use of motor patterns specific to wheelchair propulsion, and provide a valid

and reliable device for medically supervised graded exercise testing and medically prescribed rehabilitation and/or aerobic exercise.

A variety of equipment is available for the assessment and improvement of aerobic capacity and cardiovascular health of the nondisabled. However, there is a shortage of appropriate equipment for promoting the cardiorespiratory fitness of persons limited to upper body exercise because of disabilities resulting from lower limb amputation and musculoskeletal and neurological impairments. Moreover, lower limb disabled individuals are frequently sedentary; this lack of physical activity often leads to significant decrements in physical fitness and further increases the risk of cardiovascular disease.

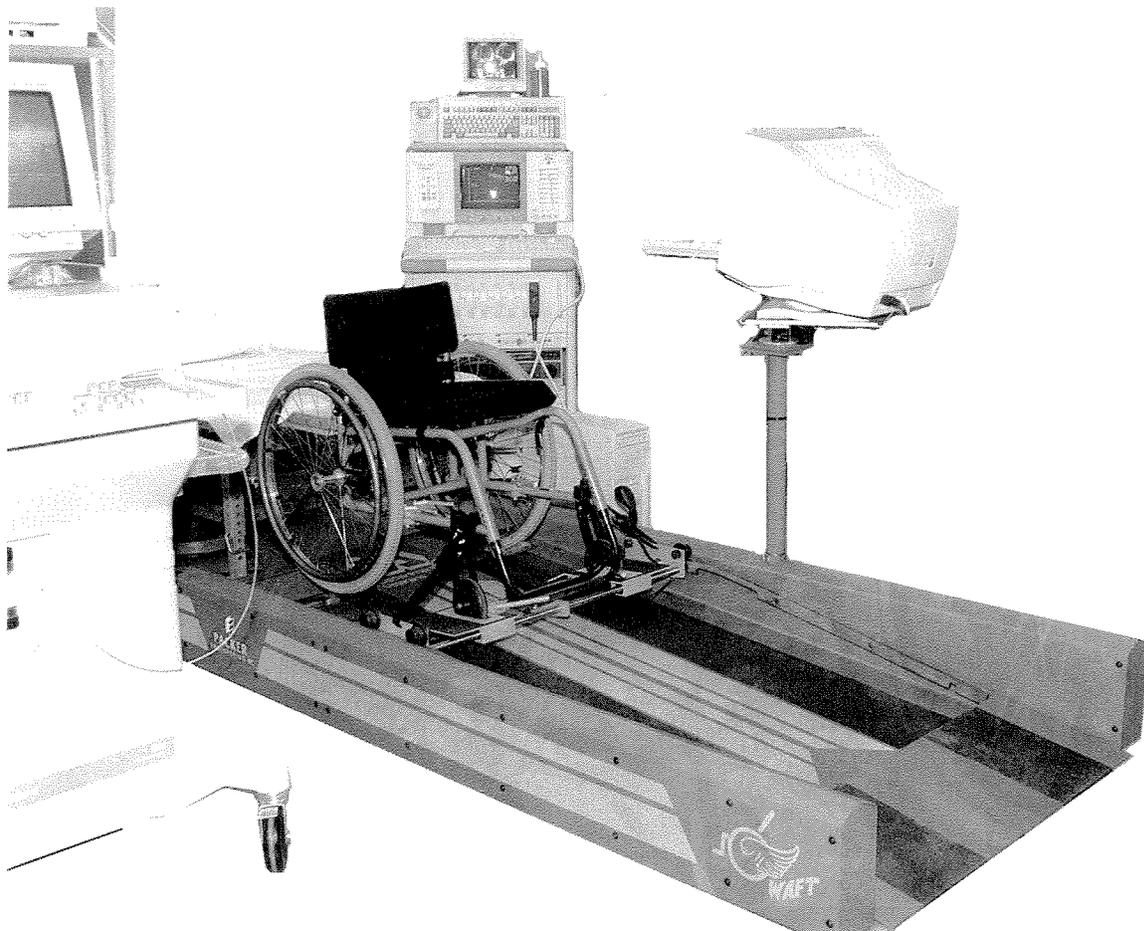
The WAFT is a stationary device. Its design uses electronic particle braking incorporated in the ergometer to provide a reliable method of creating variable power output for graded exercise testing and aerobic conditioning. The wheelchair sits on two independently computer-controlled rollers (**Figure 7**). Changes in

work load are accomplished by increasing the roller resistance created by the ergometer's electronic brake and/or by increasing the speed at which the individual pushes the wheelchair wheel (**Figure 8**); thus simulating the physical stress normally experienced during daily wheelchair propulsion. Moreover, this unique design makes the WAFT appropriate for graded exercise testing and conditioning of persons with widely varying levels of cardiorespiratory fitness.

The WAFT is interfaced to an IBM-compatible computer, which controls the ergometer's roller resistance. A computer monitor displays graphical feedback to the user, indicating right and left wheel speeds, target wheel speed, resistance setting, accumulated distance, exercise time, and expended kilocalories (**Figure 9**). Information provided by the WAFT from graded wheelchair exercise tests is useful for developing

exercise prescriptions, evaluating the effectiveness of conditioning or rehabilitation programs, charting the effects of disability on functional capacity, formulating procedures for predicting peak exercise capacity from submaximal graded wheelchair exercise testing, and conducting exercise physiology research.

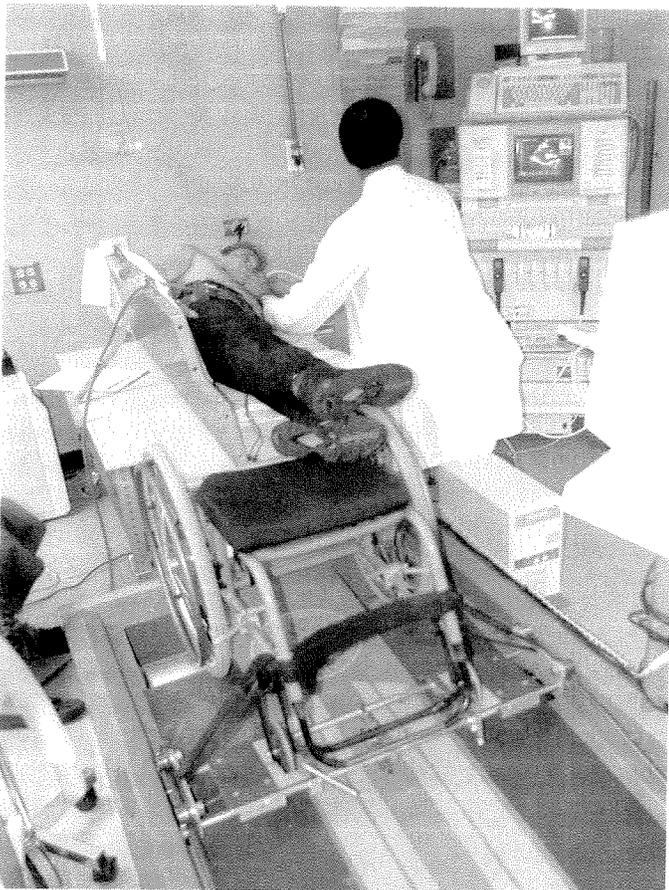
Exercise stress testing is a well-established technique for the detection of ischemic heart disease. When exercise electrocardiography (ECG) testing is combined with echocardiographic analysis of myocardial contractility, the accuracy of the stress test is improved (81,82). Clinicians and researchers often address treadmill or bicycle ergometry for exercise testing as those suitable for individuals who are not lower limb disabled (i.e., spinal cord injury or amputation). The detection and assessment of coronary artery disease in individuals with lower limb disability is a commonly encountered



**Figure 7.**  
WAFT with wheelchair alone.

problem. These individuals are unable to satisfactorily complete traditional forms of exercise testing. Many people in this population depend daily on the manual wheelchair for mobility. Therefore, the concept of specificity of exercise suggests that wheelchair exercise would be the desired mode of testing for individuals with lower limb disabilities<sup>1</sup>.

Another wheelchair exercise mode that can be useful for stress testing and training is operating a wheelchair on a motor-driven treadmill (83–86). **Figure 10** illustrates a subject with paraplegia performing an exercise stress test with his own wheelchair on a specially designed and constructed motor-driven treadmill. Exercise intensity can be regulated by adjustment of velocity, grade (i.e., elevation angle), or by applying additional resistive force via a cable-pulley system (86). Using this exercise mode, Janssen, et al. (52) had groups of individuals with lesions between C4–C8, T1–T5, T6–T10, and T11–L5 perform a maximal effort



**Figure 8.**  
WAFT in use.

stress test. Generally, the higher the lesion level, the lower were the values for these variables, as indicated previously. This type of exercise system enables better simulation of actual wheelchair locomotion than wheelchair ergometers, but is not practical for most wheelchair sports participants. For testing outside the laboratory environment, a rather simple and inexpensive technique that can be used by most wheelchair users is to propel their own wheelchair at paced or self-selected velocities over an established test course in a standardized, repeatable manner (62,63,87). Knowing the length of the course and the time to complete the given task can provide information concerning locomotive performance capability. Heart rate monitoring may be used to give an indication of relative stress for the exercise bout if cardiovascular reflexes are sufficiently intact.

### Stress Testing Protocols

The fundamental principles followed for lower body stress testing of nondisabled individuals may be employed for upper body stress testing of wheelchair users. These tests are usually progressive with respect to exercise intensity, and have well-defined submaximal or maximal effort end-point criteria. Protocol design may utilize either continuous (nonstop exercise) or discontinuous (alternating exercise and recovery periods) exercise. Discontinuous, submaximal protocols may be preferable for stress testing of wheelchair users, since they are relatively safe and comfortable, and easy to administer. A suitable protocol would be to have exercise bouts that are 4–6 minutes in duration, separated by 5–10 minutes of rest. For wheelchair ergometer and arm crank ergometry exercise, the propulsion velocity is typically held constant (e.g., wheel velocity of  $3 \text{ km}\cdot\text{h}^{-1}$  and crank rate of 50 revolutions per minute, respectively) while the braking force (resistance) is incrementally increased to elevate PO level. With wheelchair ergometry, 5 W appears to be an appropriate initial PO, as this level is frequently encountered during daily wheelchair locomotion (89). PO progression increments of 5–10 W may be usable for many individuals, and PO can be limited to 25–35 W for submaximal tests (73,89,90). For more fit individuals, the PO increment and maximal PO permitted can be greater. With arm crank ergometry, the protocol can be the same, but the PO levels used could be up to two times that for wheelchair ergometry. Steady rate physiologic responses can be determined during the last minute of each exercise bout. Criteria for exercise stress test termination include: 1) voluntary

<sup>1</sup>For further information on the WAFT, contact W. Edwin Langbein, PhD, Research Physiologist, at Edward Hines Jr., VA Hospital, Hines, IL 60141.

cessation, 2) symptoms of cardiovascular or pulmonary abnormalities (e.g., chest discomfort, inappropriate EKG changes, marked hypertension, dyspnea), 3) achievement of the maximal PO level required for the test, and 4) attainment of a predetermined heart rate—for example, 75 percent of age-adjusted heart rate reserve (1,75). However, for individuals with high-level SCI, the heart rate criterion may be less useful due to the interruption of sympathetic pathways to the heart and limited ability for cardioacceleration.

To actually determine maximal PO and peak oxygen uptake, the discontinuous, submaximal test can be extended to a maximal effort test by increasing the rate/number of exercise bouts. But drawbacks to this protocol are: 1) much time would be required to

complete the test, and 2) the multiple bouts of exercise could have fatiguing effects, which may result in reduced maximal PO and peak oxygen uptake values being obtained. Therefore, if maximal effort physiologic responses are desired, and data at several submaximal PO levels are not needed, a continuous, maximal exercise protocol can be utilized. This shorter protocol would usually begin at a low-to-moderate PO to serve as a warm-up. PO is then increased by a certain increment every 1–2 minutes until maximal effort is reached. By estimating fitness with previous submaximal stress testing, the initial PO level (e.g., 50 percent max PO) and the magnitude of the PO increments can be set so that the individual will complete the test in several minutes (71,91–94).

Stress testing fitness criteria are usually based upon the magnitudes of metabolic and cardiopulmonary responses obtained at given PO levels, as well as the maximal PO level achieved (73). At given submaximal PO levels, well-trained individuals typically exhibit lower heart rate and pulmonary ventilation responses indicating higher cardiopulmonary fitness, lower relative stress, and more functional reserve. In individuals with high-level SCI, however, care must be taken not to interpret low exercise heart rate responses as superior cardiovascular fitness. As previously indicated, cardioacceleration in these individuals is limited by insufficient sympathetic stimulation, and most observed increases in heart rate are probably due to vagal withdrawal. Nevertheless, heart rate can still be used as an indicator of fitness in this population when expressed as a percentage of heart rate reserve, such as the functional range between resting and maximal heart rate (52).

For activities that do not require much skill (e.g., arm crank ergometry), the submaximal oxygen uptake would be similar for both trained and untrained individuals. However, for activities requiring a greater degree of skill, a lower submaximal oxygen uptake response may be obtained from the trained individual indicating lower aerobic energy expenditure and higher mechanical efficiency. At maximal effort exercise, PO, as well as peak values for oxygen uptake, pulmonary ventilation, cardiac output, and stroke volume would be expected to be higher for fit individuals. But, maximal heart rate may not be markedly different between more and less fit individuals, whereas it is reduced with age. Therefore, more fit individuals would possess greater metabolic and cardiopulmonary reserve, and given submaximal tasks would be less stressful, since they are

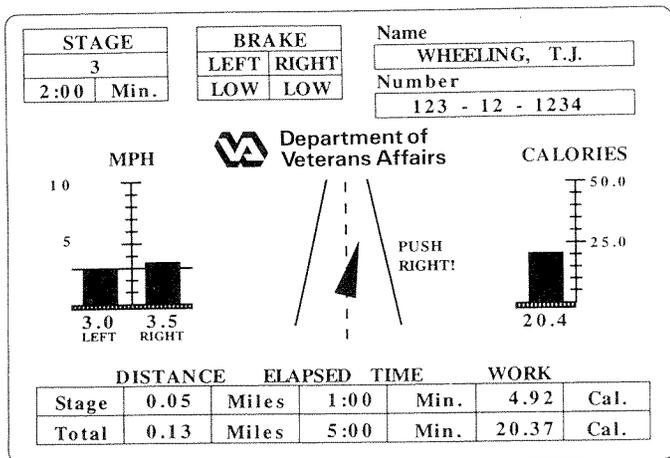


Figure 9. View of monitor reflecting activity of subject in wheelchair while using WAFT.

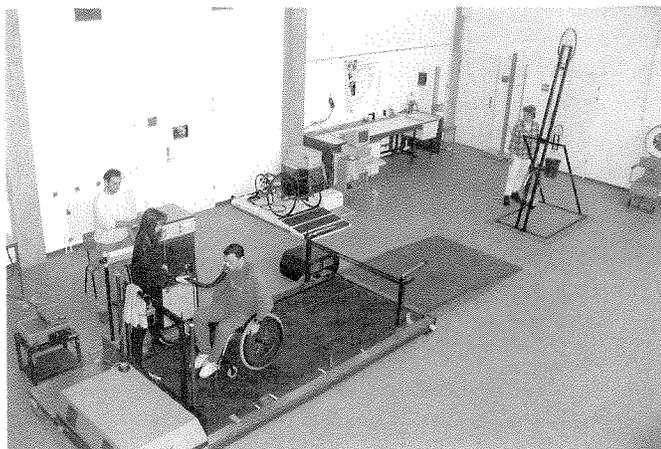


Figure 10. Maximal effort wheelchair stress test being performed by an individual with paraplegia on a motor-driven treadmill. A cable-pulley system with load weights is used to establish the work rate.

performed at a lower percentage of maximal PO, peak oxygen uptake and pulmonary ventilation, and heart rate reserve.

### **EXERCISE TRAINING TECHNIQUES FOR IMPROVING PHYSICAL FITNESS**

It had been stated that normal daily wheelchair activity may not provide sufficient exercise to train the muscular and cardiopulmonary systems, and it was indicated that supplemental exercise training is necessary to stimulate fitness improvement (32,85,95,96). Enhancing exercise capability and cardiopulmonary fitness with specific exercise training programs could increase organ system reserve and make activities of daily living less stressful since they would be performed at lower percentages of maximal PO, as well as of peak oxygen uptake, pulmonary ventilation and heart rate reserve (4,50,52). This could possibly contribute to improved functional independence and rehabilitation outcome. Indeed, with wheelchair locomotion at 7 watts (W), well-trained wheelchair athletes (mean age=25 yr) are estimated to utilize less than 7 percent of their maximal PO and 18 percent of peak oxygen uptake. This is in contrast to 9 percent of maximal PO and 29 percent of peak oxygen uptake for their sedentary colleagues. Older, sedentary wheelchair users have a more difficult plight in that 50–60-yr olds may utilize 44 percent of maximal PO and 51 percent of peak oxygen uptake, whereas 80–90-yr olds may be required to use 100 percent of their maximal PO and peak oxygen uptake for this routine locomotive task (63,90). In a 3-year study, Janssen, et al. (50) demonstrated that a decline of only 5–10 W in PO capability of sedentary wheelchair users with quadriplegia could result in a loss of independence. In contrast, however, their peers who regularly participated in sports activities and increased physical fitness generally maintained their independence and performed activities of daily living with less stress. Thus, it is feasible that regular exercise may reduce the stresses of wheelchair locomotion and other activities of daily living, retard the decline in physical capability that typically accompanies aging, and lower some of the risks associated with secondary cardiovascular disabilities.

#### **Arm Exercise Training Protocols**

To enhance muscular and cardiopulmonary fitness, as well as performance, arm exercise training for

wheelchair users should, like leg exercise training, incorporate the fundamental principle of overload (1,2,97). Thus, exercise should be performed at intensities and/or durations that are beyond those normally encountered during daily activities. Furthermore, exercise intensity and/or duration should be progressively increased as performance improves until fitness goals are reached. Regular exercise at the final intensity/duration levels is required to maintain the achieved fitness status. If exercise is discontinued, detraining will occur and fitness level will diminish in a matter of several weeks (98). For optimal outcome, exercise should also follow the principle of exercise specificity where the mode used should be closely matched to the activity in which performance improvement is desired. Thus, the biomechanics involved and the physiologic responses elicited would be more representative to produce the desired gains in performance.

Arm exercise protocols may be either continuous or discontinuous (intermittent) in design. If enhancing cardiopulmonary fitness is the primary goal, PO should be adjusted to moderate levels that enable exercise bouts of relatively long durations (e.g., 15–60 minutes for continuous bouts, and 3–5 minutes for each of the several discontinuous bouts) without eliciting excessive fatigue or respiratory distress (i.e., marked accumulation of lactate in the blood). Exercise sessions should occur 2–5 times per week (97). Traditionally, arm crank ergometry exercise has been used for endurance training of wheelchair users. This exercise mode is readily available and it has been shown to improve cardiopulmonary fitness (53,54). Although wheelchair ergometer exercise elicits similar peak metabolic and cardiopulmonary responses (77,79,92), it has the advantage of more closely resembling actual wheelchair activity so it may better enhance locomotive performance. In contrast to aerobic training, if enhancing muscular power is the primary goal, higher levels of PO would be used and exercise bouts would be of relatively short duration (e.g., from a few seconds to a few minutes). The large anaerobic energy component would result in a marked accumulation of lactate in the blood. This form of exercise would be useful for wheelchair athletes who want to improve sprinting performance, as well as for most other wheelchair users, since many activities of daily living (e.g., transfers, overcoming architectural barriers) require intense, short duration efforts.

When developing an aerobic training program for leg exercise by nondisabled individuals, a suitable

intensity can be established by maintaining heart rate between 60–90 percent of their heart rate reserve, which usually corresponds to 50–85 percent of peak oxygen uptake. The objective is to exercise at high enough intensity for a sufficient duration to permit cardiopulmonary adaptations to occur. But, exercise intensity should be kept below the point where marked anaerobiosis occurs and a high concentration of lactate accumulates in the blood, which can severely shorten endurance and create discomfort. Actual measurement of heart rate during maximal effort exercise for each individual would be preferred over prediction techniques to facilitate appropriate setting of training intensity. But for arm exercise by individuals with SCI, an effective training intensity may be more difficult to set, since heart rate response can be quite diverse. Thus, actual measurement of maximal heart rate can be important. Janssen, et al. (52) showed that percentage of peak oxygen uptake and heart rate reserve were highly correlated during wheelchair exercise on a treadmill by individuals with paraplegia and quadriplegia. However, the absolute values for heart rate were lower in the individuals with the higher level lesions. Their regression equations predicted that exercise at 50–85 percent of peak oxygen uptake corresponded to heart rate reserve values of 40–85 percent for individuals with low-level paraplegia and 30–80 percent for those with high-level paraplegia and quadriplegia. Thus, heart rate response expressed either as a percentage of heart rate reserve or maximal heart rate can be a usable indicator of exercise stress in these populations, but the actual value used would be dependent upon the exercise response characteristics of the individual (52,99). Therefore, to set arm exercise intensity for various individuals with SCI, direct determination of peak values for PO, oxygen uptake, pulmonary ventilation, heart rate, and blood lactate concentration (during stress testing) would be desirable if the instrumentation is available. In individuals who do not exhibit a clear relationship among these variables (which is more common in those with quadriplegia), training at a percentage of maximal PO may be preferable (100). Where laboratory testing is not available, intensity criteria may be established according to the subjective feeling of stress and the actual exercise endurance capability. In most cases, it is likely that several trials will be needed for each individual to effectively set exercise intensity.

### **Physiologic Adaptations to Arm Exercise Training**

Studies on individuals with lower limb disabilities indicated that several weeks of endurance-type arm exercise training can significantly increase PO capability, peak oxygen uptake, and cardiopulmonary performance (32,91,101). Arm crank ergometry training of active wheelchair users increased their peak oxygen uptake by 12–19 percent in 7–20 weeks (91). Even greater gains in cardiopulmonary fitness were obtained in only 5 weeks of training for individuals with quadriplegia who had relatively low initial fitness levels (101). Using wheelchair ergometer exercise, Miles, et al. (102) reported that 6 weeks (3 times per week) of interval training by 8 wheelchair athletes resulted in increases of 31 percent for maximal PO capability, 26 percent for peak oxygen uptake, and a 32 percent for peak pulmonary ventilation. These gains were even more remarkable considering that the athletic subjects used had relatively high levels of fitness prior to participating in the program.

Although arm exercise limits the absolute level of aerobic fitness that can be achieved with training some cardiopulmonary benefits can be expected for most participants. However, the magnitudes by which aerobic fitness and exercise performance can be increased with training appear to depend on the initial fitness level and the size of the muscle mass available for exercise. For instance, several studies on wheelchair athletes performing maximal effort arm crank ergometry and wheelchair ergometer exercise indicated that their peak oxygen uptake is in the 2–3 L/minute range (1,102–105). This is approximately one-half of the maximal oxygen uptake that would be expected for healthy nondisabled athletes performing maximal effort leg exercise (e.g., cycling, running). Greater gains in fitness may be expected from individuals with SCI who initiate training programs at relatively low fitness levels—depending upon pathological limitations (1,2). It is plausible that many of the observed gains in arm exercise performance are due to peripheral adaptations such as hypertrophy, enhanced arterial vasodilation, and improved capillary density and/or metabolic capability within muscles (which would increase arteriovenous O<sub>2</sub> difference), rather than central circulatory adaptations (106). Yet habitual arm exercise training appears to increase maximal PO capability and peak oxygen uptake, and may also decrease levels of physiologic responses for given submaximal exercise tasks and ADLs, including wheelchair locomotion (107,108).

### Exercise Training and Coronary Heart Disease

Studies suggest that habitual arm exercise training and sports participation can also reduce the risk for acquiring coronary heart disease (CHD). Cross-sectional studies on sedentary wheelchair users and those who are physically active showed that the more active individuals had a superior blood lipid profile as indicated by a lower total cholesterol (TC), lower low-density lipoprotein-cholesterol (LDL-C) level, and greater high-density lipoprotein-cholesterol level (6,47,109). In a longitudinal study, Hooker and Wells (110) reported a decrease in total cholesterol (−8 percent), a significant increase in high-density lipoprotein-cholesterol level (+20 percent), and a decrease in low-density lipoprotein-cholesterol level (−15 percent) in men with SCI following 8 weeks of moderate intensity wheelchair ergometry training (60–70 percent peak oxygen uptake; 20 minutes per day, 3 times per week). These apparently beneficial alterations in the blood lipid profile extrapolated to a mean decrease of 20 percent in the group's future risk for coronary heart disease. Thus, if high-density lipoprotein-cholesterol does have a protective effect against coronary heart disease, and total cholesterol and low-density lipoprotein-cholesterol increase its risk, these high-density lipoprotein-cholesterol, total cholesterol and low-density lipoprotein-cholesterol changes that appear to occur with increased physical activity suggest that the risk of coronary heart disease in individuals with SCI may be decreased with arm exercise intervention in a similar fashion as leg exercise training benefits nondisabled individuals. More research is necessary to develop appropriate exercise modes to document their efficacy for reducing the risk of cardiovascular disease in this population.

### Enhancing Arm Exercise Performance by Increasing Venous Return

In some individuals with lower limb paralysis, the etiology of upper body muscle fatigue may be due to a central factor that is secondary to a peripheral factor. It is conceivable that inactivity of the skeletal muscle pump combined with impaired vasoregulation in the paralyzed lower limbs and abdominal region can limit venous return of blood from the legs to the heart (peripheral factor), and thereby restrict cardiac output capability during arm exercise (central factor). Thus, pooling of blood in the legs and abdominal veins can potentially lead to a hypokinetic circulation that can reduce the availability of blood to the active upper body musculature and consequently decrease its exercise

capability (1,2). Since individuals with SCI typically perform arm exercise in an upright, sitting position, this can elevate hydrostatic pressure and blood pooling in leg veins. It is plausible that arm exercise performance may be enhanced by placing the individual in a supine (lying face up) position. This can minimize the gravitational effects on blood, facilitate venous return, elevate cardiac output, and increase arm muscle blood flow to boost resistance to fatigue.

In a preliminary study<sup>2</sup>, subjects with quadriplegia performed maximal effort arm chair ergometry in a sitting and in a supine position on separate occasions. It was found that this exercise in the supine position elicited significantly higher maximal power output, as well as peak oxygen uptake, pulmonary ventilation, heart rate, stroke volume, and cardiac output. Similar results have been found in subjects with high-level paraplegia, but not to the same degree. The greater magnitudes of these responses suggest that cardiopulmonary training capability in individuals with SCI may be enhanced by using the supine position. Indeed, McLean and Skinner (111), who used arm crank ergometry exercise to train subjects with quadriplegia in the sitting and supine positions, showed greater improvement in peak oxygen uptake (during testing in both the sitting and supine positions) when trained in the supine position. Although these studies suggest that the supine position can improve exercise outcome, more research is needed to determine advantageous protocols and long-term training effects.

Other techniques have been studied in an attempt to reduce the effects of gravity on venous return during arm exercise. Kerk, et al. (112) used an abdominal binder with wheelchair athletes with high-level paraplegia during submaximal and maximal effort wheelchair ergometry exercise, but found no differences in metabolic and cardiopulmonary responses, as well as biomechanical characteristics compared to not using the abdominal binder. Hopman, et al. (113), showed that use of a fighter pilot anti-G suit, which applied constant external pressure (52 mmHg) to the calves, thighs, and abdomen of men with paraplegia (below T5), during submaximal arm crank exercise can facilitate venous return and increase stroke volume. However, they did not show any improvement in maximal exercise capacity (114). Pitetti, et al. (115) also used a fighter pilot

<sup>2</sup>A report on the preliminary results of this pilot study entitled "Exercise Hemodynamics of Quadriplegics," by S.F. Figoni, Gupta S.C., Glaser R.M., et al., can be found on page 108 of the 1988 Rehabilitation R&D Progress Reports.

anti-G suit, but fluctuated pressure every 2 minutes to simulate skeletal muscle pump activity, and found a significant increase in peak oxygen uptake during arm crank ergometry and wheelchair ergometry exercise by individuals with predominantly high-level SCI. Although use of external compression to the lower limbs and abdomen may have some effect on facilitating venous return during arm exercise, use of rhythmic contractions of lower limb muscles that are induced by a multichannel electrical stimulator may better activate the skeletal muscle pump for more effective results.

### **FES-INDUCED EXERCISE OF THE PARALYZED LOWER LIMB MUSCLES**

Functional electrical stimulation (FES) research has been conducted for almost 20 years with the goal of inducing exercise in paralyzed lower limb muscles (116). Several devices are now commercially available, so FES-induced exercise can be used by those who are interested in expanding their training capability. This technique typically uses electrical impulses (from a stimulator), which are applied to muscle motor points via skin surface electrodes, to directly induce tetanic contractions of controlled intensity. Therefore, FES-induced exercise of the paralyzed legs has the potential of utilizing a large muscle mass that otherwise would be dormant. Furthermore, this exercise can augment the circulation of blood by activation of the skeletal muscle pump. It is thus apparent that FES exercise modes can improve the health, cardiopulmonary fitness, and rehabilitation potential of individuals with SCI to levels higher than can be attained with only arm exercise. Individuals with quadriplegia would most likely find this induced exercise mode to be particularly advantageous due to the small muscle mass that is under their voluntary control.

#### **Considerations and Precautions for FES Exercise**

The primary requirement for FES use is that the muscles to be exercised are paralyzed due to upper motor neuron damage, and that the motor units (lower motor neurons and the skeletal muscle fibers they innervate) are intact and functional. The presence of stretch reflex activity and spasticity may indicate that the individual can perform FES exercise. But, if the individual retains some degree of feeling in the skin, FES may cause discomfort or pain at the high

stimulation current levels required to induce forceful contractions.

Before participating in an FES exercise program, the individual should undergo a medical examination, which includes radiographs of the paralyzed limbs, range of motion testing, neurological examination, and an EKG. He/she should be informed of the potential benefits and risks of FES exercise, and clearly understand that FES will not regenerate damaged neurons and cure paralysis. It should also be understood that, similar to voluntary exercise training, any health and fitness benefits derived from FES exercise training will be lost several weeks after this activity is discontinued.

FES-induced contractions should be kept as smooth as possible and the contraction force generated should be limited to a safe level to prevent injury, since the muscles, bones, and joints of paralyzed lower limbs tend to be deteriorated. Although FES exercise training can improve the strength and endurance of the paralyzed muscles, there is currently no evidence that this activity can reverse osteoporosis. Therefore, with continued training, the muscles could ultimately produce more force than the bones can endure. Furthermore, FES may trigger severe muscle spasms, so it is important that the quality of the contractions be observed by a physician to insure that they are not hazardous (117). In individuals with high-level SCI, FES exercise may provoke autonomic dysreflexia (36,116). Blood pressure should, therefore, be monitored periodically, especially during initial FES use. Of course, exercise should be discontinued immediately, as indicated above, if any response is observed that places the individual at risk.

#### **FES-Induced Leg Muscle Contractions to Promote Venous Return**

As indicated above, arm exercise performance, and the ability to develop high levels of cardiopulmonary fitness, may be restricted by hypokinetic circulation due to impaired skeletal muscle pump activity. Although techniques to promote venous return, such as exercising in a supine position and use of external compression devices, may help alleviate this problem, another viable approach to promote venous return and enhance cardiac output and blood flow to the exercising upper body muscles is FES-induced rhythmic contractions of the paralyzed leg muscles. It is feasible that FES may have several clinical applications including deep venous thrombus prophylaxis, reducing excessive edema, and alleviating orthostatic hypotension.

### FES-Induced Resistance Exercise

It has been shown that the same resistance training principles known to be effective for muscle strengthening by nondisabled individuals can be adapted for FES-induced training of paralyzed muscles. These include dynamic contractions through a specific range of motion, progressive overload, and multiple sets of exercise consisting of a relatively low number of repetitions at relatively high load resistance (117,118). Research studies clearly indicate that several weeks of FES-induced weight training exercise of the quadriceps muscles can markedly increase their strength and endurance for this induced activity (117–119).

### FES-Induced Leg Cycle Ergometer Exercise

A leg cycle ergometer (LCE) is propelled by FES-induced contractions of the paralyzed lower limb muscle groups. Computer-controlled FES is used to induce contractions of the quadriceps, hamstring, and gluteal muscle groups during particular angle ranges of the pedals. Thus, pedaling at the 50 revolutions per minute target rate induces a total of 300 muscle contractions per minute. A microprocessor, which receives pedal position and velocity feedback information from sensors, controls the cyclic stimulation pattern and current intensity. As muscle fatigue progresses during exercise, FES current increases automatically to a maximum of about 140 mA to recruit additional muscle fibers in an attempt to maintain revolutions per minute. When the pedal rate falls below 35 revolutions per minute, exercise is automatically terminated.

### CONCLUSION

This chapter presents an overview of what is known about exercise physiology as applied to those with SCI. Research has clearly shown that there can be marked differences in physiologic response patterns between individuals with SCI performing arm exercise and nondisabled individuals performing either arm or leg exercise. There can also be marked differences in physiologic response patterns among individuals with SCI as influenced by the level and extent of the lesion. Thus, when establishing guidelines for exercise testing and training techniques, programs would have to be adapted with respect to the performance characteristics of particular individuals to provide optimal efficacy and to minimize risk. Furthermore, FES-induced exercise of the paralyzed lower limb muscles can possibly elicit

superior physiologic responses than for use in only arm exercise, especially for those with quadriplegia. Clearly, individuals with SCI can derive health and fitness benefits, and reduce the relative stresses for performing activities of daily living when habitually participating in appropriately designed exercise programs and sports activities. Conversely, it is also clear that maintaining a sedentary lifestyle can cause losses in health, fitness, and rehabilitation potential. Therefore, knowledge of exercise physiology is important to provide motivation for those with SCI and to help insure successful outcome for participation in exercise and sports programs, which may have a positive impact on the quality of life.

### ABBREVIATIONS

**ADL**=activities of daily living  
**CNS**=central nervous system  
**EKG**=electrocardiogram  
**FES**=functional electrical stimulation  
**L**=lumbar  
**L/min**=liters per minute  
**mA**=milliamperes  
**SCI**=spinal cord injury  
**WAF**=wheelchair aerobic fitness trainer

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