THE DEVELOPMENT AND EVALUATION OF FUNCTIONAL ELECTRICAL STIMULATION ROWING FOR HEALTH, EXERCISE AND SPORT FOR PERSONS WITH SPINAL CORD INJURY

A thesis submitted for the degree of Doctor of Philosophy

by

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Abstract

At the beginning of this project it was known that functional electrical stimulation (FES) rowing was technically feasible, but no studies on health benefits had been conducted and it was unclear what levels of fitness could be reliably attained by spinal cord injured (SCI) users. This thesis shows that training with the first-generation of the FES-rowing system (RowStim II), seven paraplegics achieved high VO_2peak values (21.0 - 27.9 $ml \cdot kg^{-1} \cdot min^{-1}$) and a significant (10%) increase in VO_2peak. This was also found to significantly improve insulin sensitivity and leptin levels but it had no significant effect on lipid profiles or body composition, possibly caused by technological limitations of the RowStim II.

However, training volumes were positively correlated with improvements in lipid profile and body composition. This motivated further technical development of the RowStim to enable paraplegics to train harder and longer. The development included a more stable seat configuration with redesigned trunk retaining straps, a rigid low friction carriage/brake system, improved leg stabiliser, improved stimulation control and a gravity-assisted return phase. This RowStim III has enabled paraplegics to participate in the British (2004, 2005 and 2006) and World Indoor Rowing Championships (2006). The rowers have achieved higher exercise intensities (26.8 -31.0 $ml \cdot kg^{-1} \cdot min^{-1}$) and increased exercise volumes (1,150 $kcal \cdot week^{-1}$) with the RowStim III. Such levels of physical activity, which are difficult to achieve for paraplegics using traditional exercises, are correlated with significant health benefits in the able-bodied.

Preliminary results suggest that perfusion of the quadriceps muscle during FES-rowing might limit the exercise time in novice rowers. Other preliminary data from pressure mapping indicate that there is a dynamic pattern during FES-rowing, which might reduce the risk for pressure sores during FES-rowing.

This thesis shows that FES-rowing is now a rapidly developing exercise modality, which has been shown to enable safe and well-tolerated exercise for individuals with SCI. It can offer unprecedented levels of cardiovascular fitness, competitive challenges and potentially important health benefits.

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What I really enjoyed about working on the FES-rowing project is that the academic achievements have had a direct impact on the use of FES-rowing in 'the real world'. I am very pleased to see that FES-rowing is also viable outside the research lab and I would like to thank all those involved in making this important step; Robin Gibbons (Aspire National Training Centre, UK), Simon Goodey (London Regatta Centre, UK), Brian McGirr (Demand, UK), John Wilson (Concept 2, UK) and many others.

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Structure of the thesis and hypotheses

The treatment of spinal cord injury (SCI) has changed significantly in the past century. Some of the secondary complications of SCI that were almost always fatal in the beginning of the twentieth century are now no longer life threatening. However, other medical conditions are now significant threats to the quality and quantity of life in SCI. The aim of the literature review presented in Chapter 1 is to explore health in chronic SCI and the role of physical activity in health promotion for this population. I will address the following questions:

Lit 1	Identify threats to the health of persons with chronic SCI and explore similarities with common health problems in the able-bodied population.
Lit 2	Identify from able-bodied studies what levels of physical activity are required to obtain optimal reduction in the risk for common long-term diseases, such as cardiovascular diseases, non-insulin dependant diabetes, obesity and osteoporosis.
Lit 3	Assess the validity of adopting these optimal levels of physical activity to the SCI population.
Lit 4	Explore the compliance to these optimal levels of physical activity

It will become clear that there is a need for a type of exercise that enables persons with SCI to exercise effectively and efficiently. Earlier work by Wheeler and co-workers has suggested that functional electrical stimulation (FES) rowing could be such an exercise (Wheeler et al., 2002, Laskin et al., 1993, Olenik et al., 1995). However the fitness benefits had to be confirmed in a follow up study and no data was available on potential health benefits of FES-rowing. Therefore the first aim of this thesis is to evaluate the health and fitness benefits of FES-rowing.

The following hypotheses are central:

H 1	FES-rowing is a high intensity exercise and an effective cardiovascular training for persons with paraplegia.
H 2	FES-rowing training will affect cholesterol and blood lipids in persons with paraplegia.
H 3	FES-rowing training will affect leptin levels and insulin sensitivity in persons with paraplegia.
H 4	FES-rowing training will affect body composition in persons with paraplegia.
H 5	FES-rowing will affect bone mineral density in the lower extremities of persons with paraplegia.

These hypotheses form the basis for Chapters 2-6. It will become clear that although large fitness benefits can be obtained with FES-rowing training, the health benefits are sub-optimal (see Chapter 7). This could have been caused by technological shortcomings of the FES-rowing machine, the RowStim II. Therefore I decided to further develop the FES-rowing technology. The aim of this development was to develop FES-rowing to such an extent that it could be used by paraplegic rowers in indoor rowing competitions. This would not only fully test the technology, but also to motivate the rowers to train for harder and longer. The resulting RowStim III is presented in Chapter 8. This new technology allowed for testing of the following hypothesis (Chapter 9):

H 6	Introducing a competitive element to FES-rowing will improve training compliance and enable larger training intensities and volumes to be achieved.

Chapter 10 is the overall discussion and Chapter 11 presents the overall conclusion and suggestions for further research. Chapters 3 - 6, 8 and 9 are all structured as scientific publications, which can be read independently from the other chapters.

The failure to obtain optimal health benefits with the RowStim II came as a surprise and resulted in a major change in direction of my PhD project. Initially the focus was going to be on the health benefits of FES-rowing, but the initial findings implied that the FES-rowing technology was not able to provide such benefits and more work had to be done on the technological development of FES-rowing.

This thesis brings together elements of epidemiology, health sciences, exercise physiology, (bio)engineering and sport sciences. These disciplines work together in order to realise the aim of this thesis:

'To develop and evaluate FES-rowing for health, exercise and sport for persons with spinal cord injury'

Publications and presentation that were formed from the content of this thesis are listed in Appendix 1, together with a list of organisations that have taken over the outcomes of this research project.

List of abbreviations

AD	Autonomic Dysreflexia
ADL	Activities of Daily Living
BIRC	British Indoor Rowing Championships
BP	Blood Pressure
BMD	Bone Mineral Density
CHD	Coronary Heart Diseases
CO	Cardiac Output
CVD	Cardio Vascular Diseases
DEXA	Dual Energy X-ray Absorptiometry
EIEE	Exercise Induced Energy Expenditure (see note below)
FES	Functional Electrical Stimulation
FFA	Free Fatty Acids
Hb-	Reduced Haemoglobin
HbO_2	Oxygenated Haemoglobin
HDL	High Density Lipoprotein Cholesterol
HOMA	Homeostasis Model Assessment
LDL	Low Density Lipoprotein Cholesterol
MET	Metabolic Equivalent Task
NIDDM	Non Insulin Dependant Diabetes Mellitus
NIRS	Near Infrared Spectroscopy
PAL	Physical Activity Level
PO	Power Output
RER	Respiratory Exchange Ratio (VCO_2/VO_2)
RMR	Resting Metabolic Rate
RR	Relative Risk
SCI	Spinal Cord Injury
SR	Stroke Rate (in rowing)
SV	Stroke Volume (of the heart)
TC	Total Cholesterol

TG	Triglycerides
TPR	Total Peripheral Resistance
VCO_2	Carbon Dioxide Exhalation
VE	Ventilation (pulmonary)
VO_2	Oxygen Consumption (see note below)

Conversion of units of measure

- In this thesis energy expenditure is expressed both in $kcal \cdot week^{-1}$ and $kJ \cdot week^{-1}$. Although joule is the official System International unit for energy, many publications used in the literature review have given energy in calories. For clarity, where necessary (kilo-)calories have been converted into (kilo-)joule by multiplying by 4.2.
- In this thesis oxygen consumption is preferably expressed in $mL \cdot kg^{-1} \cdot min^{-1}$ since this controls for body weight, however body weight data is not always available. Therefore $L \cdot min^{-1}$ has also been used.

Chapter 1

Literature review

1. Literature review

The aims of the literature review are to:

Lit 1 Identify threats to the health of persons with chronic SCI and explore similarities with common health problems in the able-bodied population.

Lit 2 Identify from able-bodied studies what levels of physical activity are required to obtain optimal reduction in the risk for common long-term diseases, such as cardiovascular diseases, non-insulin dependant diabetes, obesity and osteoporosis.

Lit 3 Assess the validity of adopting these optimal levels of physical activity to the SCI population.

Lit 4 Explore the compliance to these optimal levels of physical activity in SCI.

Optimal exercise is defined here as an exercise protocol that fulfils the minimum criteria on exercise intensity, exercise volume and type of exercise. The focus will be on motor complete lesions (ASIA A or B) of the thoracic spinal cord.

Abstract

Cardiovascular diseases, non-insulin dependant diabetes mellitus, obesity and osteoporosis are major threats to the quantity and quality of life for persons with chronic SCI. These diseases have been studied extensively in the able-bodied population, which has resulted in effective and efficient prevention programmes. Physical activity plays a key role in the prevention of all these four diseases, however it appears that optimal risk reduction is only achieved when minimum criteria on exercise intensity, exercise volume and exercise type are fulfilled. There is, however, insufficient evidence to establish if these criteria can be transferred to the SCI population. In the absence of such evidence, the author suggests that the recommendations for the able-bodied serve as conservative guidelines to set upper targets for persons with SCI. However the literature suggests that the majority of the SCI population is not able to achieve these targets using traditional exercise modalities available to them. Early work on the feasibility of FES-rowing for SCI suggests that high exercise intensities are achievable, but a definitive statement cannot be made. No data is available on the potential health benefits of high intensity FES-rowing training.

1.1 Spinal Cord Injury

In the twentieth century spinal cord injury (SCI) has changed from a condition that was in most cases fatal within a few weeks to a chronic condition that restricts life expectancy by only a few years (Go et al., 1995, O'Connor, 2005, Samsa et al., 1993). Other medical conditions now threaten the quality and quantity of life of those with SCI. Chronic conditions associated with physical inactivity are one of the main causes of death for the general and the SCI population (Whiteneck et al., 1992, Samsa et al., 1993). In the general population physical exercise is a key element of public health initiatives that aim to reduce the incidence or suffering from the above diseases (American College of Sports Medicine, 1993, National Heart Lung and Blood Institute, 1998). Since the effects of a spinal lesion may alter the exercise response of individuals with SCI (Davis, 1993), it remains to be determined if these recommendations transfer to SCI.

A lesion in the spinal cord results in a number of direct and indirect changes in the physiology and anatomy of the human body. The most obvious ones are paresis or paralysis of muscles below the level of lesion and reduced or absent sensory feedback from the affected body parts (all sensory systems can be affected: pain, pressure, hot, cold, fine touch and proprioception). However, alterations to the autonomic nervous system might have just as far-reaching consequences as the more visible motor and sensory consequences. One can think of changes in hormone secretion, the ability to sweat and restrictions in vasoconstriction and vasodilatation of the blood vessels in the affected body parts. To what extent these motor, sensory and autonomic symptoms have an impact on the functioning of the body of an individual with SCI depends first of all on the extent of the damage and secondly, on the location of the lesion. Complete lesions high in the spinal cord will result in a more extensive range of symptoms than incomplete lesions lower in the spinal column.

The annual incidence of SCI in the United Kingdom is about 10 to 15 per million of the general population (Swain and Grundy, 2002, Gardner and Kluger, 2004). Reports from other countries show a wide range of incidence rates (2.5-57.8 per million per year), which can probably be explained by differences in record keeping and data collection (Burt, 2004). Approximately 50% of the spinal breaks are in the thoracic or lumbar region, leading to paraplegia (Burke et al., 2001). This implies that every year 300-450 persons acquire paraplegia in the United Kingdom. The vast majority of this group are young males since incidence rates of SCI are approximately four times higher in men than in women and 59% of the new patients are 30 years of age or younger at the time of injury (Guttmann, 1976, 2000, Burt, 2004). This age and gender distribution can be explained by studying the causes of injury. The main causes of SCI include road traffic accidents, falls, sporting accidents (diving, rugby) and in certain geographical areas violence (stab or gunshot wounds) (Burt, 2004). On average, young men take more risks in these activities and as a result they suffer more often the consequences. A second peak in incidence rates for SCI is seen in the elderly since this group is at risk for SCI due to falls (Burt, 2004).

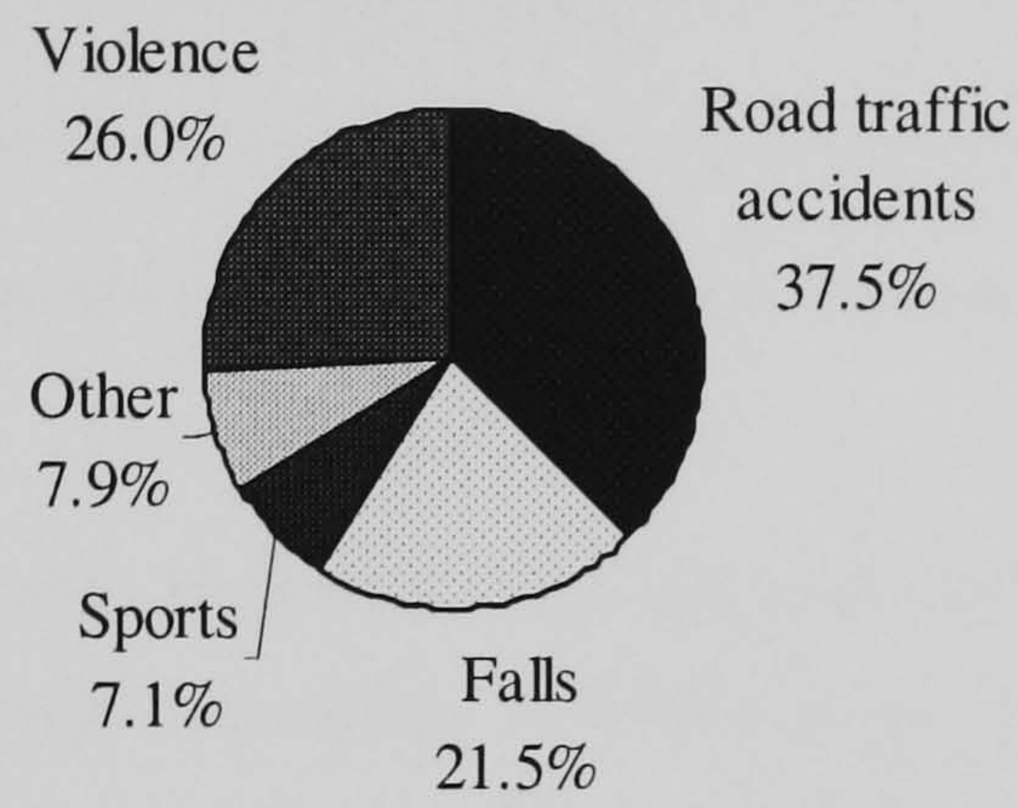

Figure 1.1: Causes of spinal cord injury since 1990 in the United States. Data is from the National Spinal Cord Injury Statistical Centre, which captures approximately 13% of the new SCI cases in the US (National Spinal Cord Injury Statistical Centre, 2000).

Death as a direct consequence of SCI has steadily decreased over the years. The ancient Egyptians described spinal cord injury as "an ailment not to be treated" and that view remained in place until after the World War I where approximately 90% of the soldiers who sustained a SCI died within one year (Hughes, 1988, Swain and Grundy, 2002). Significant changes to the treatment and consequently prognosis of SCI took place after World War II. One of the most important pioneers of that era was Sir Ludwig Guttmann at Stoke Mandeville Hospital in the United Kingdom. Guttmann was a great advocate of active rehabilitation for patients with SCI and in combination with a growing body of knowledge on the pathology of SCI this lead to a much improved outlook for paraplegics and quadriplegics (Samsa et al., 1993, Swain and Grundy, 2002). Table 1.1 shows the death rate of veterans with SCI admitted to Stoke Mandeville Hospital. When this data is corrected for non-SCI related deaths, a considerable decline in death rate due to SCI is visible.

Table 1.1: Death rate in 1963 of ex-military personnel with spinal cord injury admitted to Stoke Mandeville Spinal Unit. Data from Guttmann (1976, p.660).

	Number of deceased veterans in 1963	**Deaths as a consequence of SCI**
World War I veterans (n=67)	39 (58.2%)	15 (22.4%)
World War II veterans (n=468)	125 (26.7%)	103 (22.0%)
Post 1946 veterans (n=218)	16 (7.3%)	14 (6.4%)

Nowadays the life expectancy for persons with long-term SCI is approaching the life expectancy of the general population (Bracken et al., 1990, DeVivo et al., 1990, O'Connor, 2005), especially for those with low or incomplete lesions (Stover and Fine, 1986). Eighty to eighty-five per cent of new SCI patients surviving three months post injury, will also survive at least 10 years post-injury (Kurtzke, 1975). And on average this group lives for an additional 39 years after their injury, which is 85% of the life expectancy of their able-bodied peers of similar age (Samsa et al., 1993). Interestingly, this study by Samsa et al. (1993) on long-term survival after SCI found no differences in survival based on level or completeness of injury

The consequence of this improved long-term survival is that at any one time there are more persons living with SCI. The UK Spinal Injuries Association estimates that there are about 40,000 persons with a SCI living in the United Kingdom (Spinal Injuries Association, 2006). Integration of this large group of persons with spinal injuries back into society is on the forefront of many governmental and non-governmental initiatives. In the United Kingdom the Disability Discrimination Act has given the disabled community the right to be treated similar to the able-bodied population. This is not only for the benefit of individuals with SCI, but also for society since SCI no longer restricts people from taking up their responsibilities as a member of society. And to take up this role it is essential for persons with SCI to be in an optimal physical and mental condition (Noreau and Shephard, 1995).

Before this optimal physical and mental condition can be achieved, it is crucial to fully understand the impact of a spinal lesion on the functioning of a body. The following sections will go into more detail, but due to wide variation in level and extent of spinal lesions and the consequences of these lesions, this section will focus on paraplegia, in particular, those with spastic paraplegia (level of lesion between T1 and T12/L1). The reason for this is that FES-rowing, the central focus of this thesis, is in particular suitable for individuals with spastic paralysis and reasonable control of the upper extremities.

1.1.1 Motor and sensory dysfunction in paraplegia

Lesions in the thoracic area of the spinal cord result in impaired motor and sensory function of the lower extremities and the trunk. The extent of this dysfunction depends on the level of lesion, however, in all complete lesions between T1 and T12-L1, muscles groups around the hip, knee and ankle are completely paralysed. The main difference between an individual with a T1 lesion and an individual with a T12 lesion is the extent to which they are able to stabilise their trunk and assist their breathing with muscles in the thorax. The intercostal muscles play an important role in particularly heavy breathing and are innervated at T1-T12. Other muscles in the trunk important for breathing and/or postural balance are rectus abdominis, transversus abdominis, obliquus internus abdominis, obliquus externus abdominis, erector spinae and latissimus dorsae. Except the latissimus dorsae and the upper part of the erector spinae, all these muscles are innervated between T1 and T12 and thus will determine the level of motor function in persons with thoracic SCI. The higher thoracic lesions will have more difficulties with balance and will rely more on diaphragm breathing than persons with lower thoracic lesions.

Sensory nerves exiting the spinal cord between T1 and T12 innervate the skin region ranging from roughly the pelvis to the armpits. A thoracic complete lesion results in complete absence of any sensation in the lower extremities and to some extent the trunk. Some of these affected sensory systems could have far-reaching consequences, for example the inability to feel pressure increases the risk for pressure sores. Persons with intact sensory feedback would change their position if they feel that they have been sitting to long in one position, however a person with a complete SCI does not have this input and thus has to make a conscious decision to change their position regularly. Another sensory system that able-bodied persons mostly only use at a subconscious level is proprioception; the ability to know in what position your body is with your eyes closed. Golgi tendon organs and muscle spindles perceive the amount of stretch and tension in skeletal muscles and tendons and this information is crucial for postural balance and movement. Individuals with complete lesions have to rely on eyesight to receive information on the position of their paralysed body parts.

1.1.2 Autonomic dysfunction in paraplegia

The effect of a lesion in the spinal cord on motor and sensory function is localised, but the impact on the autonomic nervous system will in most cases have an effect on the body as a whole. This is of particular interest for this thesis as the exercise response in SCI could be very different from able-bodied due to differences in autonomic control.

Complete lesions in the thoracic spinal cord lead to impaired vasoconstriction, vasodilatation and sweating in the lower extremities and to some extent in the trunk (depending on level of lesion). The two main consequences of this are an impaired body temperature regulation system and an impaired blood circulation control system (Price and Campbell, 2003, Dawson et al., 1994, Theisen et al., 2001).

An important element of body temperature regulation is changing the amount of blood in the skin, where the blood can radiate energy to the environment. Persons with paraplegia are not able to do this in their lower body parts, neither are they able to vasoconstrict their superficial blood vessels to prevent heat loss in cold circumstances. Consequently, it is much harder for persons with SCI to cope with heat stress during exercise.

A second consequence of the impaired control over the diameter of blood vessels and the absence of motor control in the lower extremities is that blood can pool in the legs. The heart pumps blood to all extremities, but the return of this blood from the extremities to the heart is supported by contracting skeletal muscles. This is especially important in the legs as the gravitational force makes it harder for blood to return to the heart. The absence of this muscle pump and the inability to reduce the diameter of the blood vessels in the lower extremities results in blood pooling in the lower body. This leads to a decreased preload of the heart and consequently stroke volume of the heart is limited (as described in the Frank-Starling law of the heart) (Starling and Vischer, 1927). During exercise there is a need for more oxygen supply to the active muscle tissue and this is primarily achieved by increasing cardiac output of the heart. Cardiac output is determined by stroke volume and heart rate (CO=SV x HR). The increase in cardiac output in SCI is limited due to the restriction in stroke volume and subsequently the exercise response is limited (Hopman et al., 1992, Dela et al., 2003).

The inability to regulate blood vessel diameter has another, in some cases very dangerous, consequence. A noxious stimulus to the paralysed body parts (e.g. a cut, a full bladder, an electrical impulse, a wound, etc) can initiate a local response whereby arteries in the periphery constrict. This (excessive) vasoconstriction leads to an increase in peripheral resistance in the blood circulation. Blood pressure is determined by the cardiac output and total peripheral resistance (BP= CO x TPR). Blood pressure will rise due to the increased peripheral resistance and this is detected by the baroreceptors in the arteries of the neck. When the blood pressure rises outside the normal range, the brain will send a signal to the heart to decrease heart rate and send a signal to the periphery to reduce total peripheral resistance by decreasing vasoconstriction. This ensures that in normal circumstances blood pressure is brought back to the normal range. However in SCI, the signal to the periphery is blocked and vasoconstriction or vasodilatation cannot be controlled by the higher centres. Although the heart rate will decrease to reduce blood pressure, in some cases this might not be enough. Especially in persons with a lesion above the sixth vertebrae the dysregulation in blood pressure control could be to a degree that severe peripheral vasoconstriction cannot be compensated for. This is called autonomic dysreflexia (AD) and in some cases can lead to a very high blood pressure (>200 mm Hg) combined with a very low heart rate. Patients with a severe AD response should immediately receive adequate medical treatment since high blood pressure increases the risk for spontaneous bleedings (e.g. stroke). Since electrical stimulation could be a noxious stimulus able to trigger an AD response, blood pressure and heart rate should always be closely monitored in the first few FES sessions, especially in persons with high thoracic or cervical lesions.

1.2 The impact of spinal cord injury on health

In the previous section the motor, sensory and autonomic consequences of SCI have been discussed. The central theme of the following section is the impact of these consequences on health in SCI.

The World Health Organisation has defined health as: 'A state of complete physical, mental and social well-being and not merely the absence of disease or infirmity.' This thesis will mainly focus on the prevention of secondary complications after SCI and its effects on physical well-being. However there is no doubt that mental and social well-being are also positively affected by preventing secondary complications and optimising physical well-being (Rimmer, 1999).

In the past, urinary tract infections and pressure sores were a major concern to individuals with SCI. However nowadays, due to improved medical care, these conditions are in most cases no longer life threatening (Imai et al., 1996, Middleton et al., 2004, McColl et al., 2004). A more serious threat to the health of individuals with SCI, especially those with chronic SCI, comes from obesity related diseases and conditions such as cardiovascular diseases (CVD) and non-insulin dependant diabetes mellitus (NIDDM). Survival after SCI has greatly improved over the past century and this has resulted in an aging SCI population. In this group death due to CVD is the number one killer, while death due to infectious diseases has decreased over the past decades (Whiteneck et al., 1992). Samsa and colleagues published in 1993 a detailed report on the long-term survival of 5,545 American veterans with SCI. In total 2,342 veterans died in this period. Cause of death and the number of years these subjects had lived with their spinal cord injury were collected from their medical records. The number one cause of death for persons who had lived for more than 10 years with a SCI was diseases of the circulatory system (which is the term used in the International Classification of Diseases), responsible for 18.8%-32.0% of all deaths (see Figure 1.2). In deceased veterans with shorter time since injury (3 months- 5 years), death due to diseases of the circulatory system was the third most common killer (14.0%). Numbers one and two were poisoning and death due to external conditions, 22.6% and 18.3% respectively. In the group who passed away 6-10 years post-injury, the number one cause of death was injury and poisoning (15.8%), followed by diseases of the circulatory system (14.4%). Death as a consequence of diseases of the genitourinary system (ICD 580-629) was higher in the SCI group than a non-disabled control group, but only represented a small proportion of the total deaths in the SCI group (4.3%-9.4%, the 5th-8th most common cause of death).

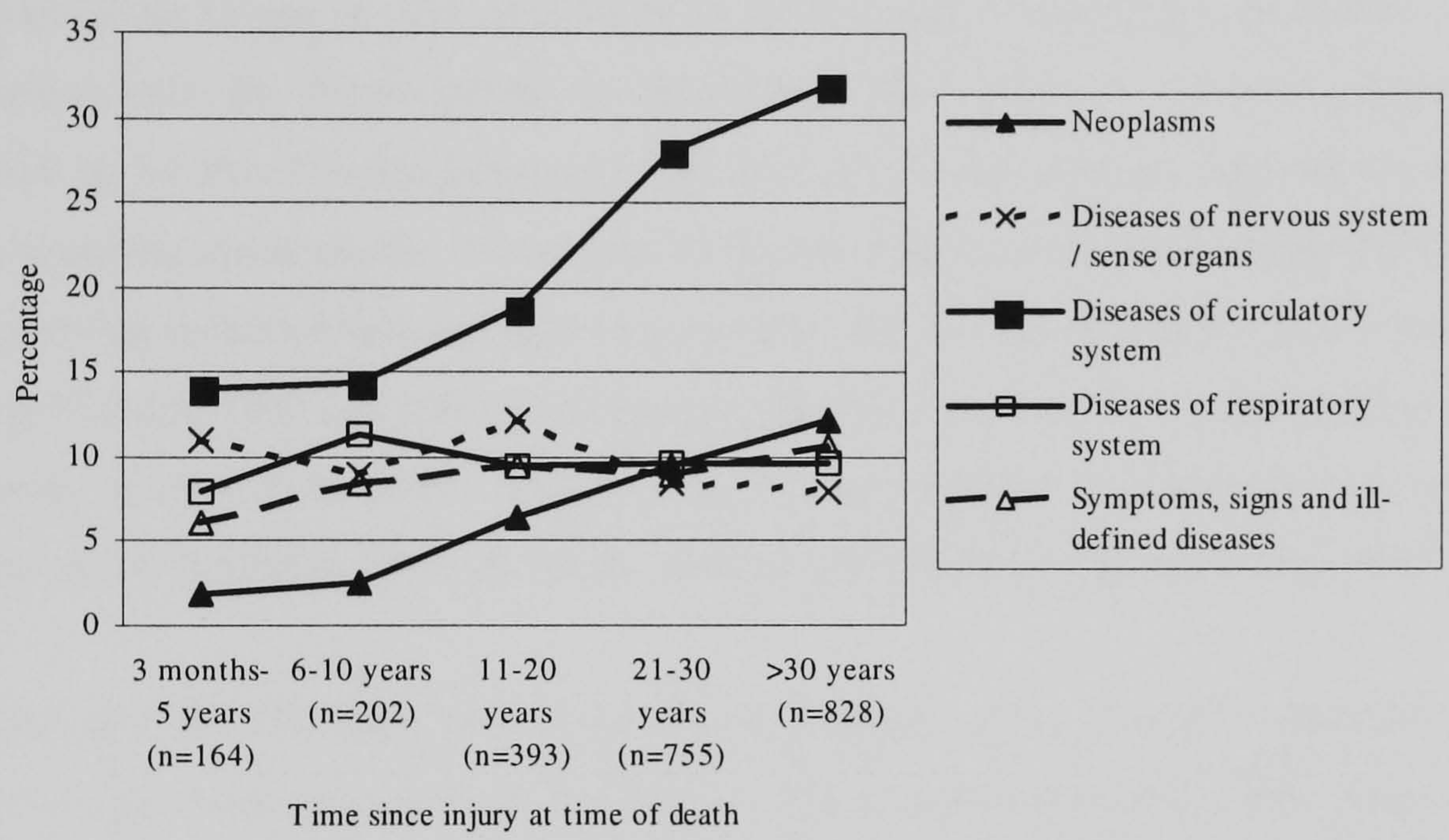

Figure 1.2: Causes of death in 2342 veterans with SCI. Only the five most common causes of death at >30 years post injury are displayed and their course over time. Data derived from Samsa et al. (1993).

This study by Samsa et al. (1993) is the only large study investigating long-term survival of persons with SCI. Although the characteristics of this sample might limit generalisation (89% were white, average age at injury was 23 years, 90% were injured before 30 years of age), it nevertheless gives a good indication of the prognosis of SCI and shows the increasingly aging SCI population. The data shows that cardiovascular diseases are a major threat to the lives of persons with SCI. It also appears that the fact that these persons are paralysed puts them at a higher risk for CVD, since they die of the same causes as their able-bodied counterparts, but at a younger age.

Other diseases common in SCI are not so much reflected in the causes of death, but these conditions can still have a significant impact on the quality of life in SCI.

One of these diseases is non-insulin dependant diabetes mellitus mellitus or non-insulin dependant diabetes mellitus (NIDDM). NIDDM is a metabolic disorder characterised by impaired insulin sensitivity and glucose tolerance. Blood insulin levels can be normal, elevated or reduced but tissue (mainly muscle and adipose tissue) is no longer or less responsive to insulin and consequently the uptake of glucose from the blood stream is diminished. This results in elevated glucose levels in the blood (hyperglycemia). The beta cells in the pancreas respond to this by secreting more insulin, however even higher insulin levels are not effective in improving insulin dependant glucose transport into the muscles cells. In the long term the beta cells can become exhausted and insulin secretion decreases (this is similar to type 1 diabetes mellitus, whereby the principle malfunction is in the beta cells) (Albright, 1997, Bauman and Spungen, 2000, Guyton and Hall, 1996).

Although NIDDM does have a genetic component, environmental factors play also a significant role (Malecki and Klupa, 2005, Guyton and Hall, 1996). One of the main contributors to NIDDM is obesity; 80% of the able-bodied persons with NIDDM were obese at the onset of NIDDM, although the mechanisms responsible for this are still poorly understood. Another risk factor for NIDDM is low levels of physical activity. Large cross-sectional studies have shown that NIDDM is less common in physically active persons (Mayer-Davis et al., 1998). This epidemiological data is supported by multiple intervention studies that found that exercise interventions are an important element of NIDDM management and a causal relation between physical inactivity and NIDDM is plausible, as suggested by Goodpaster and Kelly in their comprehensive review (Goodpaster and Kelley, 2001).

A second medical condition common in SCI is obesity. Obesity is defined as a body mass index (BMI = bodyweight / length^2) of greater than 30 $kg \cdot m^{-2}$. Prevalence of obesity in the general population varies widely worldwide, but incidence rates as high as 22% to 30% have been reported (Jakicic et al., 2001, Jakicic and Otto, 2005). Estimates of obesity in SCI based on BMI might underestimate the real problem since it has been suggested that anthropometric measures in SCI does not accurately reflect body fat mass (Jones et al., 1998). The BMI does not take into account differences in fat mass and fat free mass and therefore this method might be flawed. A more reliable method is determination of body fat percentage, which can be measured using underwater weighting, Dual Energy X-ray Absorptiometry (DEXA) or the tritiated water method. A healthy body fat percentage for men is around 15% and 23% for women. Percentages above 25% and 32% respectively, are defined as obese. George et al. (1988) found that sedentary SCI men have an average body fat percentage of 24.5%, while weight matched able-bodied controls had only 17% body fat. It has also been shown that body fat percentage increased with lesion height. Nuhlicek et al. (1988) measured body composition with tritiated water in high quadriplegics (above C6), low quadriplegics (C6-T2) and high paraplegics (T2-T10) and found 35.3%, 35.7% and 30.1% respectively.

On a positive note, exercise seems to be able to improve body composition in SCI. Ide et al. (1994) found in 2677 wheelchair marathon racers that body fat percentages ranged from 17.6% to 18.7%. It should be noted however that this study group also included persons with disabilities other than SCI and that body composition was measured with the skinfold method, which is less reliable than DEXA or hydrodensitrometry. Bulbulian et al. (1987) studied body composition by hydrodensitrometry in 22 paraplegic athletes and found an average body fat percentage of 22.4%.

The reason for the elevated levels of obesity in SCI might lie in the fact that, on average, persons with SCI lead a more sedentary lifestyle than able-bodied. Daily energy expenditure is lower in SCI, most likely as a consequence of the reduced amount of body mass that contributes to energy expenditure (Monroe et al., 1998, Sedlock and Laventure, 1990). Also, participation in sport and exercise programmes is lower in SCI than in able-bodied (Dearwater et al., 1986).

It is not surprising that obesity, cardiovascular diseases and non-insulin dependant diabetes mellitus are more common in SCI, since these three conditions are closely linked. Bauman and colleagues have done extensive research into the metabolic changes seen in chronic SCI (Bauman and Spungen, 2001, Bauman et al., 1999b). They described this process as follows: "SCI leads inherently to inactivity and changes in body composition (decrease in muscle mass and increase in fat mass). In many this is associated with a state of insulin resistance, high levels of insulin in the blood and glucose intolerance. The elevated insulin levels contribute to dyslipidaemia and hypertension, which are risk factors for CHD. In addition depressed levels of growth hormone and testosterone are seen in SCI and these changes adversely affect body composition, lipid profile and exercise response." Bauman concluded that adequate treatment of these abnormalities is an important step towards improving quality and quantity of life in SCI.

One other threat to the health of SCI individuals, which is not directly associated with the above discussed conditions, is osteoporosis. Long term immobilisation of a limb results in a rapid loss in bone mineral content of the trabecular bones (Uebelhart et al., 1995). In paraplegia and tetraplegia this can be very pronounced in the lower limbs. Shortly after acquiring a SCI, calcium absorption increases and bone is lost throughout the body, although later on this mainly affects the paralysed body parts (Claus-Walker and Halstead, 1982). Two to five years post injury calcium levels reach a new equilibrium, although lower than before the paralysis (Biering-Sorensen et al., 1988). This loss in bone mineral content is present in almost all individuals with SCI; Claus-Walker et al. reported that 100% of the individuals with SCI have mild to moderate osteoporosis in the bones below the level of injury (Claus-Walker and Halstead, 1982). Biering-Sorensen et al. (1988) reported that SCI men have a 25% and 50% bone mineral deficit in the femoral neck and shaft respectively. This reduced BMD increases the risk for fractures as a result of minor traumas (e.g. a fall, stress fractures) and the periods of casting after a fracture gives the individual an even more restricted mobility.

To summarize; there are four major health threats to the quality and quantity of life in SCI:

- Cardiovascular diseases
- Non-insulin dependant diabetes mellitus
- Obesity
- Osteoporosis

The first three are also common in the general population, while osteoporosis is more a problem in the elderly and certain patient populations. However, physical activity or an active life style can, to a more or lesser degree, play a role in the prevention and treatment of all four, as will be discussed in the following section.

1.3 Physical activity and health in able-bodied

Exercising for health and fitness is nothing new, records from the ancient Greeks and even ancient China (circa 2500 B.C.) indicate that at that time physical exercise was already seen as an important element of treating diseases (Lee and Paffenbarger, 2001, Berryman, 1989). Modern evidence-based medicine has resulted in a better understanding of the relationship between physical exercise and the body of evidence supporting the vital role of exercise in a healthy life style has seen continuous growth. The twentieth century saw a number of very large epidemiological studies on exercise habits and health, such as the bus drivers and conductors study by Morris and co-workers, the Harvard Alumni Study and the Health Professionals Follow-up Study (Morris et al., 1953b, Morris et al., 1953a, Paffenbarger et al., 1978, Tanasescu et al., 2002). These studies in combination with numerous smaller intervention studies have proven that physical activity is an important element of a healthy life style. In the following sections epidemiological data will be presented that supports this statement and where feasible, recommended exercise intensities and volumes for optimal health benefits will be presented.

1.3.1 Cardiovascular diseases

Cardiovascular diseases are characterised by an impairment in the blood supply to a certain tissue or organ. A blockage can have serious consequences when vital organs are affected such as the heart (coronary heart diseases, CHD) or the brain (stroke). The most common cause of a blockage is the build up of plaque on the inner wall of the artery. This process is called atherosclerosis. Under normal circumstances the blood supply might still be sufficient for the patient not to have any symptoms, but under (exercise) stress blood supply might be limited due to the narrower arteries. This is noticed by the patient as pain in the chest (angina pectoris), sometimes radiating to the shoulders and arms and in the worst case scenario low oxygenation of heart tissue leads to cardiac arrest and permanently damaged heart tissue or death. The Department of Health (UK) reports that each year 1.4 million people in the UK experience angina and 275,000 have a heart attack. More than 110,000 persons die every year of CHD and this makes CHD the number one killer in the UK. Many of these deaths can be prevented with appropriate interventions like raising levels of physical activity in the population.

One of the earliest epidemiological studies in this area comes from Morris and co-workers in London (Morris et al., 1953a, Morris et al., 1953b). They found a remarkable difference in the incidence of heart diseases in bus drivers and bus conductors and explained this by differences in activity pattern. The bus drivers, who spend their working day sitting behind the wheel, had a much higher risk for CHD than their colleagues at the back of the bus who were walking around most of the day. A second study of this research team was conducted in British civil servants (who all had a similar activity pattern at work) and aimed at mapping the benefits of physical activity during leisure time (Chave et al., 1978, Morris et al., 1990, Morris et al., 1980). 9,376 men were asked to fill in a detailed questionnaire on their leisure time activities. On average this group was followed for 9.3 years and in that period 474 men developed coronary heart disease (CHD). The reported activities were divided into vigorous sport ($\geq$7.5 kcal$\cdot$min^{-1} or $\geq$6 times the resting metabolic rate (MET)) and non vigorous (<7.5 kcal$\cdot$min^{-1} or <6 MET). All analyses were controlled for smoking, body mass index and personal and family medical history. Frequency of participating in vigorous sport was significantly correlated with a decrease in relative risk (RR) for CHD, while no such correlation was found for participation in non-vigorous exercise (Table 1.2).

Another important finding of the study by Morris and co-workers was that only current participation in vigorous sport was associated with a lower RR for CHD. Individuals with a history of regular participation in vigorous sports, but who were no longer involved in these activities, had similar RR for CHD as the group who never participated in vigorous sport (see Table 1.3). This study by Morris was one of the very few studies that addressed type, intensity and frequency of physical activity in relation to CHD.

Table 1.2: Relative risk for Coronary Heart Disease for different exercise patterns. Data from Chave et al., 1978, Morris et al., 1990, Morris et al., 1980

Physical activity (sessions per 4 weeks)	Number of CHD events	Incidence Rate (per 1,000)	Relative Risk
Vigorous sport			
None	413	5.8	1.00
1-3	37	4.5	0.78
4-7	17	4.1	0.71
≥8	7	2.1	0.36
			$p<0.005$ for trend in RR
Non-vigorous sport			
None	310	5.4	1.00
1-3	85	5.9	1.09
4-7	52	5.9	1.09
8-11	19	3.5	0.65
≥12	8	6.8	1.26
			$p>0.05$ for trend in RR

Table 1.3: Incidence rate for Coronary Heart Disease for sport participation during various periods in life. Data from Chave et al., 1978, Morris et al., 1990, Morris et al., 1980.

When did you participate in vigorous activity?	Incidence rate for CHD (per 1,000 persons)
Never	5.9
Before 25 years of age	5.1
Before 30 years of age	5.1
Before 40 years of age	6.5
Till after 40 years of age but not at the present	5.2
Still participating in vigorous sport (at least eight times in previous 4 weeks)	2.1

A second large epidemiological study by Paffenbarger and colleagues followed a large cohort of Harvard University alumni who graduated between 1916 and 1950 (Paffenbarger et al., 1986, Paffenbarger et al., 1993b, Paffenbarger et al., 1978). Information on physical activity patterns in the subjects (n=16,936) was collected using questionnaires. For all activities an average intensity was determined (in $kcal{\cdot}min^{-1}$), which allowed the researchers to estimate the average weekly energy expenditure. This weekly energy expenditure was linked to the incidence rate of a first heart attack. During the follow-up period 1962 or 1966 to 1972, 572 participants were diagnosed with a first heart attack. When the analyses were controlled for smoking, blood pressure, fat mass and parental mortality, they found that those expending less than 2,000 kcal·week^{-1} (≈8,400 kJ·week^{-1}) had a significantly higher relative risk for heart attack than those expending more than 2,000 kcal·week^{-1}, who were used as a reference group (RR: 1.64 and 1.00 respectively, incidence rate: 57.9 and 35.3 respectively). In addition, the results from the Harvard Alumni Study also showed the importance of present participation in physical activity. Those who were active at start of study but not at the present had an incidence rate for CHD of 92.7 per 10,000 person years, while those who were active at the present, but not at start of study had a much lower incidence rate of 33.3 per 10,000 persons years.

To explore the value of energy expenditure from vigorous and non-vigorous physical activity, the researchers analysed a group of 17,321 of the Harvard alumni in more detail (Lee and Paffenbarger, 1997, Lee et al., 1995). In this report, energy expenditure from vigorous (≥6 metabolic equivalent tasks, MET) and non vigorous (<6 MET) was separately linked with the RR for CHD. In total 465 men died from a heart attack in the follow-up period 1962 or 1966 to 1988. The results showed a statistically significant trend ($p=0.02$) of a reduction in RR when more energy was expended during vigorous physical activity (see Figure 1.3). No such trend was visible in energy expenditure from non-vigorous physical activity (see Figure 1.4). This data was again controlled for age, smoking, hypertension, diabetes mellitus, body mass index and early parental death. Diet could have been a confounder although a subset of the cohort provided dietary information in 1988 and this revealed that there were no statistical differences between the groups in fat consumption or saturated fat consumption. This, however, assumes that diet in 1988 was a good indicator of diet earlier in life.

The Harvard Alumni Study shows that a certain exercise volume (>2,000 kcal·week^{-1}) and exercise intensity (≥6 MET) need to be reached for significant reduction in CHD. Moreover, exercise volume derived from vigorous exercise (≥6 MET) is more important than exercise volume derived from non-vigorous exercise (<6 MET).

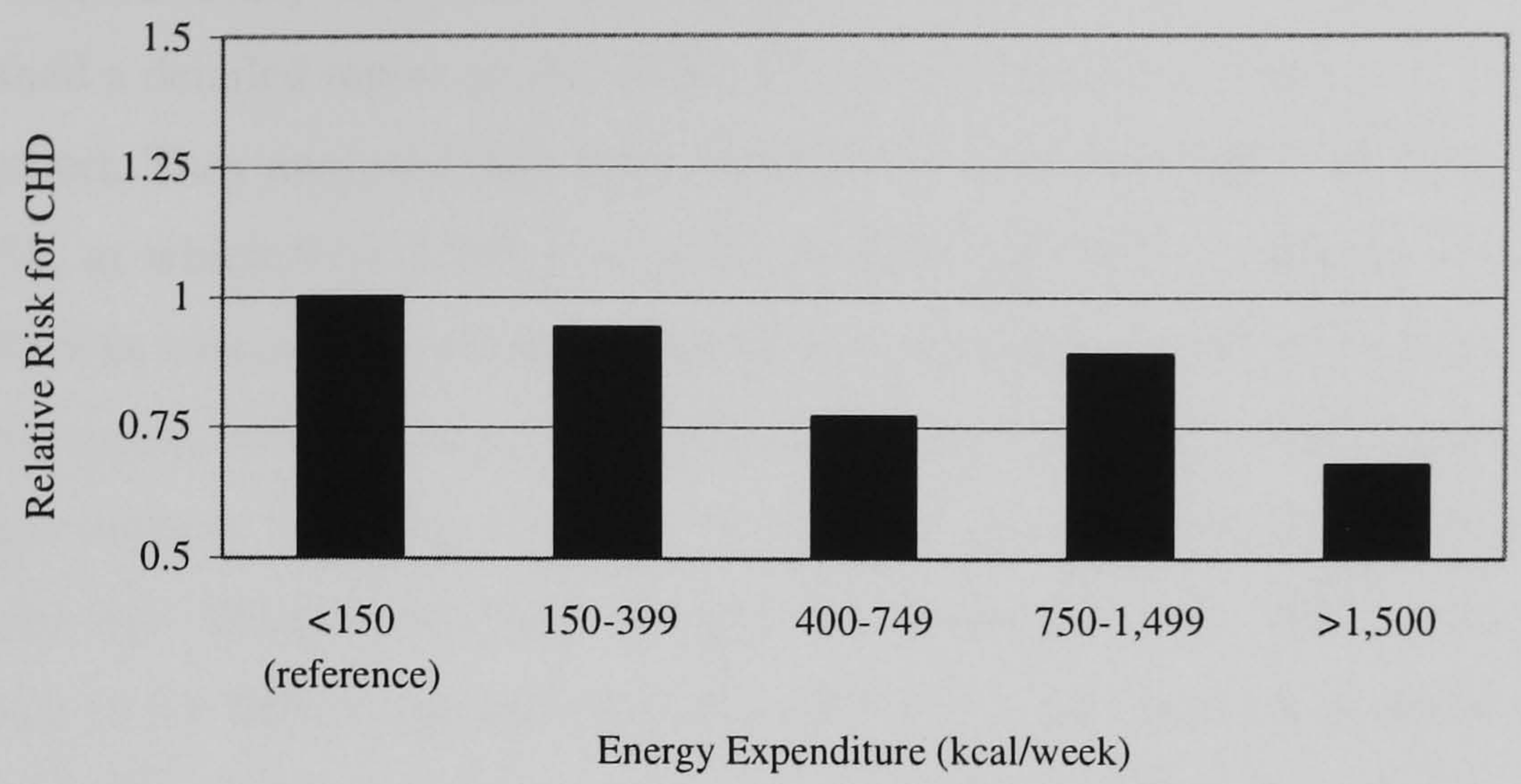

Figure 1.3: The effect of energy expenditure from vigorous exercise (≥6 MET) on relative risk for coronary heart diseases. The decrease in RR with increasing energy expenditure is statistically significant (p=0.02). Data is derived from the Harvard Alumni Study (Lee et al., 1995, Lee and Paffenbarger, 1997).

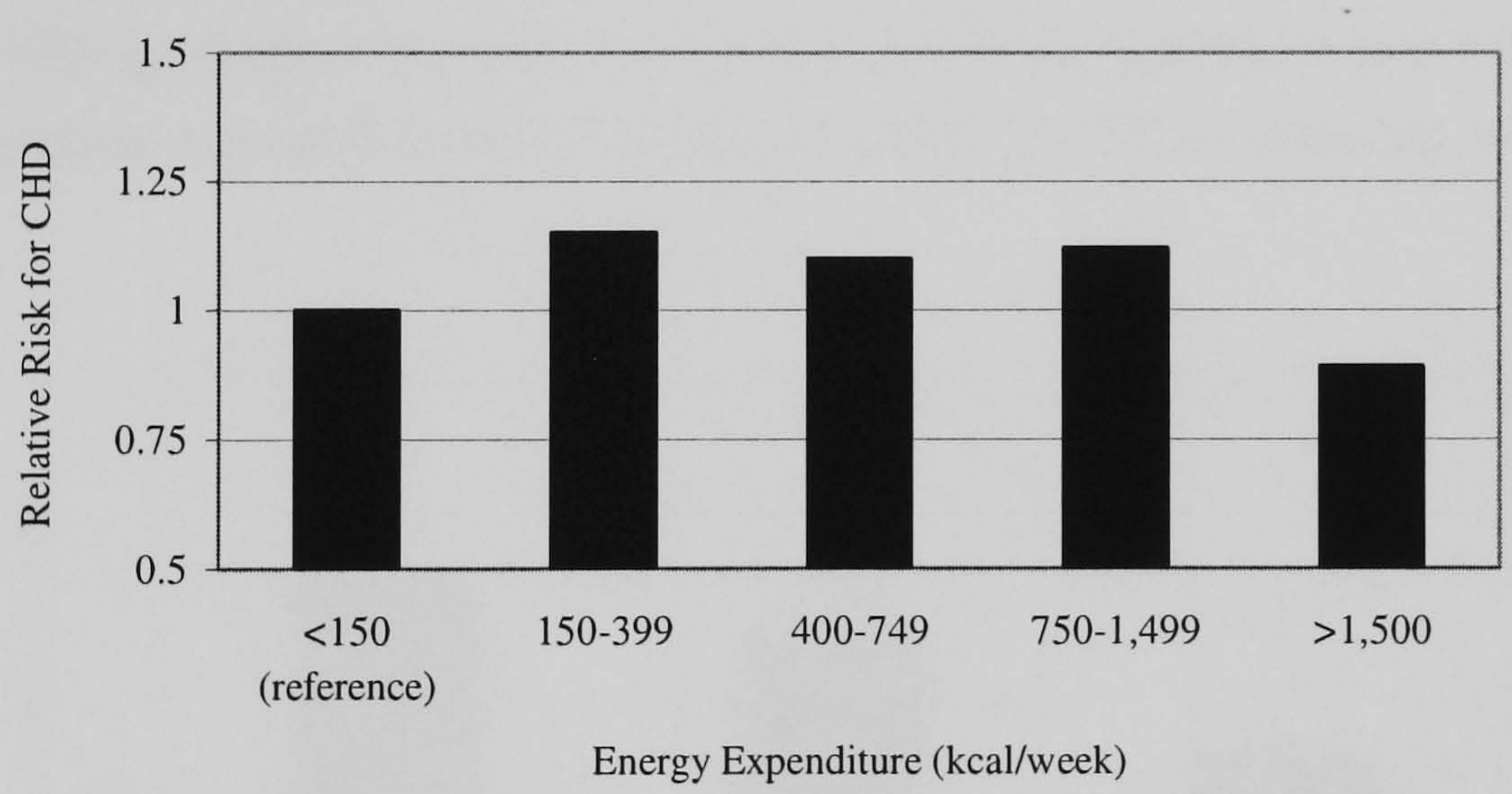

Figure 1.4: The effect of energy expenditure from non-vigorous exercise (<6 MET) on relative risk for coronary heart diseases. Data is derived from the Harvard Alumni Study (Lee et al., 1995, Lee and Paffenbarger, 1997).

A third large longitudinal study to be discussed in this section on CHD is the Health Professionals Follow-up Study (Tanasescu et al., 2002). This study started in 1986 when 55,529 health professionals in the United States completed detailed questionnaires on diet, lifestyle and medical background. The same questionnaires were sent out every two years in the period 1988-1998. Tanasescu et al. (2002) published a detailed report on the effect of exercise type and intensity on CHD in this cohort. They analysed data from 44,452 men who were followed from 1986 to 1998, at which time 1,700 new cases of CHD had been diagnosed. Physical activity was assessed by asking the subjects how much time they had spent on various sports and activities. All activities were assigned a MET score and average exercise intensity for each participant could be calculated. Exercise intensity was divided into three groups: low intensity (1-3.9 MET), moderate intensity (4-5.9 MET) and high intensity (≥6 MET). All data was controlled for alcohol consumption, smoking, family history of myocardial infarction, nutrient intake, presence of diabetes, high cholesterol and hypertension at baseline and exercise volume. The group with the lowest average exercise intensity (<4 MET) was used as the reference group. RR for CHD in the moderate intensity group (4-6 MET) was not statistically different from the low intensity group (0.94 95% confidence interval: 0.83-1.04). Only the high intensity group had a significantly lower RR for CHD (0.83, 95% CI: 0.74-0.97) than the reference group (see Figure 1.5). This again shows the importance of exercise intensities higher than 6 MET and confirms the earlier work by Morris et al. (1953a, 1953b) as discussed earlier.

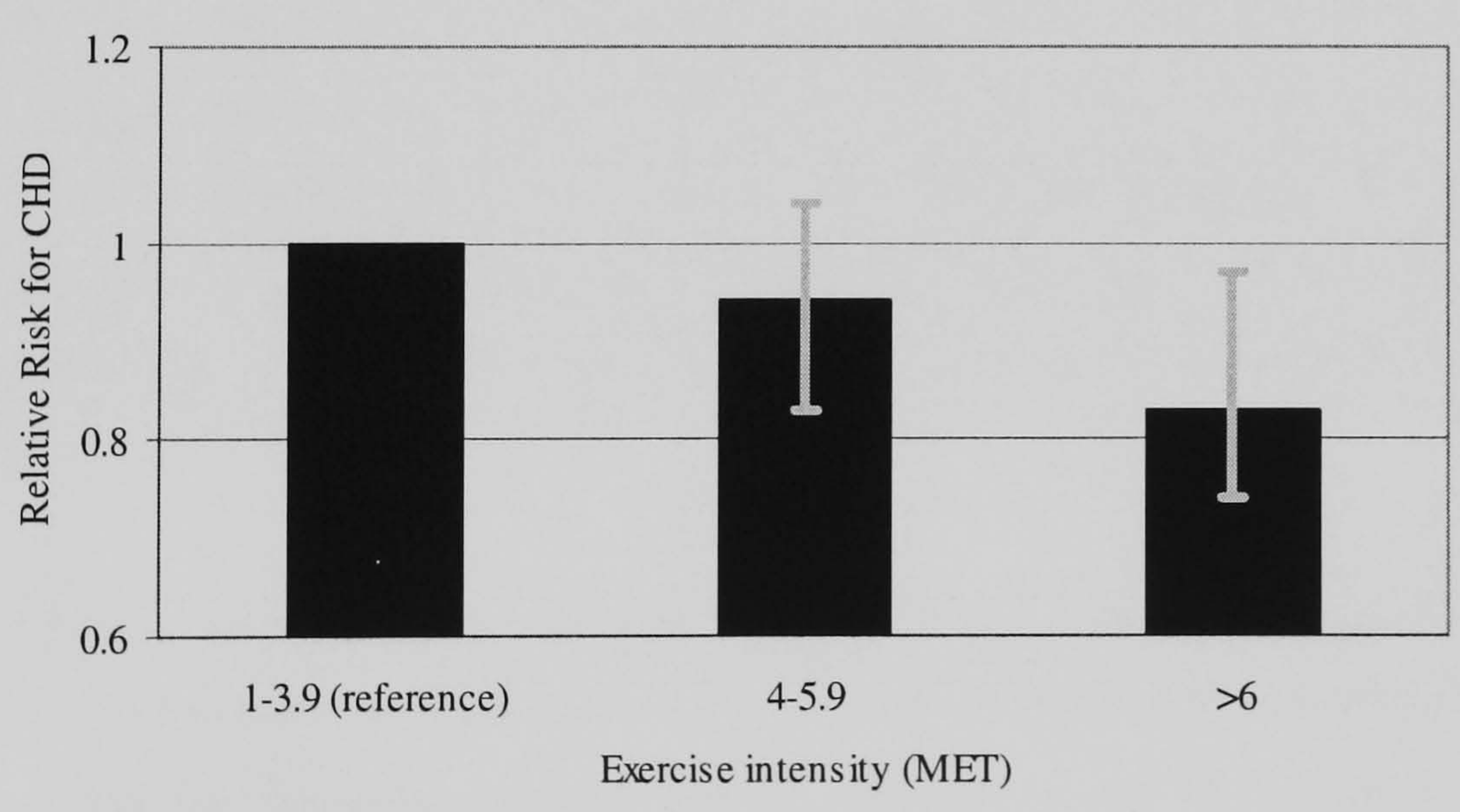

Figure 1.5: The effect of exercise intensity on Relative Risk for Coronary Heart Disease as reported by Tanasescu et al. (2002). The group with an exercise intensity of 1-3.9 MET has been defined as the reference group. Grey lines indicate 95% confidence intervals.

Exercise volume in the Health Professionals Study was measured in weekly MET-hours (exercise intensity of the activity multiplied by time spent on that activity). Controlling for the same variable as mentioned above, it appears that only a minimal exercise volume of 25 MET-hours leads to a significant reduction in RR for CHD (see Table 1.4). 1 MET-hour is the equivalent of exercising at 1 MET for one hour, 1 MET is 1.25 kcal·min^{-1}, i.e. 25 MET-hour= 25*60*1.25= 1,875 kcal·week^{-1}. This benefit of exercise volume identified in this study was independent of exercise intensity and confirms the conclusion from the Harvard Alumni Study.

Table 1.4: Exercise volume quintiles and relative risk for Coronary Heart Disease. Data derived from Health Professionals Study (Tanasescu et al., 2002).

Exercise volume (MET-hours)	**Relative Risk for CHD (95% CI)**
0 - 6.32	1.00 (Referent)
6.33 - 14.49	0.90 (0.78 - 1.04)
14.50 - 25.08	0.88 (0.76 - 1.01)
25.09 - 41.98	0.84 (0.72 - 0.98)
≥ 41.99	0.72 (0.61 - 0.85)

Finally, the analysis on the effect of exercise type on RR for CHD showed that only running, weight training and rowing (all for at least one hour per week) resulted in significant reductions in RR for CHD. Participating in cycling, jogging, swimming and racquet sports for at least one hour per week did not result in significantly lower RR compared to those who never participated in these sports.

In summary, there is a large amount of epidemiological data available showing that reductions in RR for CHD are associated with physical activity, but only if:

- Exercise intensity exceeds 6 MET (Morris et al., 1953a, Morris and Heady, 1953, Tanasescu et al., 2002, Lee et al., 1995).
- Exercise volume exceeds 1,875-2,000 kcal·week^{-1} (≈7,875-8,400 kJ·week^{-1})(Tanasescu et al., 2002, Paffenbarger et al., 1986).

In addition it appears that the more time is spent on exercising at high intensity ($\geq$6 MET), the more reduction in risk for CHD can be expected (Tanasescu et al., 2002, Lee et al., 1995) and it is important to stay active throughout life (Morris et al., 1990, Paffenbarger et al., 1993b).

However, the above studies have limitations that could have influenced the conclusion. First of all, selection bias could have played a role. All of the above studies include only a sub-group of the general population and it is debatable if bus drivers, Harvard alumni or those working in the health care sector are a good representation of the general population. Secondly and perhaps even more important, it is assumed that at baseline all included subjects had similar options to become physically active and their choice to do so or not, had a direct impact on their health. However, the above studies fail to distinguish healthy people becoming active from active people becoming healthy. This inability to distinguish cause and consequence is a significant limitation of epidemiological studies.

Thirdly, all described studies use questionnaires to assess physical activity patterns. This method relies on the ability of the subjects to recollect and assess their physical activity patterns. The authors of the Harvard Alumni Study assessed the validity and reliability of physical activity questionnaires. They found that although the correlation between the questionnaire and an external criterion for aerobic power was only moderate (r=0.52) (Paffenbarger et al., 1993a), it is comparable to other commonly used questionnaires such as the questionnaire by Godin and Shephard (1985).

A second source of bias associated with questionnaires might be introduced when coding the responses of the subjects into standard activities and intensities. For example the Health Professionals Follow-up Study asks the subjects how much time they have spent on various sports and activities. All sports and activities are assigned a certain MET-score as an indicator of intensity after which the exercise profile of the subjects can be compiled. This assumes that all subjects writing down three hours of playing tennis per week, play tennis at the same intensity. Although this assumption might not be true for individual cases, as the sample size increases it is less likely that these analyses are systematically under- or overestimated. However, in other cases unreliable estimates might have affected the conclusions. Bassett et al. (1997) and Shephard (1999) suggested that the energy expenditure given to stair climbing in the Harvard Alumni Study might have been too high and consequently the average energy expenditure and exercise intensity might have been over-estimated. Moreover, Shephard (1999) noted that the most commonly reported sports in the Harvard Alumni Study (tennis, golf and swimming) are seasonal pursuits in many parts of the Unites States. Consequently the subjects might have over-reported the frequency and duration of their sports involvement.

In the calculation of average energy expenditure it is important to distinguish net energy expenditure from gross energy expenditure. The gross value includes the resting metabolic rate, i.e. the energy needed to keep your body alive. This is not always clear from the studies as shown by Shephard (1999). The recommendation from the Harvard Alumni Study to expend at least 2,000 $kcal \cdot week^{-1}$ (during the exercise periods) was the gross energy expenditure.

A fourth limitation is drop-out of subjects. Although the studies have attempted to follow up all subjects included in the baseline measures, a considerable amount would have had to drop out for various reasons. It would be of interest to analyse the characteristics of these drop-outs and to determine if they were significantly different in baseline characteristics from those who completed the full study.

Bearing these limitations in mind, it is remarkable that the described studies all come to similar conclusions on the benefits of physical activity. Nevertheless large randomised controlled trials (RCTs) are essential in studying the possible causal relationship between physical activity and health. It is however in this instance questionable if such a design is ethical or affordable (Lee and Paffenbarger, 2001). For this reason RCTs in this area have focussed on individual risk factors for CVD, such as lipid profile, body composition and insulin sensitivity.

As reviewed by Lee and Paffenbarger (2001), a number of important risk factors for CVD are positively influenced by physical activity, such as:

- Physical activity increases oxygenation of the heart, improves myocardial contraction and electrical stability of the heart (Lee and Paffenbarger, 1997).
- Physical activity results in a lower sympathetic tone, heart rate and blood pressure at rest (Hagberg and Brown, 1995, Dunn et al., 1999, Andersen et al., 1999).
- Physical activity increases the diameter of the coronary arteries and decreases the rate of plaque forming in the arteries (atherosclerosis) (Hambrecht et al., 1993).
- Physical activity improves blood lipid levels, in particular increasing High Density Lipoprotein Cholesterol (HDL) and decreasing Low Density Lipoprotein Cholesterol (LDL) (Wood et al., 1991, Stefanick et al., 1998, Dunn et al., 1999, Andersen et al., 1999).
- Physical activity reduces body fat content and improves body composition (Jakicic et al., 2001, Saris et al., 2003).
- Physical activity improves insulin sensitivity and glucose tolerance (Mayer-Davis et al., 1998, Goodpaster and Kelley, 2001).

This implies a biologically plausible link between physical activity and health and supports the conclusions from the large epidemiological studies mentioned above. Moreover it justifies using other endpoints than CVD events in intervention studies. This gives valuable additional insight in the most effective exercise programmes for CVD risk reduction. Of particular interest for this thesis are lipid profile and body fat content.

Body fat content, Low Density Lipoprotein Cholesterol (LDL), High Density Lipoprotein Cholesterol (HDL), free fatty acids (FFA) and triglycerides (TG) can to some extent all be influenced by physical activity. Durstine et al. (2001) published a review in which they analysed the effect of training volume on blood lipids and concluded that blood lipids may be altered at relative low training volumes, although certain thresholds might need to be reached. For increases in HDL they concluded that exercise volumes in excess of 1,200 $kcal \cdot week^{-1}$ ($\approx$5,040 kJ·weeks^{-1}) are effective, although exceptions apply. For triglycerides the threshold is also around 1,200 kcal·week^{-1} although some studies reported significant decreases in TG with 1,000 kcal·week^{-1}. For total cholesterol and LDL it is less clear what the effect of exercise training is. Only few training studies have shown improvements in total cholesterol or LDL, mostly if training volumes exceeded 1,200 kcal·week^{-1}. Evidence from cross-sectional studies came up with somewhat higher thresholds; a training volume of 1,500-2,200 kcal·week^{-1} was associated with an increase in HDL of 3.5-6 mg·dL^{-1} and a 7-20 mg·dL^{-1} decrease in TG. Further increases in energy expenditure were associated with larger improvements in HDL and TG levels.

Body composition, in particular body fat percentage, is, in normal circumstances, mainly determined by the energy balance of the body (Harvey, 1969). Once a person takes in more energy via his or her diet than he or she uses in the same period, energy in the form of fat will be stored in the body (positive energy balance). Consequently, weight loss can be achieved by increasing exercise induced energy expenditure and simultaneously maintaining or lowering energy intake. A more detailed description of the effect of physical activity on body composition and body weight is given in section 1.3.3.

1.3.2 Non Insulin Dependant Diabetes Mellitus

Diabetes is a disturbance in the glucose uptake from the blood stream, leading to elevated blood glucose levels. In many this goes without clinical symptoms and therefore accurate diagnosis can only be made by assessing blood glucose levels using a fasting plasma glucose test or an oral glucose tolerance test. Blood glucose levels can range from normal to glucose intolerant to diabetic. Abnormal levels of glucose can be caused by two factors:

- Impaired insulin production in the pancreas, or
- Impaired response of peripheral tissue to insulin (insulin resistance).

The first is often present from early an age and is called insulin dependant diabetes mellitus and can be treated by regularly administering insulin. The latter (non insulin dependant diabetes mellitus) is more often diagnosed in adults later in life and are usually not treated with insulin administration. This chapter will only discuss NIDDM since this variant is more common in SCI.

There are fewer large epidemiological studies on exercise and NIDDM than on exercise and CVD. One well-conducted study is the Insulin Resistance Atherosclerosis Study, which included 1,467 American men and women of various ethnic backgrounds with normal glucose tolerance to mild diabetes (Mayer-Davis et al., 1998). All these subjects came to the lab for glucose tolerance and insulin sensitivity tests. Questionnaires were used to assess physical activity patterns. The main interest was the effect of participation in vigorous activity (≥6 MET) on insulin sensitivity. When controlling the data for potential confounders (age, sex, ethnicity, clinical centre, dietary fat and alcohol intake, smoking and hypertension), those who never participated in vigorous activities had significantly lower insulin sensitivity than those who were involved in vigorous activities at least 5 times per week (0.90 vs. 1.59 $min \cdot \mu U^{-1} \cdot mL \cdot 10^{-4}$, $p<0.001$). The opposite was found for the association between participation in vigorous exercise and fasting insulin levels (see Table 1.5).

Table 1.5: The association between participation in vigorous exercise (≥6 MET) and risk factors for NIDDM (Mayer-Davis et al., 1998).

Participation in vigorous (≥6 MET) activities		**Insulin sensitivity ($min \cdot \mu U^{-1} \cdot mL \cdot 10^{-4}$) (95% CI)**	**Fasting insulin levels ($pmol \cdot l^{-1}$) (95% CI)**
Rarely or never	(n=485)	0.90 (0.83-0.97)	113.86 (104.40-123.33)
1-3 times per month	(n=290)	1.12 (1.02-1.22)	109.34 (98.79-119.89)
1 time per week	(n=179)	1.38 (1.23-1.53)	101.66 (89.11-114.22)
2-4 times per week	(n=381)	1.43 (1.31-1.55)	92.98 (84.95-101.02)
5 times per week	(n=132)	1.59 (1.39-1.79)	83.87 (71.61-96.14)

For the group, total energy expenditure, energy expenditure from vigorous activity and energy expenditure from non-vigorous activity were all positively correlated with insulin sensitivity. However fasting insulin levels were only negatively associated with total energy expenditure and energy expenditure from vigorous activities. The conclusion of the authors of this report was that increased participation in vigorous and non-vigorous activity is associated with a better insulin sensitivity and they support the current guidelines on moderate intensity exercise for health benefits. However the results of this study also suggest that superior benefits might be achieved with vigorous exercise.

In 2004, the American Diabetes Association issued a joint statement with the North American Association for the Study of Obesity and the American Society for Clinical Nutrition on physical activity recommendations for the prevention of NIDDM (Klein et al., 2004). The reason for these three organisations working together is that risk factors for NIDDM include overweight/obesity, hypertension and dyslipidaemia. These three risk factors are themselves influenced by physical activity (as discussed in sections 1.3.1 and 1.3.3) and therefore the exercise recommendations for the prevention of NIDDM are similar to those published for the prevention of CHD and obesity (as endorsed by the American College of Sports Medicine, the Surgeon General's Office, American Heart Association and others). These recommendations state: 30-45 minutes of moderate intensity activity (40-60% VO_2max or 50-70% maximal heart rate) on 3-5 days of the week, gradually increasing the duration and frequency of the activity. The American Heart Association adds that greater reduction in risk for CHD could be achieved by increasing the duration or intensity of physical activity.

Moderate intensity exercise appears to be effective in reducing the risk for NIDDM, although more vigorous exercise might have additional benefits. In terms of exercise volume the literature seems to agree on 30-45 minutes on most if not all days of the week.

1.3.3 Obesity

Body weight is regulated by a comprehensive neural and hormonal system that is still the topic of much research. Leptin, a hormone that is secreted by fat tissue, has been suggested as a key messenger in body weight regulation (Zhang et al., 1994). In simple terms: leptin acts as a negative feedback loop that initiates a decrease in energy uptake when a certain fat mass is achieved. Disturbed leptin levels or leptin intolerance have been associated with obesity in animal models and humans (Farooqi et al., 1999, Halaas et al., 1995), however there are still many factors in the aetiology of obesity that need to be studied. This is of great importance since obesity is a significant problem in many countries in the Western world. Some countries report prevalence rates as high as 55-60% for overweight (body mass index $\geq$25 kg·m^{-2}) and approximately 22% for obesity (body mass index $\geq$30 kg·m^{-2}) (Flegal et al., 1998, Kuczmarski et al., 1997, Must et al., 1999). Moreover, the proportion of the population with higher than desired body weight is still increasing (Flegal et al., 1998). Besides a healthy and balanced diet to control energy intake, increasing physical activity to elevate energy expenditure is of the upmost importance. In this section, recommendations on physical activity for weight loss and prevention of weight gain will be discussed as published by several leading organisations.

The American National Institute of Health (NIH) recommends weight loss to persons with a body mass index (BMI) of 25 kg·m^{-2} and higher (National Heart Lung and Blood Institute, 1998). Although more sophisticated methods of determining body composition (e.g. computed tomography, DEXA, under-water weighting) are available, the NIH has not agreed on criteria based on these methods (Jakicic et al., 2001). The American National Heart Lung and Blood Institute's recommends men with an abdomen girth of $\geq$102 cm or women with a abdomen girth of $\geq$88 cm to lose weight (National Heart Lung and Blood Institute, 1998). These recommendations are based on the observation that in particular visceral obesity is a risk factor for CHD. The National Heart Lung and Blood Institute continues that these persons should aim to lose 5-10% body weight and sustain that loss. This is based on the fact that even modest reductions in body weight already carry significant health benefits, although long-term health benefits may be maximized with sustained weight loss of in excess of 10% initial weight (National Heart Lung and Blood Institute, 1998, de Groot et al., 2003).

The stance of the American College of Sports Medicine (ACSM) as published in 2001 (Jakicic et al., 2001) states the following recommendations for weight loss through increasing energy expenditure:

- Amount, type and intensity of exercise should depend on fitness status of the subjects.
- The standard recommendation for health benefits through physical activity (30 minutes of moderate intensity exercise on most, preferably all, days in the week $\approx$150 min·week^{-1}) might not be sufficient to maintain long-term weight loss. It is more likely that 200-300 min of exercise per week (equivalent to approximately 2,000 kcal·week^{-1}) is more effective, although implementation of this recommended volume might be a problem for some.
- Not much evidence is available regarding the optimal exercise intensity for weight loss. In the absence of this evidence ACSM recommends moderate intensity exercise (55-69% of maximal heart rate or 3-6 MET), although vigorous exercise ($\geq$70% maximal heart rate or >6 MET) might be necessary.
- These exercise recommendations could be integrated into life style changes or be part of structured exercise programmes.
- For optimal weight loss, increases in energy expenditure should be complemented with decreases in energy intake.

Organisations other than the ACSM came to similar recommendations. A consensus meeting held in May 2002, where experts in the field of physical activity and body weight control discussed exercise recommendations, came to the following statement:

> "...The current physical activity guideline for adults of 30 minutes of moderate intensity activity daily, preferably all days of the week, is of importance for limiting health risks for a number of chronic diseases including coronary heart disease and diabetes. However for preventing weight gain or regain this guideline is likely to be insufficient for many individuals in the current environment. There is compelling

evidence that prevention of weight regain in formerly obese individuals requires 60-90 minutes of moderate intensity activity or lesser amounts of vigorous intensity activity. Although definitive data are lacking, it seems likely that moderate intensity activity of approximately 45 to 60 minutes per day, or 1.7 PAL (Physical Activity Level) is required to prevent the transition to overweight or obesity..."

Saris et al. (2003)

PAL is a method of expressing energy expenditure while controlling for basal metabolic rate; 1.7 PAL means that total energy expenditure divided by basal energy expenditure should equal 1.7 or more. In other words, to prevent weight gain your exercise induced energy expenditure should be at least 70% of your resting energy expenditure. Interestingly, the benefit of vigorous activity is also highlighted in this consensus statement.

In summary: weight loss and maintenance of weight loss should be achieved by decreasing energy intake and increasing energy expenditure. Traditionally a minimum of 150 minutes of moderate intensity exercise per week should be sufficient for health benefits but it appears that for long-term weight loss, a larger training volume might be needed (>2,000 kcal·week^{-1}). Using high intensity exercises would reduce the time needed to achieve these volumes.

1.3.4 Osteoporosis

Osteoporosis is a condition whereby the bones become less dense (lower mineral concentration) due to a reduction in calcium absorption in the bone matrix. This results in weaker bones that are more at risk for fractures. The World Health Organisation has defined osteoporosis as a Bone Mineral Density (BMD) of more than 2.5 standard deviations below a value defined as healthy. This reference value is in most cases taken from a young Caucasian female, since the vast majority of the research on osteoporosis is conducted in post-menopausal women. Research in this population has lead to the finding that the BMD of young women is associated with the lowest risk for fractures and is therefore often used as the 'normal value'. The further away from this value, the higher the risk for fractures. However these reference values might not be valid in women from other ethnic origins or men. Therefore BMD is also often compared to the average value for the peer group, controlled for age, gender and ethnicity, although the associations with fracture risk has not been determined for all these groups (Nordin et al., 1995).

Osteoporosis mainly affects post-menopausal women and certain patient population (those with long term immobilisation). Nevertheless exercise has been suggested in the prevention and treatment of osteoporosis (Nordin et al., 1995, Kohrt et al., 2004), although these recommendations are derived from a relatively small number of observational and intervention studies (Kohrt et al., 2004).

One large study (n=755) in young healthy men found a significant positive correlation between time spent on exercise and BMD (Ruffing et al., 2006). Exercise habits were assessed by questionnaire and subjects were grouped per average weekly exercise time: 1-3 hours·week^{-1} (n=35), 4-6 hours·week^{-1} (n=123), 7-10 hours·week^{-1} (n=189) and ≥11 hours·week^{-1} (n=273). In Caucasian males, the authors found a positive significant correlation between exercise volume and BMD in calcaneus (3% increase in BMD with each additional 3 hours of exercise) and cortical thickness (r=0.13). Those reporting 11 hours of exercise or more had a significantly higher BMD in hip (5.1%, $p<0.016$) and spine (5.4%, $p<0.008$) than those in the lowest exercise volume group. Type or intensity of exercise were not assessed, but the authors suggested that the impact of increased mechanical loading during exercise might explain the higher BMD values in the exercise group.

This benefit of high-impact, weight-bearing exercise for BMD has indeed been found in multiple studies (Gross and Srinivasan, 2006, Vainionpaa et al., 2005). However potential thresholds in exercise intensity and volume for optimal improvement in BMD remain the topic of research. Some work in this area has found superior benefits of high intensity exercise (Vainionpaa et al., 2006), but the weight of this evidence is insufficient to base recommendations on.

These findings on exercise for the prevention of osteoporosis are reflected in the position stand of the American College of Sports Medicine on exercise for bone health as published in 2004 (Kohrt et al., 2004). The ACSM suggests that for maintaining bone health in adults, people should lead an active lifestyle, with special emphasis on weight bearing activities (e.g. jogging, stair-climbing), activities that involve jumping (e.g. volleyball, basketball) and/or resistance training (weight lifting). These activities should be performed for 30-60 minutes per day for 2-5 days per week. The intensity of these activities, in terms of bone-loading, should be moderate to high, although it was acknowledged that quantifying bone loading forces is currently not easy to conduct. However in general, these forces increase with increasing intensities as measured by more conventional methods (e.g. percentage maximal heart rate) (Kohrt et al., 2004).

In summary; the body of evidence on optimal exercise programmes for bone health is much smaller than for the previously described conditions. It appears that the type of activity is the most important element of an exercise programme; weight bearing, jumping and resistance training result in bone loading forces that are essential in maintaining bone mineral density. These activities should be performed on 2-5 days per week for 30-60 minutes per session. Superior benefits might be expected if these activities are performed at a high intensity.

1.3.5 Summary of physical activity recommendations for health

Table 1.6 summarizes the physical activity recommendations for health benefits as reported in the literature and endorsed by leading non-governmental and governmental organisations.

Vigorous exercises (>6 MET) have been suggested to be essential if optimal risk reduction for CHD is to be achieved. Although NIDDM and obesity might be prevented with exercises of a lower intensity, the additional benefits of higher intensities have also been acknowledged in the prevention and management of these conditions.

Table 1.6: Exercise recommendations for prevention of common diseases in able-bodied.

Disease/ Condition	Recommended exercise intensity	Recommended exercise volume
Coronary Heart Disease	>6 MET	1,200-2,200 kcal·week^{-1}, or >2,000 kcal·week^{-1}
Non Insulin Dependant Diabetes Mellitus	4-6 MET, or possibly >6 MET	30-45 minutes on 5-7 days·week^{-1}
Obesity	4-6 MET, or possibly >6 MET	30-45 minutes on 5-7 days·week^{-1}, or >2,000 kcal·week^{-1}
Osteoporosis	Weight bearing exercises, preferably high intensity	Wight bearing exercises on 2-5 days per week, 30-60 min·session^{-1}

In terms of optimal exercise volumes, 1,200-2,200 kcal·week^{-1} appears to be recommended for optimal reductions in CHD risk. It should be noted however that this recommendation is based on improvement in lipid profile, which is an indirect way of assessing CHD risk. Epidemiological studies directly comparing the incidence of CHD and exercise habits, have suggested a minimal exercise volume of 2,000 kcal·week^{-1}. This is comparable to the recommended exercise volume on preventing obesity. For NIDDM exercise volume has not been expressed as kcal·week^{-1}, however an estimate can be made based on the recommended exercise intensity and exercising 5-7 times per week for 30-45 minutes per session.

An average male of 75 kg exercising at the recommended 6 MET, would work at an oxygen consumption of 1.575 L·min^{-1} (1 MET =3.5 mL·kg^{-1}·min^{-1}, 6*3.5*75/1000=1.575), which is the equivalent of 7.875 kcal·min^{-1} (1 litre $O_2 \approx$ 5 kcal). If this individual would adhere to the minimal recommendation of five 30-minute sessions per week, he would burn 1,181 kcal·week^{-1}. Seven 45-minute sessions would result in 2,481 kcal·week^{-1}. Obviously, if he would exercise at lower intensities these values would be lower. Also, persons with a lower body weight would not expend as many calories as this 75 kg individual in the same time. Nevertheless this calculation gives an indication of the exercise volume one could achieve if one would exercise five to seven times per week for 30-45 minute per session.

The optimal exercise volume for prevention of the diseases describe above appears to be in the range of 1,200-2,200 $kcal \cdot week^{-1}$. Volumes exceeding 2,000 $kcal \cdot week^{-1}$ seem to be necessary to achieve significant reduction in the risks for coronary heart diseases, non-insulin dependant diabetes mellitus and obesity.

The current recommendations on exercise for the prevention of osteoporosis are not based on exercise intensity and volume. Exercise programmes aimed at benefits in bone mineral density should encompass two to five weekly 30-60 minute sessions of high-intensity, weight-bearing exercises.

It is important to realise that the optimal exercise volumes are derived from studies that have looked at physical activity. Physical activity is wider than just exercise and sport. Therefore the volumes described above do not necessarily have to be achieved with participation in sport and exercise, but other activities of daily life (ADL) can also contribute to the recommended exercise volume. For example the Harvard Alumni Study included stair climbing and walking in the questionnaire that was used to assess physical activity. These activities are therefore reflected in conclusions on optimal exercise volumes for health benefits.

Secondly it is important to distinguish net energy expenditure from gross energy expenditure. Gross energy expenditure includes the basal metabolic rate, while net energy expenditure only includes the energy used to do things on top of the basal metabolic rate.

Although some of these details might affect the exact value of the optimal exercise intensity and volume, the underlying recommendation remains the same. Dose-response relationships favour higher intensities and higher volumes. Moreover, high intensity exercises are a time-effective way of achieving large exercise volumes.

For optimal health benefits, it is advisable to fulfil all criteria on exercise intensity, exercise volume and type of exercise. Therefore people are advised to:

- Expend a minimum of 2,000 $kcal \cdot week^{-1}$ on physical activity

- Participate regularly in high intensity exercise of at least 6 MET (a VO_2 of 21 $mL \cdot kg^{-1} \cdot min^{-1}$).
- Participate in weight bearing exercises.

The key question is if these recommendations can be transferred to the SCI population. Earlier in this chapter it was shown that cardiovascular diseases, NIDDM, obesity and osteoporosis are major threat to the health of persons with chronic SCI. However there is insufficient data available to make specific exercise recommendations for persons with SCI. There are no large epidemiological studies in SCI that give similar information as the Harvard Alumni Study, the Health Professionals Follow-Up Study or any other study that formed the basis for the exercise recommendations in able-bodied.

A conservative approach would be to adopt the able-bodied guidelines and to continue investigating the benefits of the full range of exercise programmes. Unless there is any reason to believe that the situation would be different in SCI. Perhaps there are protective factors present in this population. This will be discussed in the following section.

1.4 Is Spinal Cord Injury a confounder in the effect of exercise on health?

The previous chapter has shown that, in the able-bodied population, there is a large number of studies available that form the basis of detailed exercise recommendations for optimal health. Unfortunately, no large epidemiological studies exist to support such recommendation for persons with SCI. However, studying the underlying physiological mechanisms for the development and treatment of CVD, NIDDM, obesity and osteoporosis might reveal reasons to accept or refute the adoption of the able-bodied recommendations to SCI. A comprehensive overview on how physical activity impacts health in able-bodied has been published by Hardman and Stensel (2003). In the following paragraphs this review is discussed in the light of a possible effect of SCI on the link between exercise and health.

Cardiovascular diseases

Risk factors for CVD can be grouped in modifiable and non-modifiable factors. The most important non-modifiable factors include family history, age, gender and ethnicity (Hardman and Stensel, 2003). There is no reason to believe that family history and ethnic background are different in the SCI population than in the general population. However, age and gender distribution in the SCI population is different from the general population. For every woman with a SCI there are approximately four men with SCI (Burt, 2004). And although most individuals incur their SCI at a relatively young age, the improved survival of acute SCI has resulted in an aging SCI population (Samsa et al., 1993, DeVivo et al., 1992, O'Connor, 2005). Older age and male gender are risk factors for CVD.

Some of the modifiable risk factors for CVD are also more common in SCI than in able-bodied, in particular obesity, diabetes mellitus, dyslipidaemia and physical inactivity (see also Chapter 1.2) (Tomey et al., 2005, Bauman et al., 1992b, Spungen et al., 2003). The prevalence of hypertension in SCI and its role in the development of CVD in persons with SCI is still being investigated, however the unstable blood pressure control seen in many persons with SCI (e.g. orthostatic hypotension, autonomic dysreflexia) has been identified as a risk factor for CVD

(Claydon et al., 2006). Less is known about smoking behaviour, pro-coagulent state and plasma homocysteine in SCI.

In conclusion, the literature tends to show that a number of the various sub-factors of the total CVD risk are more common in SCI than in the general population. Hypotension might be a protecting factor, but it is currently unknown to what extent this can lower the overall risk for CVD.

Non-Insulin Dependant Diabetes Mellitus

Modifiable risk factors for NIDDM include obesity, sedentary lifestyle, smoking and diabetogenic drugs (e.g. corticosteroids) (Hardman and Stensel, 2003). Obesity and physical inactivity are by far the most important risk factors for NIDDM and both are more common in SCI (Tomey et al., 2005, Monroe et al., 1998). It has also been suggested that persons with SCI are more often (over)exposed to corticosteroids, either in the treatment of acute SCI or as medication to fight inflammations in chronic SCI (Nash, 2000), although a significant impact might only be expected after long-term use of corticosteroids. In addition older age and male gender are important non-modifiable risk factors for NIDDM present in SCI (British Heart Foundation, 2002). There is no reason to believe that other risk factors for NIDDM (family history, smoking, ethnicity) are different in SCI from able-bodied. It is therefore unlikely that a protective factor for NIDDM is present in SCI.

The exact pathway via which physical activity influences NIDDM is still under investigation but it seems that glucose clearance is a key factor (Ivy et al., 1999). A large proportion (70-90%) of plasma glucose during an oral glucose tolerance test is taken up by skeletal muscle, whereby GLUT-4 proteins play an important role (MacLean et al., 2000). Even a single bout of exercise can increase the concentration of GLUT-4 and as a result improve glucose tolerance. Other adaptations in the muscle, e.g. capillarisation, can further facilitate this. Secondly, exercise induced weight loss will result in a reduction in adipocytes size. It has been suggested that adipocytes size is inversely related to insulin sensitivity of these adipocytes. Therefore weight loss seems an important element of NIDDM prevention and possibly treatment, although improvements have also been observed in the absence of weight-loss (Hardman and Stensel, 2003).

As mentioned before SCI leads to a reduction in active muscle mass and this affects the amount of glucose that can be taken up by GLUT-4 in skeletal muscle tissue. This puts persons with SCI at a disadvantage compared to their able-bodied peers. However, studies have shown that GLUT-4 can be increased by electrically stimulating paralysed muscles and consequently improve glucose tolerance (Chilibeck et al., 1999).

Obesity

Obesity is a major risk factor for various diseases such as CVD and NIDDM. While a genetic component may be present, obesity is caused by either too much energy intake or too little energy expenditure. Since 60-75% of the energy expenditure comes from the resting metabolic rate (RMR) (Poehlman, 1989), it has been suggested that a low RMR is the cause for the development of obesity (Ravussin et al., 1988). It should be noted however that not all studies support this finding (Goran et al., 1998). However persons with SCI have a lower RMR than able-bodied, mainly due to the decreased amount of active muscle mass (Monroe et al., 1998). This could put them at risk for obesity.

One possible mechanism for the effect of exercise on obesity is that physical activity raises energy expenditure after the exercise bout in order to restore muscle and liver glycogen and reduce body temperature. This so-called excess post-exercise oxygen consumption (EPOC) is present for 1-12 hours after the exercise bout, depending on the intensity and duration of the exercise. Therefore persons can permanently raise their RMR if they exercise at least twice a day. Dieting however, will lower the RMR. There is no reason to believe that a SCI affects this effect of physical activity on RMR (Hardman and Stensel, 2003).

Secondly, abnormal levels of leptin or impairments in the pathways via which leptin has its effect on body weight homeostasis have been suggested as a reason for the high incidence of obesity in SCI. Leptin is produced by adipocytes and impacts food intake and energy expenditure via the sympathetic nervous system, however this is impaired in persons with high SCI. In able-bodied subjects, leptin is closely correlated with fat mass and RMR, but in SCI there is no association between leptin and RMR (Jeon et al., 2003b, Jeon et al., 2003a).

Osteoporosis

The most important factor in the maintenance of good bone health is weight-bearing (Kocina, 1997). Bone will respond to a strain imposed on the bone whereby the magnitude of the response will dependant on the magnitude, rate, distribution and frequency of the strain (Hardman and Stensel, 2003). It is however unknown if it is the mechanical or biochemical component of the strain that triggers the bone growth. It is difficult to distinguish these two components in able-bodied intervention studies since both occur in parallel. Obviously weight-bearing of the lower extremities is absent in most persons with paraplegia, which explains the low BMD values seen in the lower extremities of these people. However, neuronal and vascular abnormalities, in particular venous stasis, could also play a role in the negative bone balance in SCI (Kocina, 1997, Bergmann et al., 1977, Chantraine, 1978). This might explain why passive standing does not result in improvements in BMD in SCI (Ogilvie et al., 1993). Optimal benefits might therefore be expected if both the mechanical and the biochemical component are being addressed.

In summary; studying the physiological pathways via which physical activity can influence the development of CVD, NIDDM and obesity, shows that it is unlikely that a SCI can significantly alter these mechanisms. Therefore in the absence of reliable evidence that would support or refute the adoption of the able-bodied exercise recommendations to the SCI situation, a conservative approach is suggested. Persons with SCI should follow the same recommendation on optimal exercise intensity, exercise volume and type of exercise as the general population.

The only exception might be exercise interventions for osteoporosis. Since in able-bodied, weight bearing is accompanied by a biochemical stimulus, no special consideration has been given to the exact pathways via which physical activity can trigger bone growth. In the absence of certainty on such a pathway, exercise programmes in SCI should address both the mechanical and biochemical component of the stimulus for bone growth.

It should be noted that the above statements are conservative and might place thresholds higher than necessary. However achieving optimal health benefits implies that the exercise programme should fulfil all criteria and for that reason it is preferred to exceed thresholds than to not achieve them. In addition, dose-response relationships identified for many diseases and risk factors favour higher intensities and volumes. There is no evidence that suggests that exercise thresholds in SCI are higher than in the able-bodied population. Therefore, in this thesis, the above identified intensities and volumes will be used as upper targets for optimal exercise programmes for persons with SCI.

1.5 Exercise limitations in Spinal Cord Injury

As explained above, there is insufficient evidence to support or refute adopting the able-bodied exercise recommendations to the SCI population. However, designing exercise programmes for SCI that comply with the able-bodied recommendations, would not only enable a full investigation of the range of exercise programmes that can be achieved, it would also serve as a conservative recommendation to optimise health in SCI. It is therefore of interest to explore the ability of individuals with SCI to comply with the able-bodied recommendations.

A first problem arises around the recommended high-impact weight bearing or resistance exercises for optimal bone health. The effect of exercise on bone health is local (Iwamoto et al., 2001) and since in SCI, bone mineral density is mainly affected in the legs and hips (Szollar et al., 1997, Zehnder et al., 2004), exercises would need to be performed with the (paralysed) lower body.

It remains questionable if assisted standing (using standing frames) can improve bone mineral density in the lower body of persons with chronic SCI (Ben et al., 2005, Dauty et al., 2000, Frey-Rindova et al., 2000). This could be explained by the fact that not only mechanical unloading plays a role in the decrease in BMD after SCI, but also other neurological consequences such as lack of (voluntary) muscle contractions and venous stasis (Maimoun et al., 2006, Dauty et al., 2000). This is supported by observations that spasticity has a positive effect on BMD in the femur (Eser et al., 2005). If the latter mechanism is true, mechanical loading of the legs will be ineffective in improving BMD.

Controversy in this area remains, mainly due to the fact that the vast majority of these studies included small sample sizes. However, it is clear that the recommended exercise for optimal bone health cannot be achieved by most persons with SCI as a direct consequence of the paralysis.

For optimal reduction in risks for CHD, NIDDM and obesity, the important elements of an exercise programme were intensity and volume. Unfortunately, these recommendations can also be hard to adhere to for persons with SCI:

- High exercise intensities can be achieved if large amounts of energy are used in short periods of time, which could either be achieved by having a small amount of metabolic active tissue (i.e. muscle) working at a very high rate, or having a large amount of metabolic active mass working at an average rate.
- High exercise volumes can be achieved either by exercising for prolonged periods of time at a lower intensity or exercising for shorter periods of time at higher intensities.

Paralysis inherently leads to a restriction in the amount of active muscle mass and consequently high exercise intensities can only be achieved by working hard with a limited amount of metabolically active tissue mass. Obviously there is a peak to the energy expenditure that can be achieved with limited muscle mass and the question is whether this peak is above or below the recommended exercise intensity of 21 $mL \cdot kg^{-1} \cdot min^{-1}$ (6 MET). Secondly, can optimal exercise volumes (>2,000 $kcal \cdot week^{-1}$) be achieved if exercising at these exercise intensities? Or are unreasonably long periods of time needed to achieve these volumes?

To illustrate these thresholds; how long would a 75 kg male have to exercise at the recommended intensity to achieve the recommended volume? In general the maximal intensity that can be sustained over a prolonged period of time (<15 min) is approximately 80% of the maximal exercise potential. This implies that a person working at 6 MET (21 $mL \cdot kg^{-1} \cdot min^{-1}$) would need to have a VO_2max of at least 26.3 $mL \cdot kg^{-1} \cdot min^{-1}$. In the case of the 75 kg male, this would mean an absolute VO_2max of 1.97 $L \cdot min^{-1}$ (80%VO_2max =1.58 $L \cdot min^{-1}$). One litre of oxygen gives approximately 5 kcal, although this depends on the ratio energy derived from glucose: energy derived from fats (4.686 $kcal \cdot l^{-1}$ if all energy comes from lipids, 5.047 $kcal \cdot l^{-1}$ if all energy derived from carbohydrates) (Zuntz, 1901). Based on this assumption, an oxygen consumption of 1.58 $L \cdot min^{-1}$ is the equivalent of 7.9 $kcal \cdot min^{-1}$. The recommended 2,000 $kcal \cdot week^{-1}$ would in that case take 4 hours and 10 minutes of exercise at 80% VO_2max per week.

Crucial in the calculation of exercise volume is the exercise intensity. Therefore in the next section the typical exercise intensities seen in persons with SCI during various types of exercise will be discussed. If only a small percentage of the SCI population is able to achieve the recommended exercise intensity, could this perhaps explain the high incidence of CHD, NIDDM and obesity as discussed in section 1.2?

1.5.1 Measuring cardio-respiratory fitness

First of all, distinction should be made between VO_2peak and VO_2max. In this thesis the term VO_2max will be used for the absolute maximal oxygen consumption that an individual can achieve under ideal circumstances. VO_2peak is the highest value that an individual can achieve in a certain situation under certain circumstances, for example during a specific type of exercise.

Cardio-respiratory fitness is measured by monitoring oxygen consumption during an incremental exercise test in the lab or field. The VO_2peak achieved in such a test can be influenced by many factors, for example:

- Motivation and encouragement (Andreacci et al., 2002).
- The test protocol (e.g. continous/ discontinuous, length of each step) (Duncan et al., 1997, Pierce et al., 1999).
- The type of exercise used for the test (e.g. arm cranking, wheelchair propulsion) (Roels et al., 2005, Basset and Boulay, 2000).

Although these factors can have played a role in individual tests, on a population level, variations in VO_2peak as a consequence of the above factors will be levelled out. Therefore the VO_2peak values discussed in this section are considered as the true VO_2peak in that setting. A literature study has been conducted in order to try to answer the following question:

What exercise intensities can be achieved by persons with SCI during various types of exercise?

1.5.2 Upper body exercise in spinal cord injury

In general, the literature agrees on the fact that the spinal cord injured population is at the lower end of the fitness spectrum. Noreau and co-workers (1993) concluded that 25% of healthy young individuals with paraplegia failed to reach a peak oxygen consumption of 15 $mL \cdot kg^{-1} \cdot min^{-1}$. In this study, 123 volunteers with SCI were tested on a wheelchair ergometer. The persons with lesions between T1 and T5 (n=26) showed an average VO_2peak of 21.1 ±6.8 $mL \cdot kg^{-1} \cdot min^{-1}$, those with lesions between T6 and T10 (n=25) had an average VO_2peak of 21.1 ±8.3 $mL \cdot kg^{-1} \cdot min^{-1}$. The SCI subjects tested in the Coutts et al. (1983) study showed peak VO_2 values during wheelchair propulsion of 0.97-2.42 $L \cdot min^{-1}$, although the six subjects with lesion between T1 and T10 had an average value of 1.62 $L \cdot min^{-1}$ Another homogeneous group of nine paraplegics (T4-T6) showed an average VO_2peak value of 23.8 ±2.0 $mL \cdot kg^{-1} \cdot min^{-1}$ during arm cranking and 24.8 ±1.7 $mL \cdot kg^{-1} \cdot min^{-1}$ during wheelchair propulsion (Gass et al., 1995). Janssen et al. (1997) reported VO_2 peak values achieved during wheeling in two groups of paraplegics; those with lesions between T1 and T5 (n=5) reached 17.0 ±2.3 $mL \cdot kg^{-1} \cdot min^{-1}$, those with lesion between T6 and T10 (n=10) reached 24.3 ±6.1 $mL \cdot kg^{-1} \cdot min^{-1}$. A second report by Janssen et al. (2002) summarized oxygen consumption values for subjects that had participated in various studies conducted by this research team. The twenty-three subjects with T1-T5 lesions and thirty-four subjects with T6-T10 lesions showed average VO_2peak values of 22.8 ±8.9 $mL \cdot kg^{-1} \cdot min^{-1}$ and 24.7 ±9.1 $mL \cdot kg^{-1} \cdot min^{-1}$ respectively. Bostom et al. (1991) studied nine paraplegics with lesion between T5 and T12 and found and average VO_2peak during arm cranking of 29.1 ±3.6 $mL \cdot kg^{-1} \cdot min^{-1}$.

Although all these studies only report on small numbers of subjects (as is often the case in SCI research studies), the data tends to show that persons with high to mid thoracic lesions (T1-T12) seldomly showed VO_2peak values during upper body exercise higher than 25 $mL \cdot kg^{-1} \cdot min^{-1}$. All of the above data came from sedentary to moderately active persons. Given the fact that many individuals with SCI have a sedentary lifestyle (Dearwater et al., 1986), it is likely that the low intensities reported in SCI during upper body exercise is representative for the wider SCI population.

This implies that the exercise intensity thresholds reported in the able-bodied literature are out of reach for many persons with SCI. And secondly, to achieve the optimal exercise volume of 2,000 kcal·week^{-1}, these individuals would have to exercise for prolonged periods of time. For example Table 1.7 shows that for an average person with a VO_2peak of 20 mL·min^{-1}·kg^{-1}, it would take 5.5 hours to achieve the recommended exercise volume (these values are based on the assumptions mentioned earlier in this section; 75 kg person, one litre of oxygen gives 5 kcal).

Table 1.7: Time needed to reach optimal exercise volume (2,000 kcal·week^{-1}) when exercising at various intensities. Calculations are based on a 75 kg individual.

VO_2peak (mL·kg^{-1}·min^{-1})	**VO_2peak (L·min^{-1})**	**80% VO_2peak (L·min^{-1})**	**Time needed to burn 2,000 kcal (h:m)**
10	0.75	0.60	11:06
15	1.13	0.90	7:24
20	1.50	1.20	5:33
25	1.88	1.50	4:27
26.3	1.97	1.58 (6MET)	4:13
30	2.25	1.80	3:42

A possible problem associated with adhering to such a strenuous exercise programme is musculoskeletal overuse of the upper body. Long-term wheelchair users have to perform all activities of daily life with their upper body and consequently they are at risk for overuse syndrome. Prevalence rates of up to 70% have been reported for musculoskeletal pain in shoulders and arms, especially after long-term manual wheelchair use (Burnham et al., 1993, Dyson-Hudson and Kirshblum, 2004, Gironda et al., 2004, Fullerton et al., 2003, Samuelsson et al., 2004).

Two areas of concern exist in the aetiology of pain in the upper body of many SCI individuals: the high mechanical forces in the upper body (mainly shoulder) seen during transfers and the continuous musculoskeletal loading of the upper body as seen during (manual) wheelchair propulsion (Burnham et al., 1993, Samuelsson et al., 2004, Van Drongelen et al., 2005). Both are difficult to avoid since all activities of daily living and mobility have to be performed with the upper body in SCI, even when pain arises.

During upper body exercise it is particularly the chronic loading of the musculoskeletal system of the upper body that gives reason for concern. Indeed wheelchair propulsion and arm crank ergometry have been associated with increased levels of shoulder pain and injury. These activities mainly involve the anterior deltoid, triceps and pectoral muscles, which increases the risk of overuse of these muscle groups and moreover could result in an imbalanced shoulder. The shoulder joint is a rather loose joint that is designed for mobility rather than stability (this as compared to for example the hip joint). The stabilising forces in the shoulder need to come from the many muscles around the shoulder. An imbalance in these muscles impairs the stability of the shoulder joint and this might result in pain (Burnham et al., 1993). Therefore it might be advisable to avoid similar mechanical stress on the musculoskeletal system during exercise as seen during wheelchair propulsion.

However there is also evidence that suggests the opposite. Fullerton and co-workers (2003) sent a questionnaire to 257 wheelchair users (86% SCI) to inquire about sports participation, shoulder pain, age, level of lesion, duration of injury and wheelchair use. In this study athletes were defined as having at least two of the following three criteria: a) trained at least 3 hours per week, b) competed at least three times per year, and c) had a sport specific wheelchair. Of the total 257 subjects, 172 were athletes and 85 non-athletes. Of the non-athletes, 66 % reported shoulder pain while only 39 % of the athletes reported shoulder pain ($p<0.0001$). However further analysis showed that the athletes were significantly younger than the non-athletes (34.34 vs 46.06, $p<0.0001$) and also the persons reporting pain were older than those without pain (41.73 vs 34.99, $p<0.0001$). Logistic regression modelling revealed that both age and athlete status were predictors for pain, but athlete status explained more of the variance than age. A limitation of this type of study is that it only shows associations and no causal relations. It is possible that those with shoulder pain never made it to the athlete status due to pain in the upper extremities.

The exact answer as to what extent sport participation prevents or contributes to shoulder pain remains open. But the evidence on the mechanism behind the high prevalence of overuse in the upper extremity in SCI suggests that is important to prevent muscular imbalances around the shoulder. Upper body exercise machines that deal with this problem, such as a special arm pull exercise (Jacobs, 2004), have been developed, but it might be preferable to also look at possibilities to use the paralysed muscle mass for exercise. The only way to do this is by using functional electrical stimulation (FES).

1.6 Functional Electrical Stimulation

In most persons with spastic paralysis (lesions above T12/L1), the peripheral motor neurons and muscles in the paralysed body parts are intact, although heavily de-conditioned and atrophied. This de-conditioning can be reversed by artificially stimulating the muscles using functional electrical stimulation (FES) (Scremin et al., 1999, Baldi et al., 1998). Most FES systems stimulate the muscles at the motor neuron/ motor endplate level, although systems for denervated muscles have also been developed (Kern et al., 1999, Gallasch et al., 2005). FES systems discussed in this thesis are for innervated muscles only.

The electrical stimulation is delivered to the muscle by electrodes that are either placed on the skin or implanted close to the motor neuron. Implanted electrodes have the advantage of a high specificity and consequently a smaller current is needed to depolarise the neuron (Peckham and Knutson, 2005, Gorman, 2000). Although the surgical procedures to place these electrodes are becoming less invasive, surface electrodes tend to be more user-friendly (Peckham and Knutson, 2005). These are placed as patches on the skin over the targeted muscle group. Surface electrodes are easy to apply and re-usable, but have the disadvantage of low specificity. Subcutaneous fat and other tissue can impair the conductivity and subsequently a larger current is needed to reach the neurons. Controlling the direction that this current travels is difficult and as a result neighbouring muscles can also be stimulated.

The power of an FES-induced contraction is dependant on multiple factors (Gorman, 2000, Peckham and Knutson, 2005); including:

- The placement of the electrodes (close to the motor point of the muscle gives the best response).
- The distance between the active and indifferent electrode.
- The conductivity of the tissue between the electrode and the target nerve/muscle.
- The training status of the muscle.

- The frequency of the current (higher frequencies will result in fused contractions, while low frequencies will result in individual twitches).
- The pulse width of the current (a larger pulse width results in a more intense stimulation and thus a more powerful muscle contraction).
- The amplitude of the current (a larger amplitude will results in a more intense stimulation and thus a more powerful muscle contraction).

By controlling these parameters, 'normal' muscle contractions can be simulated and used for various activities, e.g. grasping, standing, walking, cycling and rowing (Andrews and Wheeler, 1995, Gorman, 2000).

There are a few significant differences between normal muscle contractions and FES-induced contractions, however. In normal movement the brain sends very specific signals to the muscles to coordinate the various muscles and the various motor units within each muscle. Artificial stimulation of muscles lacks this subtlety, especially when surface electrodes are being used (Hainaut and Duchateau, 1992, Mizrahi, 1997).

In normal muscle contractions there is a distinct order of motor unit recruitment. Small motor neurons that mainly innervate type 1 fibres will be recruited first to generate relatively low forces that can be sustained over prolonged periods of time. When more muscle force is needed the larger motor neurons will fire and these activate mainly type 2 fibres that can deliver high forces but have a low fatigue resistance (Jones et al., 2004). Electrical stimulation of muscles results in the opposite recruitment order; the larger motor neurons are easier to excite and thus type 2 fibres are activated first. With increasing stimulation intensity the smaller neurons will depolarise as well and the fatigue resistant type 1 fibres are activated (Mizrahi, 1997, Hainaut and Duchateau, 1992).

A second factor limiting the time to fatigue in FES induced contractions in persons with SCI, is the extreme de-conditioned state of the muscle after long-term paralysis (Bogie and Triolo, 2003). After a lesion in the spinal cord, the muscles in the paralysed body parts undergo a series of changes.

The most significant changes include:

- A decrease in metabolic enzymes content in the muscle (Kjaer et al., 2001).
- A decrease in number and size of muscle fibres, especially type 2a fibres (Gregory et al., 2003).
- A decrease in blood circulation (Gerrits et al., 2001).

This results in a muscle with a very low fatigue resistance, although it will still be able to deliver reasonable forces (as seen during a spasm). Regular training with FES is able to reverse many of these effects of paralysis (Bogie and Triolo, 2003, Kjaer et al., 2001, Mohr et al., 1997a).

For the use of FES in cardiovascular exercises in SCI it is essential to have the skeletal muscles contract powerfully over prolonged periods of time. The optimal stimulation parameters for this FES-training are still topic of debate. Animal models show that chronic low frequency stimulation is able to increase time to fatigue dramatically (Barron et al., 1998, Jarvis et al., 1996). Some work in spinal cord injured humans has been able to replicate this (Harridge et al., 2002), although high frequency stimulation has also shown to result in sustainable powerful contractions (Eser et al., 2003b).

Even with these limitations, FES is still a valuable tool in the long term care of SCI. Although the number of subjects in most SCI intervention studies is small, there is reasonable evidence that suggests regular FES use can have the following physiological benefits;

- Improved blood circulation in paralysed body parts (Bogie and Triolo, 2003).
- Increased muscle size (Scremin et al., 1999).
- Improved muscle endurance and strength by improving morphological and histochemical characteristics of the muscle (e.g. fibre size, oxidative capacity, fibre composition) (Kjaer et al., 2001).
- Increase in GLUT 1 and GLUT 4 transporter proteins in muscles cells (Chilibeck et al., 1999).

Besides these physiological benefits at the muscle site, general fitness can also be improved with FES (Andrews and Wheeler, 1995, Gorman, 2000, Jacobs and Nash, 2001). The most common types of cardiovascular FES-exercises are FES-cycling, FES-hybrid exercise and FES-rowing. These exercises are of particular interest as the increased amount of active muscles mass during FES-exercise might contribute to achieving the recommended exercise intensity and volume.

A systematic review of the literature has been conducted to identify all relevant studies that monitored oxygen consumption values during FES-cycling, FES-hybrid exercise and/or FES-rowing in persons with spinal cord injury. The results are presented in the following sections.

1.6.1 FES-cycling

Most FES-cycling systems use stimulation of the quadriceps and hamstrings, sometimes complemented with glutei stimulation. One FES-cycling system is commercially available; the ERGYS bike (Therapeutic Alliances Inc, Fairborn, Ohio, USA), which is a spin off of the prototype developed and evaluated by Petrovsky and co-workers in the late 70's and early 80's (Petrofsky and Phillips, 1984). The ERGYS bike is a stationary bike in which a computer monitors the crank position and movement and uses this information to determine the stimulation parameters. When the pedal rate decreases, stimulation intensity is increased to give stronger muscle contractions. The seat of the bike is equipped with a high back with straps and arm rests to provide sufficient postural support to those with limited trunk function. Leg stabilisers prevent the legs from abduction and adduction. The ERGYS system has been used in the majority of the FES-cycling studies. At the same time other research groups have started developing their own stationary FES-cycling systems (Fornusek and Davis, 2004). And besides these stationary bikes, road-worthy FES-tricycles have also been developed (Gfohler and Lugner, 2000, Hunt et al., 2004), although the practical use of these bikes as a method of transport might be limited due to the low power generated in FES-cycling (Theisen et al., 2002, Raymond et al., 2002).

Of particular interest is the value of FES-cycling for cardiovascular exercise training. Using the lower extremities for these activities might reduce the risk for overuse syndrome in the upper body. In the light of the thresholds in exercise intensities and volumes reported in able-bodied for optimal health benefits (see section 1.2), it is useful to evaluate the exercise intensities that can be achieved with FES-cycling.

A systematic review of the literature has revealed 23 articles that have reported oxygen consumption in FES-cycling programmes (see summary in Table 1.8 and full details in Table 1.9 and 1.10). Eleven of these are cross-sectional measurements and twelve used an experimental design with pre and post training measurements.

Table 1.8: Exercise intensity during FES-cycling.

		Time of Measurement	**Number of studies**	**Total n (para/tetra)**	**Average VO_2peak**	**Range**
Peak	Absolute VO_2 ($L \cdot min^{-1}$)	Pre-training	9	86	0.96	0.51-1.30
		Post-training	9	86	1.17	0.83-1.43
		Cross-sectional	3	22	1.10	0.65-1.36
		All	12	194	1.07	0.51-1.43
	Relative VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	Pre-training	7	67	13.5	7.5-17.7
		Post-training	3	24	16.5	12.5-19.4
		Cross-sectional	2	15	17.6	17.4-17.8
		All	9	106	14.7	7.5-19.4
Sub-peak	Absolute VO_2 ($L \cdot min^{-1}$)	Pre-training	1	13 (8/5)	0.57	0.57
		Post-training	1	13 (8/5)	0.69	0.69
		Cross-sectional	9	69 (39/30)	1.13	0.47-2.5
		All	10	95	0.99	0.47-2.5
	Relative VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	Pre-training	1	13 (8/5)	7.4	7.4
		Post-training	0	-	-	-
		Cross-sectional	5	32 (26/6)	16.7	7.1-34.7
		All	6	45 (34/11)	14.0	7.1-34.7

Thirteen studies have reported VO_2 peak values as achieved during an incremental FES-cycling test, which is performed by increasing the resistance of the bike stepwise until the subject is no longer able to pedal at a certain pedal rate (the ERGYS system uses a pedal rate of 35 rpm as the minimal value, a lower pedal rate is regarded as fatigue and in that case the exercise is stopped). Ten studies have only reported VO_2 at sub-maximal intensities. Table 1.8 shows the VO_2peak and sub-max values reported in all FES-cycling studies published in the period 1980- September 2005.

The average peak oxygen consumption reported in the FES-cycling studies was 1.07 $L \cdot min^{-1}$ (range: 0.51 – 1.43 $L \cdot min^{-1}$) or 14.7 $mL \cdot kg^{-1} \cdot min^{-1}$ (range: 7.5 – 19.4 $mL \cdot kg^{-1} \cdot min^{-1}$), based on 194 and 106 subjects respectively. Peak values obtained during a max test, cannot be sustained over prolonged periods of time and are therefore of limited value when evaluating exercise intensities for optimal health benefits (section 1.2). On average most individuals will be able to sustain an activity if the intensity does not exceed 80% of their maximal exercise capacity. This would imply that during FES-cycling a relative VO_2 of 11.8 $mL \cdot kg^{-1} \cdot min^{-1}$ can be sustained over prolonged periods of time.

Sub-maximal oxygen consumption values reported in other FES-cycling studies (Table 1.9) show slightly higher values than this estimate based on VO_2peak. The average sub-max VO_2 is 0.99 $L \cdot min^{-1}$ (range 0.47 – 2.5 $L \cdot min^{-1}$) or 14.0 $mL \cdot kg^{-1} \cdot min^{-1}$ (range 7.1 – 34.7 $mL \cdot kg^{-1} \cdot min^{-1}$). Nevertheless both these values are well below the recommended 21 $mL \cdot kg^{-1} \cdot min^{-1}$. Only one study reported an oxygen consumption during FES-cycling exceeding this threshold (Petrofsky and Stacy, 1992), although it is unknown why this study reported such high values since the exercise protocol appears to be similar to most other FES-cycling studies.

Table 1.9: VO_2peak values reported in the FES-cycling literature.

Author	Subjects	N	Timing of measurement	Average absolute VO_2 peak ($L \cdot min^{-1}$)	Average age (years)	Average body weight (kg)	Average relative VO_2 peak ($mL \cdot min^{-1} \cdot kg^{-1}$)
Barstow et al., 1996	7 para, 2 tetra (C5-L1) 9 males	9	pre-training	1.28 ±0.31	34.4	76.4	16.8
		9	post-training	1.42 ±0.34		?	?
Barstow et al., 2000	8 para (T4-L1) 8 males	8	cross-sectional	1.27±0.27	34.3	73.1	17.4*
Bhambhani et al., 2000	4 para, 3 tetra (C5-T12) 6 males, 1 female	7	cross-sectional	0.65±0.18	26-65 (range)	55-110	?
Burke-Gurney et al., 1998	4 para, 2 tetra (C4-T10) 6 males, 2 females	6	pre-training	0.55	30.2	?	?
		6	post-training (6 weeks)	1.00		?	?
Goss et al., 1992	3 para, 2 tetra (C5-T10) 3 males, 2 females	5	pre-training	0.79 ±0.23	29.6	62	12.7*
		5	post-training (6 months)	1.01 ±0.25	?	?	?
Hjeltnes et al., 1997	5 tetra (C5-C7) 5 males	5	pre-training	?	35	76.6	7.5 ±1.3
		5	post-training (8 weeks)	?		?	12.5 +1.5
Holme et al., 2001	4 para (T?-T7)	4	cross-sectional	0.91- 1.76	36.8	76.6	?
	3 tetra (C5-T1)	3		1.25-1.66			?
	4 para, 3 tetra (C5-T7) 6 males, 1 female	ave		1.36 ±0.1			17.8*
Hooker et al., 1992	8 para, 10 tetra (C5-T11) 17 males, 1 female	18	pre-training	0.78 ±0.01	30.6	76.1	10.2*
		18	post-training (36 sessions)	0.95 ±0.01		?	?

Table 1.9: continued.

Author	Subjects	N	Timing of measurement	Average absolute VO_2 peak ($L \cdot min^{-1}$)	Average age (years)	Average body weight (kg)	Average relative VO_2 peak ($mL \cdot min^{-1} \cdot kg^{-1}$)
Hooker et al., 1995	6 para, 2 tetra (C5-L1) 8 males	8	pre-training	1.29 ±0.3	36	76.7	17.7 ± 5.8
		8	post-training (14 sessions)	1.42 ±0.39		?	19.4 ±7.5
Krauss et al., 1993	7 para, 1 tetra (C7-T1) 7 males, 1 female	8	pre-training	0.51 ±0.05	32	?	?
		8	post-training	0.83 ±0.06		?	?
Mohr et al., 1997	4 para, 6 tetra (C6-T4) 8 males, 2 female	10	pre-training	1.2 ±0.08	35.3	?	?
		10	post-training (1 year)	1.43 ±0.09		?	?
Mutton et al., 1997	9 para, 2 tetra(C5-L1) 11 males	11	pre-training	1.30 ±0.27	35.6	77.4	16.8*
		11	post-training	1.42 ±0.34		?	?
Pollack et al., 1989	4 para, 7 tetra (C4-T6) 7 males, 4 females	11	pre-training	0.79 ±0.15	18-54 (range)	?	12.7
		11	post-training	1.04 ±0.13		?	16.2

* Calculated by reviewer based on average absolute VO_2 and average body weight reported in original study.

Table 1.10: VO_2 sub-peak values reported in the FES-cycling literature.

Author	Subjects	N	Timing of measurement	Average absolute VO_2 peak ($L \cdot min^{-1}$)	Average age (years)	Average body weight (kg)	Average relative VO_2 peak ($mL \cdot min^{-1} \cdot kg^{-1}$)
Arnold et al., 1992	7 para, 5 tetra (C5-T4) 10 males, 2 females	12	cross-sectional	0.92 ±0.44	22.8	?	?
Barstow et al., 1995	4 para, 2 tetra (C6-T9) 6 males, 2 females	6	cross-sectional	1.03 ±0.16	35.8	78.4	13.1*
Faghri et al., 1992	8 para, 5 tetra (C4-T10) 12 males, 1 female	13	pre-training	0.57	30.5	77.4	7.4*
		13	post-training (36 sessions)	0.69		?	?
Kjaer et al., 1999	3 para, 4 tetra (C6-T4) 6 males, 1 female	7	cross-sectional	0.9 ±0.07	36	79	11.4*
Kjaer et al., 2001	4 para, 6 tetra (C5-T7) 8 males, 2 females	10	cross-sectional	1.39	27-45	58-87	?
Mohr et al., 1998	2 para, 7 tetra (C5-T4) 9 males	9	cross-sectional	1.03 ±0.15	35	?	?
Nash et al., 1995	6 tetra (C5-C6) 6 males	6	cross-sectional	0.71 ±0.3	25.8	?	?
Petrofsky & Stacey, 1992	8 para (T4-T11) unknown gender	8	cross-sectional	2.5 ±0.2	19-26	72	34.7*
Raymond et al., 2002	6 para (T5-T9) 6 males	6	cross-sectional	0.75 ±0.11	38	72	10.4*
Theisen et al., 2002	5 para (T4-T9) 5 males	5	cross-sectional	0.47 ±0.09	33	66	7.1*

* Calculated by reviewer based on average absolute VO_2 and average body weight reported in original study.

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Although FES-cycling might not give optimal health benefits based on exercise intensity, FES-cycling has potentially two significant advantages over upper body exercise. During FES-cycling mechanical forces are applied over the lower extremities and these could be important in the prevention and/or treatment of osteoporosis (Mohr et al., 1997b). This will be discussed in Chapter 4. Secondly, using a FES induced lower body exercise avoids musculoskeletal stress on the upper body and subsequently might reduce the risk for overuse as described in section 1.5.2.

The oxygen consumption values reported in FES-cycling could be augmented if simultaneously an upper body exercise is performed. This so-called FES-hybrid exercise will be discussed in section 1.6.2.

1.6.2. FES-hybrid exercise

FES-hybrid exercise systems consist of a FES induced lower body exercise combined with a voluntarily upper body exercise. In this chapter only FES-hybrid systems consisting of FES-cycling and arm cranking will be discussed, since this system is the most common type of FES-hybrid exercise. It should be noted that this type of exercise consists of two individual exercises (namely FES-cycling and arm cranking) that are performed simultaneously. Therefore it would be reasonable to expect that all benefits reported for FES-cycling, also apply to this type of FES-hybrid exercise. The additional benefit of FES-hybrid exercise lies in the augmented amount of active muscle mass and the effect of this on oxygen consumption. Table 1.11 summarises the oxygen consumption values reported in studies on FES-hybrid exercise published between 1980 and September 2005, full details are given in Table 1.12 and Table 1.13.

The number of studies and subjects is small but the data suggests that oxygen consumption during FES-hybrid exercise is indeed higher than during FES-cycling. The average peak oxygen consumption during FES-hybrid exercise is 1.65 $L \cdot min^{-1}$ (range: 1.30 – 1.91 $L \cdot min^{-1}$) or 26.2 $mL \cdot kg^{-1} \cdot min^{-1}$. This absolute VO_2peak is based on 3 studies with 42 subjects, unfortunately the relative

VO_2peak is only based on one study with 10 subjects. Eighty percent of that relative VO_2peak is 21.0 mL·kg^{-1}·min^{-1}.

Table 1.11: Exercise intensity during FES-hybrid exercise.

		Time of measurement	Number of studies	Total n (para/tetra)	Average VO_2	Range
Peak	Absolute VO_2 (L·min^{-1})	Pre-training	2	16 (7/1)	1.50	1.30-1.69
		Post-training	2	16 (7/1)	1.70	1.49-1.91
		Cross-sectional	1	10 (10/0)	1.81	1.81
		All	3	42	1.65	1.30-1.91
	Relative VO_2 (mL·kg^{1} ·min^{-1})	Pre-training	0	-	-	-
		Post-training	0	-	-	-
		Cross-sectional	1	10 (10/0)	26.2	26.2
		All	1	10 (10/0)	26.2	26.2
Sub-peak	Absolute (L·min^{-1})	Pre-training	0	-	-	-
		Post-training	0	-	-	-
		Cross-sectional	3	23 (12/11)	1.27	1.02-1.58
		All	3			
	Relative (mL·kg^{-1} ·min^{-1})	Pre-training	0	-	-	-
		Post-training	0	-	-	-
		Cross-sectional	3	23 (12/11)	18.3	14.0-23.4
		All	3	23 (12/11)	18.3	14.0-23.4

Average reported sub-maximal VO_2 is 1.27 L·min^{-1} (range: 1.02 – 1.58 L·min^{-1}) or 18.3 mL·kg^{-1}·min^{-1} (range: 14.0 – 23.4 mL·kg^{-1}·min^{-1}). One study made a direct comparison in VO_2 during FES-cycling and FES-hybrid exercise and indeed supported the higher VO_2 in FES hybrid exercise (Mutton et al., 1997).

Although FES-hybrid exercise might give persons with SCI the opportunity to exercise at more optimal intensities and thus shorten the time to reach optimal exercise volumes, the practicalities of this type of exercise could limit its implementation. FES-hybrid exercise has no purpose other than exercise for the sake of exercise. Two cyclical movements are performed simultaneously but there is no link between the two. This is one of the reasons why Drs Garry Wheeler and Brian Andrews started thinking about the potential of FES-rowing as a new FES-hybrid exercise for SCI.

Table 1.12: VO_2peak values reported in the FES-hybrid exercise literature.

Author	Subjects	n	type of study	Average absolute VO_2 peak ($L \cdot min^{-1}$)	Average age (years)	Average body weight (kg)	Average relative VO_2 peak ($mL \cdot kg^{-1} \cdot min^{-1}$)
Krauss et al., 1993	7 para, 1 tetra (C7-L1) 7 males, 1 female	8	pre-training	1.3 ±0.15	32	?	?
		8	post-training (6 weeks)	1.49 ±0.14		?	?
Mutton et al., 1997	Unknown level of lesion 8 males	8	pre-training	1.69 ±0.64	35.6	?	?
		8	post-training	1.91 ±0.85		?	?
Raymond et al., 1999	10 para (T5-T12) 10 males	10	cross-sectional	1.81 ±0.1	36	69	26.2*

* Calculated by reviewer based on average absolute VO_2 and average body weight reported in original study.

Table 1.13: VO_2 sub-peak values reported in the FES-hybrid exercise literature.

Author	Subjects	n	Time of Measurement	Average absolute VO_2 peak ($L \cdot min^{-1}$)	Average age (years)	Average body weight (kg)	Average relative VO_2 peak ($mL \cdot kg^{-1} \cdot min^{-1}$)
Hooker et al., 1992	8 tetra (C5-C8) 7 males, 1 female	8	cross-sectional	1.02 ±0.02	32.6	73	14.0*
Phillips & Burkett, 1998	5 para, 3 tetra (C6-T12) 7 males, 1 female	8	cross-sectional	1.24*	33	69	18 ±5
Raymond et al., 1997	7 para (T4-T12) 5 males, 2 females	7	cross-sectional	1.58 ±0.12	31.9	67.3	23.4*

* Calculated by reviewer based on average absolute VO_2 and average body weight reported in original study.

1.6.3 FES-rowing

FES-rowing uses a standard Concept 2 rowing ergometer (Concept 2 inc, USA) that has been adapted with a special seat and leg stabilisers to provide sufficient postural support for paraplegic rowers (this prototype is known as the RowStim II). Leg movement for the rowing action is provided by stimulating the quadriceps and hamstrings of both legs. Timing of this stimulation is done by the rower himself by pressing or releasing a switch on the handle bar of the rowing machine. A full description of the FES-rowing prototypes used in this project is given in section 2.2.

The rationale behind FES-rowing is that is should enable persons with SCI to exercise at high oxygen consumption values and at the same time prevent repetitive musculoskeletal stress to the upper body as seen during wheelchair propulsion. To test these hypotheses Wheeler and Andrews and co-workers conducted a series of pilot studies, which are summarized below.

Laskin et al. (1993) investigated the cardiorespiratory responses to FES-rowing and its use as a training tool for SCI (Laskin et al., 1993). Six quadriplegic and two paraplegic subjects (average body weight 63.2 kg) completed a series of three tests; FES leg stimulation, arms only rowing and FES-rowing (in random order). The group averages are displayed in Table 1.14. During FES-rowing, oxygen consumption, ventilation and heart rate were all significantly higher than during stimulation only or rest. Compared with arms only rowing, FES-rowing gave significantly higher oxygen consumption and mean arterial pressure (MAP). Six subjects participated in a qualitative evaluation of FES-rowing and they perceived FES-rowing to be easier than arms only rowing, even although FES-rowing was conducted at a significantly higher percentage of their maximal exercise capacity than the arms only rowing (82.9% vs 71.0% of the VO_2max as determined by an incremental arm crank max test). This implies that the high intensity of FES-rowing could be sustained for prolonged periods.

Table 1.14: Physiological values during rest, FES stimulation of leg muscles, arms only rowing and FES-rowing in eight SCI volunteers.

	Rest	FES only	Arms only rowing	FES-rowing
VO_2 ($L \cdot min^{-1}$)	0.229[a,b,c]	0.464[b,c,d]	0.825[a,c,d]	1.020[a,b,d]
VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	3.64[a,b,c]	7.49[b,c,d]	13.27[a,c,d]	16.34[a,b,d]
VE ($L \cdot min^{-1}$)	8.9[a,b,c]	16.7[b,c,d]	32.9[a,d]	34.4[a,d]
RER	0.77[a,b,c]	0.94[d]	0.99[d]	0.96[d]
HR (bpm)	69[b,c]	71[b,c]	112[a,d]	105[a,d]
MAP (mm Hg)	82.2[c]	95.4[b]	76.7[a,c]	96.5[b,d]

[a] Statistically significant different ($p<0.05$) from Stim only
[b] Statistically significant different ($p<0.05$) from Arms only rowing
[c] Statistically significant different ($p<0.05$) from FES-rowing
[d] Statistically significant different ($p<0.05$) from Rest

Olenik et al. (1995) studied the potential of rowing in the prevention of overuse syndrome in the upper body of persons with SCI. One of the possible underlying mechanisms of these pain complaints is an imbalance in scapular retractor and protractor muscles as a result of long-term wheelchair use. Restoring strength in the retractors could play a role in prevention of pain in the upper body. Three exercises to achieve this were investigated in this study; backwards wheeling, a special retractor exercise and rowing. EMG activity in the retractor muscles was monitored throughout these three exercises in seven able-bodied and seven SCI volunteers. In-dwelling electrodes validated the placement of the surface electrodes in a subgroup. Rowing resulted in similar retractor recruitment as the special retractor exercise, and both gave higher retractor recruitment than backward wheeling. They concluded that rowing could be of value in the prevention of overuse in the upper body of long term wheelchair users.

Verellen et al. (2007) explored peak exercise responses in five SCI volunteers using arm cranking, FES-cycling, FES-hybrid exercise (FES-cycling combined with arm cranking) and FES-rowing. Each participant performed three tests using all four exercise modalities to test reliability of the results. The average peak results for the group are displayed in Figure 1.6.

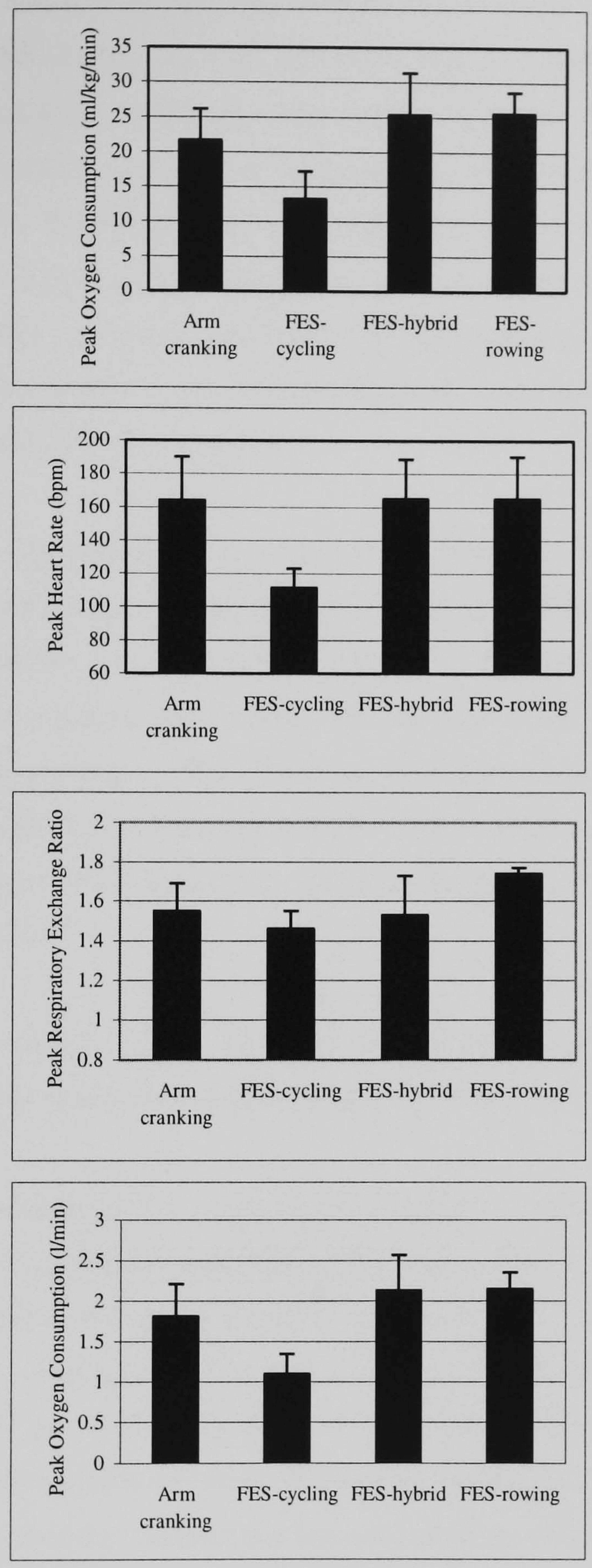


Figure 1.6: Peak oxygen consumption, heart rate and respiratory exchange ratio during arm cranking, FES-cycling, FES-hybrid and FES-rowing max-tests. Values are averaged over three tests per exercise modality in five SCI subjects (15 tests in total). Peak oxygen consumption and heart rate during FES-cycling were significantly lower than during the other three exercises ($p<0.05$) (Verellen et al., 2007).

FES-rowing resulted in a higher peak oxygen consumption than arm cranking, FES-cycling or FES-hybrid exercise although only the difference with FES-cycling was statistically significant. Peak heart rate during FES-rowing, FES-hybrid and arm cranking were similar, but peak heart rate during FES-cycling was significantly lower. Respiratory Exchange Ratios in all four exercise modalities were well above 1.0 indicating that physiological peak values were achieved in all tests. The intra-class correlation coefficients for VO_2 and heart rate showed very good reproducibility in all four exercise modalities ($r= 0.82-0.99$; $p<0.05$), except heart rate during the FES-cycling trials.

A fourth FES-rowing pilot study published by Wheeler et al. (2002) investigated the use of FES-rowing as a cardiovascular training device in six SCI subjects. Participants performed 22-36 30-minute sessions of FES-rowing at 70-75% of their pre-test physiological peak. After the training period (approximately 3 months), distance rowed (+25%), VO_2 peak (+11.2%) and peak oxygen pulse (+11.4%) all significantly increased ($p<0.05$). These values are comparable to FES-hybrid exercise and upper body exercise training in SCI as reported by Wheeler et al. (2002).

Table 1.15 is a summary of the VO_2 peak and sub-max values reported in the various FES-rowing studies, full details are given in Table 1.16 and Table 1.17.

The number of subjects in this series of pilot studies on FES-rowing is limited, but nevertheless the results are promising. FES-rowing appears to be an effective cardiovascular training that could play a role in restoring muscular balances in the shoulder. Oxygen consumption reported in the various FES-rowing studies is approximately of the same magnitude as the FES-hybrid exercise studies. Noteworthy is that fact that the more recent pilot studies on FES-rowing report higher VO_2 values than the studies from the early nineties, which might imply that the prototypes are improving. Of interest is also that the participants in these studies indicated that FES-rowing is an enjoyable exercise and they experience FES-rowing to be easier than rowing with just their upper body at a lower intensity.

Table 1.15: Exercise intensity during FES-rowing.

		Time of measurement	Number of studies	Total N (para/tetra)	Average VO_2	Range
Peak	Absolute VO_2 ($L{\cdot}min^{-1}$)	Pre-training	1	6	1.81	1.81
		Post-training	1	6	2.01	2.01
		Cross-sectional	1	5 (4/1)	2.15	2.15
		All	2	17	1.98	1.81-2.15
	Relative VO_2 ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$)	Pre-training	1	6	22.8	22.8
		Post-training	0	-	-	
		Cross-sectional	1	5 (4/1)	25.6	25.6
		All	2	11	24.1	22.8-24.1
Sub-peak	Absolute VO_2 ($L{\cdot}min^{-1}$)	Pre-training	0	-	-	-
		Post-training	0	-	-	-
		Cross-sectional	1	8 (2/6)	1.02	1.02
		All	1	8 (2/6)	1.02	1.02
	Relative VO_2 ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$)	Pre-training	0	-	-	
		Post-training	0	-	-	
		Cross-sectional	1	8 (2/6)	16.3	16.3
		All	1	8 (2/6)	16.3	16.3

Table 1.16: VO_2 peak values reported in the FES-rowing literature.

Author + year	Subjects	n	Time of measurement	Average absolute VO_2 peak ($L \cdot min^{-1}$)	Average age (years)	Average body weight (kg)	Average relative VO_2 peak ($mL \cdot kg^{-1} \cdot min^{-1}$)
Verellen et al., 2006	4 para, 1 tetra (C7-T12) 5 males	5	cross-sectional	2.15	46.6	84.3	25.6
Wheeler et al., 2002	5 para, 1 tetra (C7-T12) gender unknown	6	pre-training	1.81	42.5	79.3	22.8*
		6	post-training	2.01		?	?

* Calculated by reviewer based on average absolute VO_2 and average body weight reported in original study.

Table 1.17: VO_2 sub-peak values reported in the FES-rowing literature.

Author + year	Subjects	N	Time of measurement	Average absolute VO_2 peak ($L \cdot min^{-1}$)	Average age (years)	Average body weight (kg)	Average relative VO_2 peak ($mL \cdot kg^{-1} \cdot min^{-1}$)
Laskin et al., 1993	2 para, 6 tetra (C6-T6) 7 males, 1 female	8	cross-sectional	1.02 ±0.05	27.9	63.2	16.3 ±0.7

1.7 Conclusion

The aims of this review were to:

Lit 1 Identify threats to the health of persons with chronic SCI and explore similarities with common health problems in the able-bodied population.

Lit 2 Identify from able-bodied studies what levels of physical activity are required to obtain optimal reduction in the risk for common long-term diseases, such as cardiovascular diseases, non-insulin dependant diabetes, obesity and osteoporosis.

Lit 3 Assess the validity of adopting these optimal levels of physical activity to the SCI population.

Lit 4 Explore the compliance to these optimal levels of physical activity in SCI.

The literature review has revealed that secondary consequences of SCI, such as reduced mobility and physical activity, are the main factor leading to the elevated risk factors for CVD, NIDDM, obesity and osteoporosis seen in this population. Physical inactivity is also a key factor in the development of the above diseases in able-bodied persons. Numerous research studies in the general population have identified optimal exercise programmes that would give significant reductions in the risk for CVD, NIDDM, obesity and osteoporosis (Table 1.18).

Table 1.18: Recommended exercise intensity and exercise volume for optimal health benefits.

Disease/ Condition	Recommended exercise intensity	Recommended exercise volume
Coronary Heart Disease	>6 MET	1,200-2,200 kcal·week^{-1}, or >2,000 kcal·week^{-1}
Non Insulin Dependant Diabetes Mellitus	4-6 MET, or possibly >6 MET	30-45 minutes on 5-7 days·week^{-1}
Obesity	4-6 MET, or possibly >6 MET	30-45 minutes on 5-7 days·week^{-1}, or >2,000 kcal·week^{-1}
Osteoporosis	Weight bearing exercises, preferably high intensity	Wight bearing exercises on 2-5 days·week^{-1}, 30-60 min·session^{-1}

It appears that an exercise intensity of 6 MET (21 $mL \cdot kg^{-1} \cdot min^{-1}$) and an exercise volume of 2,000 $kcal \cdot week^{-1}$ are the minimal values needed for optimal health benefits, although this differs between various diseases and conditions (see Table 1.18). In addition weight-bearing exercises are essential in the reduction of the risk for osteoporosis.

The review has not identified any studies of similar magnitude in the SCI population. Therefore, in the absence of similar evidence on exercise and health in SCI, a conservative approach would be to adopt the same exercise recommendations for persons with SCI. But it has also become clear that many persons with SCI would not be able to achieve these values with traditional types of exercise available to them. Although high intensities have been reported in studies on upper body exercises, it might not be recommendable to prescribe these exercises due to the potential increase in risk for overuse syndrome. FES-exercise could offer a solution since different muscle groups are activated and subsequently overuse of the upper body might be avoided. However the exercise intensities reported for FES-cycling are below the recommended values identified in able-bodied. FES-hybrid exercises and FES-rowing give higher exercise intensities, but still do not always exceed the thresholds for optimal health benefits.

SCI research is often limited in sample size and therefore no definitive conclusions can be drawn. However it is possible that the high incidence and prevalence of CVD, NIDDM, obesity and osteoporosis is caused by the inability of persons with SCI to comply with exercise regimes that have been shown to lower risk factors for these diseases. There seems to be a need for a type of exercise that combines a high exercise intensity, a high exercise volume and weight-bearing on the lower extremities. Currently, only FES-hybrid exercise and FES-rowing could offer such an exercise, although FES-rowing would be the preferred option for three reasons:

- FES-rowing is well-accepted by participants.
- Rowing could play a role in stabilising the shoulder joint.
- Rowing is a well-established sport in able-bodied.

1.8 Thesis hypotheses H1-H5

The first part of the aim of this thesis is to explore the potential of FES-rowing as a high-intensity exercise and the effectiveness of FES-rowing in reducing risk factors for cardiovascular diseases, obesity and osteoporosis. The following hypotheses will be central in Chapters 2-6:

H 1 FES-rowing is a high intensity exercise and an effective cardiovascular training for persons with paraplegia.

H 2 FES-rowing training will affect cholesterol and blood lipids in persons with paraplegia.

H 3 FES-rowing training will affect leptin levels and insulin sensitivity in persons with paraplegia.

H 4 FES-rowing training will affect body composition in persons with paraplegia.

H 5 FES-rowing will affect bone mineral density in the lower extremities of persons with paraplegia.

These hypotheses imply that it is unknown in which direction the change will occur. Indeed there is no evidence that suggests that FES-rowing training will increase or decrease the above parameters. However from studies in the general population it is known that fitness levels and health status (e.g. cholesterol levels, body composition, insulin sensitivity) will improve after exercise training. Earlier work in FES-rowing for SCI suggests that FES-rowing is an effective type of exercise training, but in the absence of definitive evidence, no direction of effect can be given.

A training study has been conducted in seven paraplegic subjects to test the above hypotheses. The general methodology of this study is presented in Chapter 2. Specific materials and protocols that were only relevant to one or two of the above hypotheses are presented in the Methods sections of Chapters 3-6.

In Chapter 3 the peak oxygen consumption values of seven paraplegics before and after FES-rowing training will be presented and compared with other studies reporting VO_2peak in FES-rowing or other FES-exercises. Blood samples were taken in the same seven paraplegics before and after training and these samples were analysed for blood lipids, which are presented in Chapter 4. Blood samples of six subjects were also analysed for leptin, glucose and insulin, which are presented in Chapter 5. A subgroup consisting of five paraplegics participated in tests to assess the effect of FES-rowing training on body composition, which is presented in Chapter 6.

Chapter 2

Methods and materials

2. Methods and materials

The hypotheses presented in section 1.8 cover a broad area, however all can be tested using a similar methodology. An intervention study has been conducted to test all hypotheses on the potential health and fitness benefits of FES-rowing. The methods and materials used to test all hypotheses will be presented in Chapter 2. It should be noted however that additional detail on methods and materials is given in the methods sections of chapters 3-6. Chapter 2 will only discuss the methods and materials that are of relevance to all the various sub-analyses that have been conducted. These sub-analyses have been conducted in the following areas:

- The effect of FES-rowing training on cardiovascular fitness (Chapter 3).
- The effect of FES-rowing training on risk factors for cardiovascular diseases (Chapter 4).
- The effect of FES-rowing training on risk factors for obesity and non-insulin dependant diabetes (Chapter 5).
- The effect of FES-rowing training on body composition (Chapter 6).

2.1 Subjects

For this project, subjects were recruited who complied with the following criteria:

- Men or women with motor complete lesions between T1 and T12/L1, ASIA scale A or B.
- Between 18 and 60 years of age.
- In healthy condition, i.e. no pacemakers, uncontrolled arhythmias, uncontrolled angina, congestive heart failure, current deep venous thrombosis, severe skin reactions to electrical stimulation, restricted range of motion in hips, knees or ankles, severe spasticity, severe non-insulin dependant diabetes or any other medical contra-indication as identified by a physician.
- Good response to electrical stimulation of the quadriceps and hamstrings.
- Sensory feedback (if present) not limiting the magnitude of the electrical stimulation.
- Able to commit to a strenuous exercise programme of at least 12 weeks duration.
- Currently not participating in a whole body exercise regime (i.e. hybrid FES-exercise or FES-rowing).

In total eight paraplegic subjects were included in this project (see Table 2.1). One subject dropped out very early on in the study and has not been included in any of the analyses. This subject had to stop participating because of moving to another area, too far from the research site. Since this is completely unrelated to the project, it is not expected that this has resulted in any bias.

All seven subjects were included in the analysis on the effect of FES-rowing training on cardio-respiratory fitness (Chapter 3) and risk factors for cardiovascular diseases (Chapter 4), however the other analyses were performed on a sub-group for the following reasons:

- Subject 4 did not comply with the training protocol and subsequently the exercise volume of this subject was found to be too low. For this reasons his data was not included in the analysis of the effect of FES-rowing training on risk factors for obesity and non-insulin dependant diabetes (Chapter 5).

- No detailed DEXA scans were available for subjects six and seven and subsequently the changes in body composition could not be determined. For this reason their data was not included in the analysis of the effect of FES-rowing training on body composition (Chapter 6).

Table 2.1: Subjects included in project

Subjects	1	2	3	4	5	6	7	8
Level of lesion	T5-T6	T4-T5	T10-T12	T4-T5	T5-T6	T4	T5	T6
ASIA scale	A	A	B	A	B	A	A	A
Age (years)	49	56	46	23	24	53	47	45
Gender	male	male	male	male	male	male	male	female
Time since injury (years)	21	36	2	2	2	21	31	12
Included in fitness analysis (Chapter 3)	yes	yes	yes	yes	yes	yes	yes	Dropped out of study due to moving away from research site
Included in cardiovascular diseases analysis (Chapter 4)	yes	yes	yes	yes	yes	yes	yes	
Included in obesity and diabetes analysis (Chapter 5)	yes	yes	yes	no	yes	yes	yes	
Included in body composition analysis (Chapter 6)	yes	yes	yes	yes	yes	no	no	

2.2 Materials

All seven subjects have used the same prototype of the FES-rowing machine for training and testing (see Figure 2.1). This prototype, the RowStim II, consisted of a Model C Concept 2 rowing ergometer (Concept 2 inc. Morrisville, Vermont, USA) that has been adapted for FES use. The seat has been equipped with a backrest and strapping system to provide sufficient postural support for the paraplegic rower. The seat was cushioned with a honey comb mat to reduce the risk for ischial pressure sores. A leg stabiliser, consisting of a metal bar with an elbow joint, was attached to the seat and the upper leg of the rower. This kept the legs in the sagittal plane and prevented the legs from falling in or outwards.

An O4CHS 4-channel stimulator (Odstock Medical ltd., Salisbury, United Kingdom) was used for all testing and training. This stimulator was set to deliver maximum frequency (50 Hz) and maximum pulse width (50 ms) stimulation. The amplitude (0-115 mA) was adjusted (by the researcher) to a level that resulted in powerful muscle contractions and was increased when fatigue occurred. Two channels were connected to electrodes (round Pals/Ultraflex electrodes, 7cm diameter) on the quadriceps and the other two channels to electrodes on the hamstrings. The stimulator was controlled by two switches mounted on the handle bar of the rowing machines; one switch triggered quadriceps stimulation and the other hamstrings stimulation. The switches were operated by the thumbs of the rower.

From previous studies (Laskin et al., 1993, Wheeler et al., 2002), it is known that the contractions in the hamstrings were not always sufficient to flex the knees and bring the rower back to so-called front stops. Therefore a spring was attached from the seat to the front of the rowing machine, which extended during the drive phase (generated by the quadriceps) and released energy during the recovery phase. Different strengths of springs were available to suit the individual rower's muscle strength.

2.3 Intervention

For FES-rowing a certain level of leg muscle strength and endurance is required. This was tested with the subject seated in their own wheelchair with their legs hanging freely, with the wheelchair footrests removed. The left and right quadriceps muscles were alternately stimulated to raise and lower the legs with a minimal knee angle of 135° degrees, for approximately 5-6 cycles per minute for 10 minutes. The intensity of the stimulation was set to obtain at least 135° degrees leg extension and increased if during three consecutive cycles less than 135° degree knee angle was achieved (defined as fatigue). If the maximum intensity was used (110 mA) and fatigue was observed before the 10-minute mark, a 2-week leg strengthening program was prescribed.

Leg strengthening involved 3-4 sessions per week. Each session comprised 75 repetitions of leg flexion-extension per session and if fatigue occurred (as defined above) a two-minute rest period was taken before continuing the exercise. The session ended if a fourth rest was required or 75 repetitions were completed. After two weeks another 10-minte test was performed with subjects either started FES-rowing or another 2 weeks of leg strengthening.

For FES-rowing training, subjects were instructed to train for 800 $kcal \cdot week^{-1}$ (3,360 $kJ \cdot week^{-1}$) at 80% VO_2peak for a total of 12 weeks. The subjects could choose to either achieve this 800 kcal in three or four sessions per week. Oxygen consumption was monitored during physiological sub-max tests and max tests every three to four weeks to determine the corresponding power output at 80% VO_2peak. Since this power output is displayed on the monitors of the Concept 2 ergometer, the subjects could ascertain the correct exercise intensity during every training sessions. The same sub-max tests revealed the time needed to expend 800 kcal.

An example of a typical training programme:
Subject A: VO_2peak tests revealed a VO_2peak of 1.8 $L \cdot min^{-1}$. A sub-max test at 80%VO_2peak (=1.44 $L \cdot min^{-1}$) shows that power output at this intensity is 35 W.

Training at 1.44 $L \cdot min^{-1}$ is the equivalent of 1.44 ($L \cdot min^{-1}$) * 5 ($kcal \cdot L^{-1}$) = 7.2 $kcal \cdot min^{-1}$. 800 kcal would thus require 111.11 min of rowing per week. Typically this would be four sessions of 28 minutes each. During each session average power output would have to be at least 35W.

Although 800 kcal is less than the exercise volumes identified in the literature review, it was felt that more than 4 weekly sessions of 30 minutes could not be expected from subjects. However, during the programme, it was noted that even 800 $kcal \cdot week^{-1}$ was too much for most subjects. Therefore some subjects trained over a longer period than 12 weeks to compensate for missed sessions. This will be discussed in the discussion sections of Chapters 3-6.

The initial two or three FES-rowing sessions were used for instruction since most subjects were not familiar with FES-rowing. The subjects were taught to row in a similar way as able-bodied rowers, i.e. starting with the knees flexed and arms extended (front-stops), first moving the legs (leg-drive), once the legs are almost fully extended, start pulling with the arms. When the arms touch the stomach, move the arms forward again and keep the legs extended. Once the hands go over the knees, start bending the knees and return to front stops (as above). The stroke rate was not controlled during the training sessions but subjects were instructed not to go under 15 strokes per minute.

The amplitude of the stimulation was used to change intensity of the stimulation when needed. Subjects were instructed to use the minimal intensity that was needed to obtain a powerful leg movement. When the contraction started to weaken (i.e. the muscle fatigues), the intensity of the stimulation was increased until a powerful contraction was once more achieved. To prevent excessive muscular fatigue, training sessions consisted of 5 minutes of rowing followed by 2.5 minutes of rest. During the program some subjects were able to extend this to 10 minutes of rowing followed by 2.5 minutes of rest. If subjects could not generate sufficient leg power (at maximum stimulation intensity) to move the seat at an appropriate stroke rate (>15 spm), assistance was provided to complete the 5-minute interval.

2.4 Testing

Although the various studies used different tests, changes in cardiovascular fitness were of relevance to all analyses. Changes in cardiovascular fitness were measured using physiological max tests before and after FES-rowing training. Before the first FES-row max test an arms row max test was performed to determine starting intensity for the FES-row max test. The arms row max test used the following protocol: crank frequency was free, starting intensity was 10W. Each two minutes intensity was increased by 10W. The test was terminated when:

- The subjects voluntarily ceased the test due to fatigue.
- VO_2 values did not increase while power output was still increasing.
- Perceived rate of exertion reached 20 out of 20 using a Borg scale.
- Any contra-indications for continuation of the test (i.e. signs of autonomic dysreflexia, angina pectoris etc).

The maximal power output achieved in this test was used as a reference for the FES-row max test. To minimise the effect of muscular fatigue in the leg muscles, the following protocol has been developed (similar to (Wheeler et al., 2002, Verellen et al., 2007)):

Step 1: two minutes of arms only rowing at 40% maximal $PO_{arm\ cranking}$

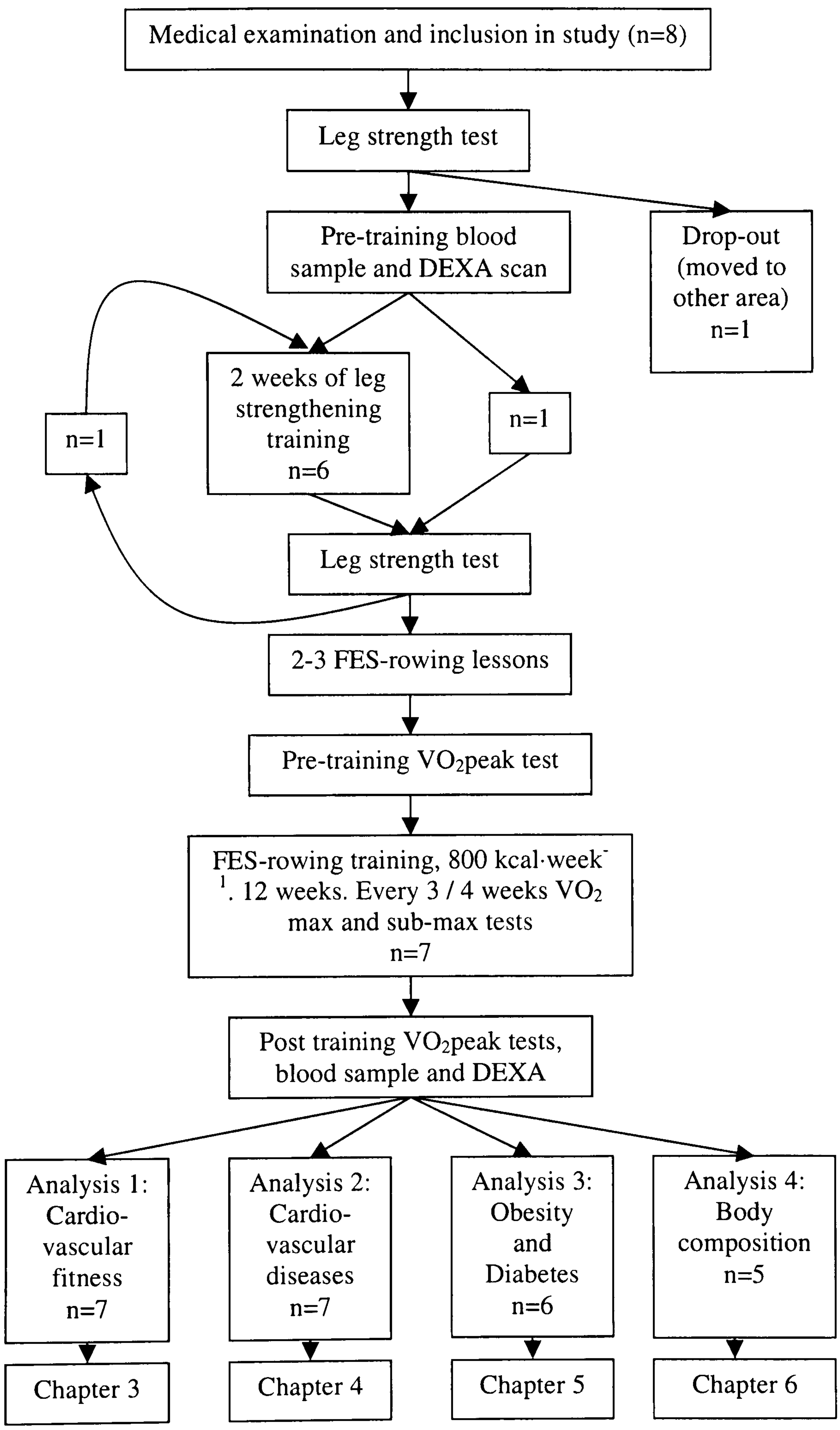
Step 2: two minutes of arms rowing with passive leg rowing at 50% maximal $PO_{arm\ cranking}$ (a research assistant is moving the seat over the rail with the same frequency as the arms rowing).

Step 3: two minutes of FES-rowing at 80% maximal $PO_{arm\ cranking}$ (i.e. arms and active leg movement).

Step 4: The subject is instructed to increase power output every 30 seconds until fatigue.

Other testing protocols will be described in the individual studies in Chapters 3-6.

2.5 Study flow chart



Chapter 3

The effect of FES-rowing training on cardio-respiratory fitness in men with paraplegia: a pilot study

3. The effect of FES-rowing training on cardio-respiratory fitness in men with paraplegia: a pilot study

At the onset of this study, FES-rowing was still in its infancy in the United Kingdom. However a second generation prototype, the RowStim II, had been used in Canada for some time and therefore this study was conducted in Edmonton, Canada under the supervision of Professor Brian Andrews and Dr Garry Wheeler.

The aim of this chapter is to confirm findings of earlier pilot studies that FES-rowing is a high intensity exercise. Results of the here presented study will be pooled with previous studies to increase statistical power. Moreover, the FES-rowing values will be compared with other FES-exercises, such as FES-cycling and FES-hybrid exercise.

This chapter has in adapted form been submitted for publications as follows:
Hettinga DM, Jeon J, Andrews BJ, Lederer R, Wheeler GD. VO_2peak in persons with spinal cord injury after functional electrical stimulation assisted rowing training.

Abstract

Seven paraplegic subjects participated in an FES-rowing training programme consisting of 32-48 sessions over a 12-week period. Training was performed at 80% VO_2peak for three or four sessions per week for a total of 277-685 $kcal \cdot week^{-1}$. Participants achieved VO_2peak values of 21.0 – 27.9 $mL \cdot kg^{-1} \cdot min^{-1}$ (1.41 – 1.96 $L \cdot min^{-1}$) after training. Combining the data with an earlier pilot study shows that FES-rowing training resulted in significant increases in cardiovascular fitness; VO_2peak increased by 10% and performance parameters such as distance rowed and sub-peak power output by 20% and 72% respectively.

Based on data from thirteen SCI subjects it can be concluded that FES-rowing is an effective high intensity cardiovascular training exercise.

3.1. Introduction

Exercise programmes have to fulfil certain criteria on exercise intensity and exercise volume in order to result in optimal health benefits. In addition to these minimal thresholds in intensity and volume, a dose-response relationship favours exercise programmes with higher intensities and larger volumes (Tanasescu et al., 2002, Lee and Paffenbarger, 2001). As discussed in Chapter 1, achieving high exercise intensities can be problematic for many individuals with SCI since only a small amount of active muscle mass can contribute to total oxygen consumption (VO_2). Indeed studies found low or even very low peak VO_2 values in a large proportion of the SCI population (Noreau et al., 1993). Some highly trained SCI individuals are able to achieve high VO_2 values with upper body exercises (e.g.(Eriksson et al., 1988, Veeger et al., 1991)), but concerns have been expressed on the role of repetitive upper body exercises in the development of musculoskeletal overuse syndrome (Burnham et al., 1993).

It would therefore be beneficial to augment VO_2 by increasing the amount of active muscles mass and not necessarily increasing the work rate of the individual muscles. The only method to achieve this is by using functional electrical stimulation (FES) to activate paralysed muscle groups.

Section 1.6 gave an overview of the reported VO_2 values in FES-cycling, FES-hybrid exercise and FES-rowing. Both cross-sectional and pre and post training values of longitudinal studies have been included in this review. Distinction should be made between VO_2peak and sub-max VO_2 values. Peak values are achieved during an incremental test aimed at achieving cardio-respiratory peak values in 10-12 minutes. The sub-max VO_2 values are from tests whereby subjects exercise at a constant load over a prolonged period of time (mostly 20-30 minutes).

Since individual subject data is not available for the majority of the included studies, average VO_2 during FES-cycling, FES-hybrid exercise and FES-rowing is based on the reported study average VO_2 and the number of subjects in the study concerning. Consequently the standard deviation for the averages is unknown, however the absolute VO_2 reported in the FES-cycling studies (peak: 1.07 $L \cdot min^{-1}$, sub-max: 0.99 $L \cdot min^{-1}$) is considerably lower than the VO_2 reported in the FES-hybrid literature (peak: 1.65 $L \cdot min^{-1}$, sub-max: 1.27 $L \cdot min^{-1}$) and FES-rowing studies (peak: 1.98 $L \cdot min^{-1}$, sub-max: 1.02 $L \cdot min^{-1}$). Controlling VO_2 for body weight results in similar differences between FES-cycling and FES-hybrid exercise and FES-rowing. However, especially the FES-rowing data is based on very small sample sizes (n=8 and n=17) and consequently replication is needed to draw more definitive conclusions.

It is also noteworthy that the more recent FES-rowing studies (Wheeler et al., 2002, Verellen et al., 2007) reported considerably higher VO_2 values than the first FES-rowing study (Laskin et al., 1993). Possibly this can be explained by the differences in technology used in the studies. The first study by Laskin et al. used a seat mounted in rollers that slid over the floor in front of a flywheel of a rowing machine. The FES-rowing machine used by Wheeler et al. and Verellen et al. consisted of a standard rowing ergometer with a special seat. It is likely that in these early stages of FES-rowing, technological developments will have an impact on the performance of FES-rowers.

Nevertheless, the results of the FES-rowing pilot studies suggest that:

- FES-rowing training can significantly increase VO_2peak (Wheeler et al., 2002), and
- FES-rowing gives reliable VO_2 values that are significantly higher than VO_2 during FES-cycling and of similar magnitude as those seen during FES-hybrid exercise and arm cranking (Verellen et al., 2007).

It would be of interest to see if these results can be replicated in a second training study. Therefore the aim of this study is to monitor changes in VO_2peak during FES-rowing training and compare the results with previously published FES-rowing data. The following hypotheses will be tested:

- FES-rowing is a high-intensity exercise.
- FES-rowing training significantly increases VO_2peak in paraplegics.

3.2. Methods

This study has been approved by the Ethics Committee of the Faculty of Physical Education and Recreation of the University of Alberta, Edmonton, Canada. All subjects gave their written informed consent before participating.

Subjects

Seven healthy men with motor complete lesions between T4 and T10 were recruited for this study. Five subjects were classified as ASIA A, the other two ASIA B. Detailed inclusion and exclusion criteria can be found in section 2.1. Full characteristics of subjects are given in Table 3.1.

Table 3.1: Subject characteristics.

Subject	Level of lesion	ASIA scale	Age (years)	Time since injury (years)
1	T5-T6	A	49	21
2	T4-T5	A	56	36
3	T10-T12	B	46	2
4	T4-T5	A	23	2
5	T5-T6	B	24	2
6	T4	A	53	21
7	T5	A	47	31

Materials and protocols

A detailed description of the materials, testing and training protocols used in this study is given in section 2.2, 2.3 and 2.4. In brief: a Concept 2 rowing ergometer was adapted to enable use for paraplegic subjects. Leg movement was induced by electrical stimulation of the quadriceps and hamstrings muscle. The rower controlled the timing of the stimulation with a switch on the handle bar of the rowing machine. This technology enabled paraplegics to exercise with their whole body.

If necessary, a leg muscle strengthening programme was conducted to ensure sufficient strength and endurance in the leg muscles. After two or three introductionary FES-rowing sessions, training programme commenced. Training was performed 3-4 times per week for at least 12 weeks. Exercise volume was 800 $kcal \cdot week^{-1}$ and intensity was set at 80% VO_2peak. Regular (every 3-4 weeks) physiological max and sub-max tests were conducted to monitor oxygen consumption during training sessions and VO_2peak tests.

Data collection

After every FES-rowing session, distance rowed and average power output were recorded. Pre-training VO_2peak was measured after 2-3 introductionary FES-rowing sessions. Post-training VO_2peak was measured one or two days after the last training session.

Analysis

Pre and post training values (VO_2peak and distance rowed) are analysed using parametric paired T-tests. In addition VO_2peak data is combined with the individual subject data from the training study by Wheeler et al. (2002) and the combined data is also analysed with parametric paired T-tests. Alpha is set at 0.05 for both tests.

3.3. Results

On average subjects completed 38 (±7) training sessions over the training period (Table 3.2). Average weekly energy expenditure from FES-rowing during this training period ranged from 277 kcal to 685 kcal (1,163 – 2,877 kJ).

Table 3.2: Training programme analysis

Subject	1	2	3	4	5	6	7	Ave ± SD
Total EE (kcal)	5554	9466	8909	6372	6989	6369	6432	7156 ±1458
Average weekly EE (kcal)	457	526	685	277	349	579	429	472 ±138
Number of training sessions	32	38	48	36	48	33	32	38 ±7

Average absolute VO_2peak for this group increased non significantly by 10% to 1.68 (± 0.20) $L \cdot min^{-1}$. Relative VO_2peak increased by 9% from 21.0 (±2.9) $mL \cdot kg^{-1} \cdot min^{-1}$ to 22.9 (±2.4) $mL \cdot kg^{-1} \cdot min^{-1}$. Power output during the training sessions (at 80% VO_2peak) increased by 72% from 32.8 (±6.0) W to 56.3 (±8.3) W. Based on detailed training data from five subjects, distance rowed per session increased by 20% from 4032 (±279) meters to 4857 (±217) meters. The combined results of the present study and a similar training study by Wheeler et al. (2002) is displayed in Table 3.3 and Table 3.4. Relative and absolute VO_2peak increased significantly after training when data is combined (Table 3.3)

Table 3.3: Changes in cardio-respiratory fitness after FES-rowing training.

	n	Increase in absolute VO_2peak		Increase in relative VO_2peak	
Present study	7	+10%	p=0.140	+9%	p=0.131
Wheeler et al. (2002)	6	+11%	p=0.001	+11%	p=0.002
Combined	13	+11%	p=0.003	+10%	p=0.004

Table 3.4 shows the individual subject data from both studies. Average pre-training VO_2peak was 1.66 ±0.32 L·min^{-1}, which is the equivalent of 21.9 ±4.0 mL·kg^{-1}·min^{-1}. Average post-training VO_2peak was 1.84 ±0.33 L·min^{-1} or 24.1 ±3.7 mL·kg^{-1}·min^{-1}. Both pre and post-training values showed large variation, ranging from 1.29 L·min^{-1} to 2.66 L·min^{-1} and 16.3 mL·kg^{-1}·min^{-1} to 33.5 mL·kg^{-1}·min^{-1}.

Table 3.4: Peak oxygen consumption before and after FES-rowing training.

Study	Subj.	Pre-training VO_2peak (L·min^{-1})	Post-training VO_2peak (L·min^{-1})	Pre-training VO_2peak (mL·kg^{-1} ·min^{-1})	Post-training VO_2peak (mL·kg^{-1} ·min^{-1})
Present study	1	1.47	1.74	19.2	23.2
	2	1.85	1.78	23.3	23.5
	3	1.42	1.71	16.9	21.0
	4	1.52	1.96	18.5	21.5
	5	1.59	1.41	24.7	21.5
	6	1.43	1.43	21.4	21.8
	7	1.45	1.73	22.9	27.9
Wheeler et al. 2002	1	1.88	2.07	23.7	26.1
	2	1.70	1.85	22.3	23.3
	3	1.49	1.77	18.8	22.3
	4	1.29	1.60	16.3	20.2
	5	2.45	2.66	30.9	33.5
	6	2.04	2.18	25.7	27.5
Average	n=13	1.66 ±0.32	1.84 ±0.33	21.9 ±4.0	24.1 ±3.7

3.4. Discussion

The increase in VO_2peak and distance rowed was of similar magnitude as the improvements reported by Wheeler et al. (2002), although the increase in VO_2peak in the present study failed to reach statistical significance. Since both the present study and the study by Wheeler and colleagues used similar training and testing protocols in similar subject populations, the data can be combined to create more statistical power. The combined data of 13 paraplegic subjects showed that VO_2peak increases significantly by 11% after 24-36 FES-rowing sessions (pre: 1.66 ±0.32 $L \cdot min^{-1}$ post: 1.84 ±0.33 $L \cdot min^{-1}$). Body weight after training was not available for the study by Wheeler et al., however an estimate can be made based on the pre-training values and the average change in body weight seen in the present study. Average bodyweight before training was 79.3 kg for the six subjects in Wheeler's study. The average body weight before training of the seven subjects of the present study was 73.80 kg and this did not change after training (73.79 kg), although it should be noted that one individual (subject 4) gained weight over the training period and this might have skewed the results. Without this individual, body weight decreased by 2.10% for the group, however since subject 4 still showed increases in cardio-respiratory fitness, it was decided not to exclude the data from this individual. Therefore the relative VO_2peak of the six subjects was calculated based on the pre-training body weight reported by Wheeler. Relative VO_2peak also increased significantly by 10% to 24.1 ±3.7 $mL \cdot kg^{-1} \cdot min^{-1}$.

The six subjects in the study by Wheeler et al. (2002) significantly increased their distance rowed per training session by 25% from 3028 ±620 m to 4012 ±588 m ($p<0.05$). Due to missing data this parameter is only available for five subjects in the present study. This subgroup significantly increased their distance rowed by 20% from 4032 ±279 m to 4857 ±217 m ($p=0.003$). A combined score cannot be calculated since individual data from the subjects in Wheeler et al's study is not available. It should be noted however that the training volume for the subjects in the Wheeler et al study was set at three 30-minute sessions per week. The training volume in the present study was 800 $kcal \cdot week^{-1}$, which translated into three or four weekly session of 26-35 minutes. This explains the higher values reported for subjects in the present study.

It is noteworthy that VO_2peak increase by ten per cent while sub-max parameters, i.e. power output at 80% VO_2peak and distance rowed per session, increased by respectively 72 and 20 per cent. This implies a large increase in efficiency and is perhaps a better indicator of cardiovascular fitness as most activities of daily living take place at sub-max intensities.

The cross-sectional study by Verellen et al. (2007) on VO_2peak during FES-rowing and various other types of exercise showed that the five subjects reached an average VO_2peak of 2.15 ±0.2 $L \cdot min^{-1}$ or 25.6 ±3.0 $mL \cdot kg^{-1} \cdot min^{-1}$. The absolute VO_2peak reported by Verellen et al. (2007) is considerably higher than the values reported in the two training studies (1.84 ±0.33 $L \cdot min^{-1}$), however this can be explained by differences in body weight (Verellen et al.: 84.3 ±5.3 kg, Wheeler et al.: 79.3 ±12.1 kg, present study: 73.80 ±8.7 kg). Controlling for body weight by calculating relative VO_2peak shows that the VO_2peak values achieved by the five subjects in Verellen's study was comparable to the post-training score of the 13 subjects in the training studies (25.6 ±3.0 $mL \cdot kg^{-1} \cdot min^{-1}$ and 24.1 ±3.7 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively).

The 11% increase in absolute VO_2peak after FES-rowing training (n=13) is comparable to the 13% increase in the same parameters reported in two FES-hybrid exercise training studies (n=16) (Krauss et al., 1993, Mutton et al., 1997). However the increase in absolute VO_2peak after FES-cycling training is considerably higher. Nine FES-cycling studies report an average increase of 22% in absolute VO_2peak (n=86) (Barstow et al., 1996, Burke-Gurney et al., 1998, Goss et al., 1992, Hooker et al., 1992, Hooker et al., 1995, Krauss et al., 1993, Mutton et al., 1997, Pollack et al., 1989, Mohr et al., 1997a). It is noteworthy however that post-training values remain well below pre-training values of FES-hybrid and FES-rowing studies. This difference in training response can be explained by differences in subject characteristics. Forty-two per cent of the subjects in FES-cycling training studies were tetraplegic, while only eight per cent of the FES-rowing subjects were tetraplegics. A similar trend is visible in the

FES-hybrid exercise subjects, although there are only data from eight subjects. Tetraplegics are likely to benefit more from cardiovascular FES-exercise since the FES-induced increases in active muscle mass form a relative large percentage of their available muscle mass. In addition it is reasonable to expect a lower level of exercise tolerance in individuals with more extensive paralysis, and consequently these persons would benefit more from an exercise programme.

Pooling all VO_2peak observations in FES-rowing from two training studies and one cross-sectional study shows that on average a VO_2peak of 1.81 $L{\cdot}min^{-1}$ is achieved. Figure 2.1 shows that this is considerably higher than the VO_2peak reported in twelve FES-cycling studies (Barstow et al., 1996, Barstow et al., 2000, Bhambhani et al., 2000, Burke-Gurney et al., 1998, Goss et al., 1992, Holme et al., 2001, Hooker et al., 1992, Hooker et al., 1995, Krauss et al., 1993, Mohr et al., 1997a, Mutton et al., 1997, Pollack et al., 1989) and marginally higher than VO_2peak reported in four FES-hybrid exercise studies (Krauss et al., 1993, Mutton et al., 1997, Raymond et al., 1999, Verellen et al., 2007). Figure 3.1 shows the average VO_2peak reported during the FES-cycling, FES-hybrid exercise and FES-rowing. Since individual subjects data was not available for the FES-cycling and FES-hybrid exercise studies, the range included in the graph is the range in average VO_2peak reported in the studies.

To date, only one study has directly compared VO_2peak in FES-rowing with VO_2peak other types of exercise in SCI (Verellen et al., 2007). Although VO_2peak during FES-rowing was the higher than during FES-cycling, arm cranking and FES-hybrid exercise, only the difference with FES-cycling reached statistical significance.

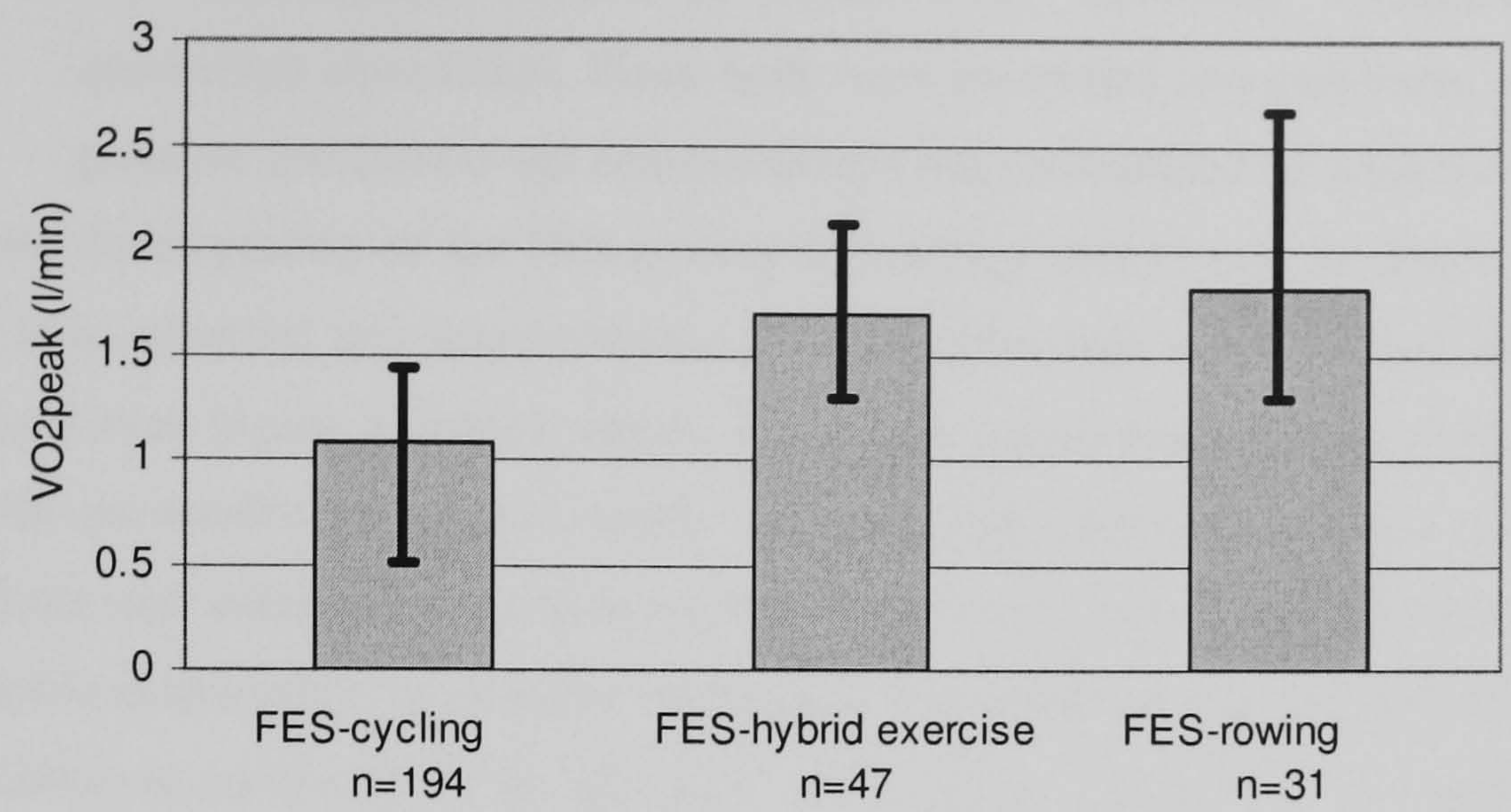


Figure 3.1: Average VO_2peak reported in the literature for FES-cycling, FES-hybrid exercise and FES-rowing. Grey columns represent average values and black lines represent the range. All studies reporting absolute VO_2peak values before or after training or cross-sectional measurements are included in this graph (12 FES-cycling studies, 4 FES-hybrid exercise studies, 3 FES-rowing studies).

On average FES-rowing gives a VO_2peak of 1.92 $L \cdot min^{-1}$ or 24.5 $mL \cdot kg^{-1} \cdot min^{-1}$, although some individuals achieved as much as 2.66 $L \cdot min^{-1}$ (33.5 $mL \cdot kg^{-1} \cdot min^{-1}$). The fact that the present study resulted in lower values than previously reported, might be caused by mechanical shortcomings of the rowing machine. These main shortcoming identified in his study include:

- The extra rolling resistance in the seat carriage system caused by the rocking of the seat-carriage system. The high backrest has resulted a long moment arm that results in large forces on the rollers that are supposed to keep the seat carriage system on the monorail.
- The inability to adjust the forces needed to support the hamstring action in the return phase of the rowing motion. The spring that was attached to the seat and the front end of the rowing machine could not easily be adjusted and consequently the spring was either too strong (which puts additional stress on the quadriceps during the drive phase) or too weak (which impaired the forward motion).

- The coordination needed to switch from hamstring stimulation to quadriceps stimulation. Since both were controlled independently, it was possible that hamstrings and quadriceps were stimulated simultaneously.

Future developments of the FES-rowing technology should address these issues and it is expected that improvements in these areas will enable FES-rowers to achieve even higher VO_2peak values. These high values could be very important in the prevention of cardiovascular diseases, non-insulin dependant diabetes mellitus and obesity since studies in able-bodied subjects have identified a dose-response relationship for exercise and health. In addition it appears that exercise intensities in excess of 21 $mL \cdot kg^{-1} \cdot min^{-1}$ are superior in reducing risk factors for cardiovascular diseases (Tanasescu et al., 2002). Moreover, exercising at high oxygen consumption values is a time-effective way of achieving large exercise volumes. Large exercise volumes could form a significant part of the recommended weekly amount of physical activity (2,000 $kcal \cdot week^{-1}$ is often mentioned as the optimal volume).

3.5. Conclusion

The results of the present FES-rowing training study support previous observations of high VO_2peak values and large increases in VO_2peak after FES-rowing training. The average VO_2peak during FES-rowing is considerably higher than VO_2peak seen during FES-cycling or FES-hybrid exercise, although it should be noted that these values were achieved in different subjects. One direct comparison supports the superior VO_2peak values of FES-rowing. This could have important implications for the prevention of cardiovascular diseases, non-insulin dependant diabetes mellitus and obesity.

The VO_2peak values achieved in the present FES-rowing study are lower than those previously reported, although it is likely that this was a consequence of mechanical limitations rather than physiological limitations. Future studies should aim to improve the return phase of the rowing motion and reduce the rolling resistance of the rowing machine.

Nevertheless, the results of the current pilot study support the hypotheses:

- FES-rowing is a high-intensity exercise.
- FES-rowing training significantly increases VO_2peak in paraplegics.

Chapter 4

The effect of FES-rowing training on risk factors for cardiovascular diseases in men with paraplegia: a pilot study

4. The effect of FES-rowing training on risk factors for cardiovascular diseases in men with paraplegia: a pilot study

The previous chapter has shown that FES-rowing is indeed a high intensity exercise, which implies that large reductions in the risk for cardiovascular diseases can be achieved. Therefore central in this chapter is the hypothesis:

- FES-rowing training will improve lipid profile of persons with paraplegia.

This chapter presents blood lipids and cholesterol parameters from the same seven volunteers who participated in the study described in Chapter 3.

Abstract

Seven paraplegic subjects participated in a FES-rowing training programme to study the effects of exercise training on cholesterol and blood lipids. The participants trained for 32-48 sessions in a 12-week period at 80% VO_2peak. Average weekly energy expenditure ranged from 277 to 685 kcal. No significant changes were found in total cholesterol, HDL, LDL, free fatty acids, triglycerides, body weight or various lipid ratios. Statistical power could have been impaired by the inclusion of one outlier in a small group of subjects. Training volume showed statistically significant correlations with the change in body weight (r=-0.87), total cholesterol (r= -0.91), free fatty acids (r= -0.83), triglycerides (r= -0.81), TC/HDL ratio (r= -0.83) and LDL/HDL ratio (r= -0.76). The data suggests that high volume exercise training is essential if risk factors for cardiovascular diseases are to be lowered. High intensity exercises are the most time-effective way of achieving large exercise volumes, but technological limitations of the RowStim II might have prevented the subjects from achieving higher intensities and larger volumes.

4.1. Introduction

Cardiovascular diseases (CVD) are a major threat to the health of persons with spinal cord injury (SCI), as described in Chapter 1 (Samsa et al., 1993, Whiteneck et al., 1992). CVD are characterized by thickening of the arterial wall, caused by plaque forming as a result of microscopic injury to the arterial wall and lipid accumulation on the site of injury (Durstine, 2001). Elevated total blood cholesterol levels (TC) (>200 $mg{\cdot}dL^{-1}$) is a well-defined risk factor for plaque forming (Pekkanen et al., 1990). Reducing TC in patients with a history of myocardial infarction results in decreased mortality and morbidity of coronary heart diseases (CHD) (1984b, 1984a, Shepherd et al., 1995), while the effectiveness of similar interventions in non-patients is less clear (The Coronary Drug Project Research Group, 1975, Committee of Principal Investigators, 1978).

Although total cholesterol is a good indicator of CVD risk, more accurate risk estimates can be made when the various sub-fractions of cholesterol are considered. Low Density Lipoprotein Cholesterol (LDL) is primarily responsible for the transport of triglycerides (TG) from the liver, where a large amount of TG is stored, to the peripheral tissue (including possible plaque sites in the arteries). High Density Lipoprotein Cholesterol (HDL) has an opposing function; transport of TG from the periphery to the liver. Consequently, LDL is also known as the 'bad cholesterol' and HDL as the 'good cholesterol', however both play an essential role in lipid metabolism and various other physiological pathways (Durstine, 2001).

Lowering LDL in patients who have previously experienced a coronary event results in a reduced CHD mortality (Scandinavian Simvastatin Survival Study Group, 1994), however in non-patients HDL is a better marker for the overall risk for CHD (Durstine, 2001). The Framingham cohort study found that men with the lowest HDL concentrations ($\leq$ 46 mg·dL^{-1}) had a six-fold higher risk for CHD than men with the highest HDL levels ($\geq$ 67 mg·dL^{-1}) (Gordon et al., 1977, Castelli et al., 1986). Of particular interest was the observation that even in subjects with low total cholesterol levels, HDL was still of predictive value for myocardial infarction (Abbott et al., 1988). Consequently, the total cholesterol/HDL ratio and the LDL/HDL ratio are strong CHD risk predictors, much stronger than total cholesterol or HDL levels alone (Durstine, 2001). In addition, triglycerides (TG) have been identified as a good marker for CHD risk; high TG levels are associated with increased risk for CHD (Brunzell and Austin, 1989).

Adequate (aerobic) exercise programmes can to a more or lesser degree influence all the above mentioned risk factors. The previously described review by Durstine and colleagues (2001) concluded that, based on the results of multiple training studies, exercise volumes of >1,200 kcal·week^{-1} were sufficient to increase HDL and decrease triglycerides. The same review also considered evidence from cross-sectional studies and this showed slightly higher optimal volumes of 1,500-2,200 kcal·week^{-1} for improvements in HDL and TG. The differences in the conclusions from longitudinal and cross-sectional studies might be explained by the presence of many potential confounders like body weight, differences in exercise regimes, alcohol intake, medication and diet. While cross-sectional studies can be valuable for hypothesis generation and exploration, causal relations cannot be proven by cross-sectional studies. Consequently, the 1,200 $kcal \cdot week^{-1}$ found by Durstine et al. (2001) based on longitudinal studies seems more valid than the higher volumes reported in cross-sectional studies.

The effect of exercise on total cholesterol and LDL is less well established and consequently Durstine and colleagues (2001) could not determine optimal exercise volumes for improvements in total cholesterol and LDL.

Although the effect of exercise on lipid profile is well documented, discussion remains on the exact mechanism behind this (Durstine, 2001). Adherence to an exercise programme is often accompanied by changes in body composition, in particular a decrease in fat mass. This change in body fat can have an effect on lipid profile. Although from a physiological point of view it is interesting to distinguish the two, from a clinical point of view, both lead to a reduction in overall risk for CVD and the exact mechanism is less crucial.

The above discussed studies were conducted in able-bodied subjects and it remains questionable if these recommendations also apply to the SCI population. Most studies agree that persons with SCI more often show elevated LDL levels and depressed HDL levels while there is conflicting evidence on total cholesterol levels (Washburn and Figoni, 1999, Bauman and Spungen, 2001). It should be noted however that in the majority of these studies possible confounders were not considered (e.g. alcohol intake, smoking, dietary intake of lipids, ethnicity) (Washburn and Figoni, 1999, Bauman et al., 1998). Physically active individuals with SCI appear to have a better lipid profile than sedentary individuals, which implies that also in SCI exercise plays a vital role in maintaining healthy blood lipid levels (Brenes et al., 1986, Bauman et al., 1992b, Hooker and Wells, 1989). In a review, Washburn and Figoni reported that increased physical activity was associated with higher HDL levels in SCI, although no description of the optimal exercise programme could be given due to the low quality and small sample size of most studies (Washburn and Figoni, 1999).

Only a few studies have investigated optimal exercise programmes for improvements in lipid profile in SCI. Hooker and Wells (1989) investigated the effectiveness of low and moderate intensity wheelchair ergometry training on lipid profile of 11 untrained SCI volunteers. Both exercise programmes consisted of three 20-minute sessions per week over an eight week period. The low intensity training (50-60% of maximal heart rate reserve) did not result in any changes in total cholesterol, TG, HDL or LDL, while the moderate intensity training (70-80% of maximal heart rate reserve) resulted in significant increases in HDL and decreases in TG, LDL and TC/HDL ratio. Of interest is that the lipid profiles of the subjects in this study were all within the normal range before starting the programme.

Similar benefits of higher exercise intensities were reported by De Groot et al. (2003). Six recently injured SCI volunteers participated in an eight week interval training programme consisting of three one-hour sessions per week during which subjects arm cranked for three minutes followed by two minutes of rest. Half the group exercised at 40-50% of heart rate reserve and the other half at 70-80% of heart rate reserve. The higher intensity group showed significantly larger reductions in TG and TC/HDL ratio than the low intensity group. Differences between the two groups in total cholesterol, LDL or HDL did not reach statistical significance.

Although these two studies by Hooker et al. (1989) and De Groot et al. (2003) suggest that higher intensities are superior in improving lipid profile (in particular the TC/HDL ratio) in SCI, the small sample size and the variation in exercise programmes make generalisation of the results difficult. Further evidence on the effectiveness of exercise on lipid profile might come from cross-sectional studies, although such research designs are inadequate in proving causal relationships.

In the able-bodied, inverse correlations have been reported for aerobic fitness and triglycerides, total cholesterol and LDL (Castelli, 1984, Berg et al., 1980, Schnabel and Kindermann, 1982). Positive correlations have been found for aerobic fitness and HDL (Gordon et al., 1977). Similar findings have been reported in SCI; positive correlations for aerobic power and HDL and negative correlations for aerobic power and TC/HDL ratio, triglycerides and LDL/HDL ratio (Bostom et al., 1991, Bauman et al., 1992b). These studies suggest that persons, who have the highest levels of cardiovascular fitness, also have the most beneficial lipid profiles (i.e. high HDL and low TC, LDL and triglycerides). However, Jansen et al. commented that these findings in SCI could have been confounded by other possible determinants of lipid profile, including age, level of lesion, smoking habits, alcohol consumption, genetic and anthropometric factors (Janssen et al., 1997). In a larger cohort of 37 SCI subjects studied by Janssen et al., age, smoking behaviour and activity level (sport participation) were the most important determinants of lipid profile. Absolute VO_2peak was not significantly correlated with any of the lipid parameters, while relative VO_2peak showed moderate correlations with total cholesterol (r= -0.39), LDL (r= -0.44), TC/HDL ratio (r= -0.35) and HDL/LDL ratio (r= 0.45).

In summary; there is limited evidence available on the effect of exercise intensity on lipid profile in SCI. However the few studies conducted in this area tend to support the superior effectiveness of high intensity exercise programmes. Given the high intensities previously reported in FES-rowing, it would be of interest to investigate the effect of FES-rowing training on lipid profile in SCI. Extrapolating from previous studies in FES-rowing and the current knowledge on the effect of exercise on blood lipids in SCI, we expect lipid profile to improve after FES-rowing training.

4.2. Methods

This study has been approved by the Ethics Committee of the Faculty of Physical Education and Recreation of the University of Alberta, Edmonton, Canada. All subjects gave their written informed consent before participating.

Subjects

Seven healthy men with motor complete lesions between T4 and T10 were recruited for this study. Five subjects were classified as ASIA A, the other two ASIA B. Complete inclusion and exclusion criteria can be found in section 2.1. Full characteristics of subjects are given in Table 4.1.

Table 4.1: Subject characteristics.

Subject	Level of lesion	ASIA scale	Age (years)	Time since injury (years)
1	T5-T6	A	49	21
2	T4-T5	A	56	36
3	T10-T12	B	46	2
4	T4-T5	A	23	2
5	T5-T6	B	24	2
6	T4	A	53	21
7	T5	A	47	31

Materials and protocols

A detailed description of the materials, testing and training protocols used in this study is given in Chapter 2. In brief: a Concept 2 rowing ergometer was adapted to enable use for paraplegic subjects. Leg movement was induced by electrical stimulation of the quadriceps and hamstrings muscle. The rower controlled the timing of the stimulation with a switch on the handle bar of the rowing machine. This technology enabled paraplegics to exercise with their whole body.

If necessary, a leg muscle strengthening programme was conducted to ensure sufficient strength and endurance in the leg muscles. After two or three introductionary FES-rowing sessions, training programme commenced. Training was performed 3-4 times per week for at least 12 weeks. Exercise volume was

800 kcal·week^{-1} and intensity was set at 80% VO_2peak. Regular (every 3-4 weeks) physiological max and sub-max tests were conducted to monitor oxygen consumption during training sessions and VO_2peak tests.

Body composition

Dual Energy X-ray Absorptiometry (DEXA) was used to assess body composition before and after the FES-rowing program. With the subject in supine position a whole body scan was made by an experienced technician. The scan revealed body fat, lean mass and fat percentage for the individual body parts and summated for total body composition.

Blood sampling and analysis

Blood samples were taken from an antecubital vein after 12 hours of overnight fasting between 8.00 am and 10.00 am. Blood was collected in chilled vacutainers containing heparin. Blood was separated by centrifugation at 4°C for 12 minutes at 1200 rpm. Plasma samples were stored at -80°C till analysis. Samples were taken at two points in time; before starting leg strengthening/FES-rowing and after completion of the FES-rowing program.

Plasma samples were sent off for analysis. An experienced technician analysed the samples for Total Cholesterol (TC), High-Density Lipoprotein Cholesterol (HDL-C), Free Fatty Acids (FFA) and Triglycerides (TG) enzymatically. Low-Density Lipoprotein Cholesterol (LDL-C) has been calculated from TC, TG and HDL-C.

Statistics

Level of significance was set at 0.05 for all tests. Normal distribution plots were compiled for each parameter after which the authors made the decision to treat the data non parametric or parametric. Non-parametric Wilcoxon tests for related samples and parametric t-tests were used to test differences between pre and post values.

Pearson's correlation coefficients (for parametric variables) and Spearman's rank order correlation coefficients (for non-parametric variables) were used to test for any correlation between training intensity (measured by average weekly energy expenditure) and the change in dependant parameters. The change in fat mass was regarded as a possible confounder. This was tested by Spearman's rank order correlation coefficients between the change in fat mass and the change in effect parameters. Additionally an ANOVA analysis was conducted to predict the changes in lipid profile out of training volume and/or change in fat mass. The Statistical Package for Social Sciences (SPSS version 11.0) software was used for all analyses.

4.3. Results

Table 4.2 displays the achieved training for all subjects. The average program consisted of 38 (± 7) training sessions with an average weekly energy expenditure (training volume) of 472 (± 138) kcal·week^{-1}. Subject 4 had the lowest average weekly energy expenditure (277 kcal·week^{-1}).

Table 4.2: Analysis of training stimulus

Subject	1	2	3	4	5	6	7	Ave ± SD
Total EE (kcal)	5554	9466	8909	6372	6989	6369	6432	7156± 1458
Average weekly EE (kcal)	457	526	685	277	349	579	429	472± 138
Number of training sessions	32	38	48	36	48	33	32	38.1± 7.1
Achieved PO (W)	47.8	43.1	36.6	46.5	44.3	51.2	44.7	44.9± 4.5

The plots for body weight, fat mass and LDL showed large variation from the normal distribution and therefore statistical tests involving these variables were non-parametric. All other variables were tested using parametric tests.
Average VO_2peak for the group increased non significantly by 9.8% to 1.68 (± 0.20) L·min^{-1}, which is the equivalent of 22.9 (± 2.4) mL·kg^{-1}·min^{-1} (see Chapter 3 for more detailed information on VO_2).

Body weight decreased for five subjects and increased in two subjects (see Figure 4.1). The two subjects who gained weight had the lowest training volumes. If the group average was calculated without the outlier (subject 4), body weight decreased significantly by 1.6 kg. The decrease in body fat percentage (-1.1% to 24.4%) failed to reach statistical significance (p=0.068).

The individual changes in lipid profile are displayed in Table 4.3 and 4.4. Since subject 4 gained a considerable amount of body weight (a known confounder for changes in lipid profile), his data was excluded from the pre-post comparisons.

For clarity, subject 4's data has been displayed in the Tables and Figures in this chapter. Changes in Total Cholesterol (-6.3%), Free Fatty Acids (-29.9%), Triglycerides (-21.2%) and Triglycerides/HDL ratio (-13.8%) were considerable but failed to reach statistical significance.

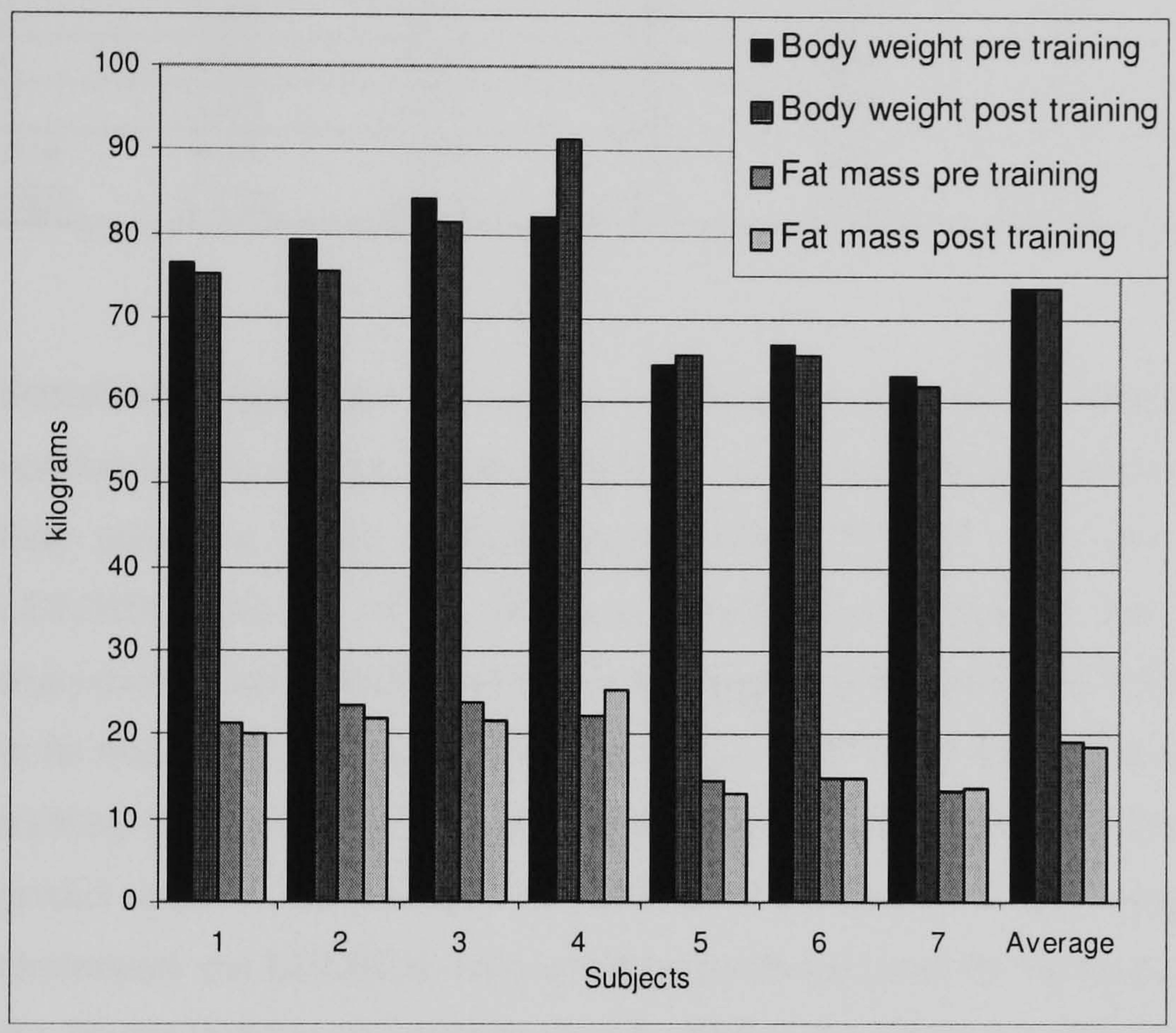


Figure 4.1: Body composition before and after FES-rowing training

Table 4.3: Lipid profile before and after FES-rowing training.

	Total Cholesterol ($mg{\cdot}dL^{-1}$)		HDL-C ($mg{\cdot}dL^{-1}$)		LDL-C ($mg{\cdot}dL^{-1}$)		Free Fatty Acids ($mmol{\cdot}l^{-1}$)		Triglycerides ($mg{\cdot}dL^{-1}$)	
	Pre	post	Pre	post	pre	Post	pre	Post	pre	post
1	197.8	219.1	32.2	32.7	111.9	140.6	0.20	0.11	116.9	99.6
2	172.2	171.3	35.4	38.0	99.4	100.4	0.49	0.47	81.3	71.5
3	237.7	186.8	26.6	33.8	99.8	107.8	0.43	0.16	242.2	98.1
4	239.9	298.4	34.5	28.6	148.2	155.2	0.24	0.43	124.2	249.1
5	164.7	175.5	47.9	50.6	87.1	102.2	0.23	0.14	64.7	49.4
6	210.0	163.7	24.9	18.0	141.1	83.6	0.35	0.20	42.0	52.7
7	153.8	148.3	31.9	22.9	102.6	101.2	0.21	0.26	95.7	135.1
Ave ±SD	196.6 ±34.6	194.7 ±50.7	33.3 ±7.5	31.1 ±10.6	112.9 ±23.0	113.0 ±25.3	0.31 ±0.12	0.25 ±0.14	109.6 ±65.1	107.9 ±69.1

Table 4.4: Lipid ratios before and after FES-rowing training.

	TC/HDL-C Ratio		**LDL-C/HDL-C ratio**		**TG/HDL-C ratio**	
	pre	Post	pre	post	pre	post
1	6.15	6.70	3.48	4.30	3.62	3.04
2	4.86	4.51	2.81	2.64	2.30	1.88
3	8.97	5.53	3.76	3.19	9.14	2.90
4	6.95	10.44	4.29	5.43	3.60	8.71
5	3.44	3.47	1.82	2.02	1.36	0.98
6	8.45	9.09	5.68	4.64	3.85	7.50
7	4.83	6.49	3.22	4.43	1.32	2.31
Ave	6.24	6.60	3.58	3.81	3.60	3.90
±SD	± 2.02	± 2.46	± 1.21	± 1.21	± 2.67	± 2.97

Statistically significant correlation coefficients were found between training volume and the change in body weight (r= -0.87), total cholesterol (r= -0.91), free fatty acids (r= -0.83), triglycerides (r= -0.81), TC/HDL ratio (R= -0.83) and LDL/HDL ratio (r= -0.76). Of these variables the changes in free fatty acids, triglycerides and TC/HDL ratio were also significantly correlated with the change in fat mass (0.81, 0.87 and 0.86 respectively). ANOVA revealed that a model with training volume and the change in fat mass as the independent variables could not predict any of the changes in lipid profile. However, the change in total cholesterol and LDL/HDL ratio could be predicted from the training volume, and the change in fat mass could be used to predict the change in HDL and TG/HDL ratio. The changes in free fatty acids, triglycerides and TC/HDL ratio could be predicted from either training volume or the change in fat mass.

4.4. Discussion

Twelve weeks of FES-rowing training resulted in considerable improvements in lipid profile of three paraplegic men, but the group changes failed to reach statistical significance. This could imply that

- The small sample size was inadequate, or
- There was no clinical benefit.

Sample size in this study was small, but comparable to many other intervention studies in SCI. However the variation in training stimulus varied widely, in particular one subject (subject 4) had a very low training volume (277 kcal·week^{-1} 1.4 standard deviations below the average) combined with a considerable increase in weight (9.2 kg). It is likely this increase in body weight, in particular the increase in body fat (2.9 kg) is the reason why all his blood lipid parameters were worse after the 12 week period. Individual improvements in lipid profile were considerable in three subjects.

Exercise volume achieved by the subjects (277-685 kcal·week^{-1}) was below the thresholds known to improve lipid profile in able-bodied (1,200-2,000 kcal·week^{-1}). Subjects trained 3-4 times per week for 30-45 minutes per session and it is probably not realistic to expect subjects to train for much longer or more frequently. The VO_2peak values after the 12-week training period showed that all subjects had values above 21 mL·kg^{-1}·min^{-1} (6 MET), however oxygen consumption during the training session was likely to be below these peak values. This implies that the recommended exercise intensity of 21 mL·kg^{-1}·min^{-1} was not achieved. Subsequently optimal reduction in risk for CVD might not have been achieved.

Other exercise interventions studies in SCI have found mixed results on lipid profile, perhaps because the exercise programmes used in these studies differed greatly. Since exercise intensities and volumes achieved in these studies is not always reported, it is difficult to evaluate the effect of exercise intensity and volume on optimal lipid profile improvements.

Upper body exercise programmes (like wheelchair ergometry (Midha et al., 1999) or arm cranking (El-Sayed and Younesian, 2005)) have resulted more often in no statistically significant improvements in lipid profile than in significant improvements. Duran et al. (2001) trained 13 thoracic SCI volunteers using a comprehensive exercise programme (including aerobic resistance training) (Duran et al., 2001). The intensity of the training was increased over the weeks from 40% to 80% heart rate reserve (HRR) and duration of the sessions increased from 15 to 40 minutes per session (3 sessions per week). LDL, HDL and TC/HDL were unchanged after this 16 week programme. Better results were reported in five spinal cord injured individuals who performed 12 weeks of arm cranking training, three times a week for 30 minutes as reported by El-Sayed et al. (El-Sayed and Younesian, 2005). Although total cholesterol did not change, HDL increased significantly (HDL is a better predictor for CVD risk). Midha et al. studied 12 subjects with a lower limb disability (of which ten had SCI) (Midha et al., 1999). They trained for 10 weeks, 2-3 sessions per week for 22.5 minutes at the ACSM recommended training intensity. Total cholesterol decreased significantly, however the better predictors for CVD risk (HDL and TC/HDL ratio) did not change significantly. Nash and colleagues trained five paraplegic men for three months using upper body resistance and endurance exercises (three sessions per week) (Nash et al., 2001). Total cholesterol and triglycerides did not change significantly after the training period but HDL increased significantly and LDL decreased significantly. Although the sample size in these studies was very small and the exercise programmes varied widely, some increases in HDL and decreases in total cholesterol and LDL have been observed after exercise training in SCI.

As stated before, the fact that changes in lipid profile did not reach statistical significance could have been caused by the variation in training stimulus (ranging from 277 to 685 $kcal \cdot week^{-1}$). To control for this variation, correlation coefficients between training volume and the change in lipid profile have been calculated. This showed that a large training volume is strongly associated with larger reductions in body weight, total cholesterol, free fatty acids, triglycerides, TC/HDL ratio and LDL/HDL ratio. This suggests that large exercise volumes are more effective in reducing risk factors for CVD than low volume programmes, similar to the able-bodied situation.

No previous studies have looked at training volume and CVD risk factors in SCI. Two studies have looked at the effect of exercise intensity on lipid profile in SCI and both reported superior effect of the higher intensity group (70-80% heart rate reserve versus <50% heart rate reserve) (de Groot et al., 2003, Hooker and Wells, 1989). Although both studies used different exercise programmes, within the studies the low and high intensity group followed a similar programme (only exercise intensity varied). Consequently the high intensity groups would also have achieved higher exercise volumes than the lower intensity groups (volume= intensity * time). The authors explained the differences in improvements in lipid profile parameters by the difference in exercise intensity between the groups, however it is unknown what the role of exercise volume was in these studies. Exercise volume increases linearly with increasing intensity and subsequently exercise volume might have been a confounder that has not been taken into consideration in the two studies by De Groot et al. (2003) and Hooker and Wells (1989).

The correlations between training volume and the improvement in total cholesterol, free fatty acids, triglycerides, TC/HDL ratio and LDL/HDL ratio seen in this study were not affected by changes in fat mass since the change in fat mass was only correlated with the change in HDL ($r= -0.77$, $p=0.04$). A decrease in fat mass was only associated with an increase in HDL. From a clinical perspective, improvements in lipid profile due to a decrease in fat mass are just as important as improvements in lipid profile directly caused by the training.

Total cholesterol is in general lower in SCI than in able-bodied (Washburn and Figoni, 1999), which is supported by our study (although some individuals peaked far above the recommended 200 $mg \cdot dL^{-1}$). However HDL levels, or more accurately the TC/HDL ratio (Freedman et al., 1994, Castelli et al., 1986), are a better predictor for CVD and these are generally worse in SCI than in able-bodied (Washburn and Figoni, 1999). HDL levels in this study are indeed low (33.3 $mg \cdot dL^{-1}$ pre training) and TC/HDL ratio high (6.2 pre training) and beyond values that are generally considered as healthy (>35 mg·dL^{-1} and <4.0 respectively) (Washburn and Figoni, 1999). FES-rowing training did not have an effect on HDL levels, potentially because it has been suggested that only vigorous exercise (>7 kcal·min^{-1}) can improve HDL levels (Washburn and Figoni, 1999). In this study 277-685 kcal (weekly energy expenditure) was burned in approximately 120 minutes (3-4 sessions of 30-40 minutes), resulting in an intensity in the range of 2.3-5.7 kcal·min^{-1}. Other exercise programmes in SCI have been inconclusive on the effect of exercise on HDL levels (Washburn and Figoni, 1999, Duran et al., 2001, El-Sayed and Younesian, 2005, Midha et al., 1999, de Groot et al., 2003).

Pre-training triglycerides levels were normal to low in most subjects, except in subject 3 and 4. Triglycerides tend to decrease with a reduction in fat mass (Midha et al., 1999) and this is visible in subjects 4 and 7, who both showed an increase in fat mass and TG after training. Those who had a lower or similar fat mass after training, also showed lowered TG levels.

Two out of the seven subjects showed a normal lipid profile (TC< 200 mg·dL^{-1}, HDL>35 mg·dL^{-1}, LDL< 130 mg·dL^{-1}, TC/HDL ratio<4.5) before and after training. As previously discussed subject 4 gained weight and subsequently showed an adverse lipid profile after training. Subject 1 also showed a more adverse lipid profile after training, but no clear explanation can be given for this subject. The remaining three subjects had on average good improvements in total cholesterol and LDL. HDL increased in one of them and decreased in the other two but stayed below the 35 mg·dL^{-1} in all cases. It is likely that a sub-group might respond better to exercise training than the group as an average. More research needs to be done to identify this sub-group, but this study suggests that those who have a normal lipid profile, will not improve further after exercise training.

Training was conducted at the power output that was associated with 80% of peak VO_2 value (as measured during a max and sub-max test in week 1, 4 and 8). VO_2 peak values increased during the 12-week programme to 21.0-27.9 mL·kg^{-1}·min^{-1}. The training intensity based on these final week values (16.8-22.3 mL·kg^{-1}·min^{-1}) are around the 21 mL·kg^{-1}·min^{-1} value that Tanasescu et al. (2002) considered as the minimal intensity to obtain a significantly lower relative risk for CHD. However it should be noted that the FES-row VO_2 max protocol used in this study might not have resulted in the true physiological max. An indication for this is the fact that all but one subject were able to exercise at a higher power output than the power output associated with 80% VO_2 max. On average subjects were able to sustain a power output 5% higher than the power output associated with supposedly 80% VO_2peak. More investigation is needed to identify a FES-row max test protocol that is able to detect the true VO_2peak during FES-rowing without peripheral fatigue in the leg muscles limiting the results.

Tanasescu et al. (2002) reported their threshold for statistical reduction in risk for CHD to be at 25 MET-h·week^{-1}. In this study subjects were training at 16.8-22.3 mL·kg^{-1}·min^{-1} (data obtained from the last week) for approximately 120 minutes per week. So training volume expressed in MET-h is in the range of 9.6-12.7 MET-h. Based on Tanasescu's data this is associated with a relative risk for CHD of 0.90, although not significantly different from the lowest training volume group.

The reasons for not reaching the optimal exercise intensity and volume, could be the result of:

- limitations in the FES-rowing equipment, and/or
- physiological limitations, and/or
- motivational problems.

The prototype of the FES-rowing machine used in this study showed a series of shortcomings that limited the rowers performance, in particular:

- Controlling the switch takes concentration since one hand operates quadriceps stimulation and the other hamstrings stimulation and it is possible that hamstrings and quadriceps were stimulated simultaneously.
- The rollers of the seat-carriage system were not designed to withstand the larger forces seen with FES-rowing. In able-bodied rowing, there are only minimal forces that would push the rollers out of line with the top flange of the monorail. However, the high backrest of the FES-rowing seat

results in a large momentum arm that results in a rocking action of the seat carriage system.

- The return phase of the rowing movement is achieved by hamstring contraction supported by a spring that pulls the seat forward. However it was difficult to fine-tune the forces needed for an effective return phase with the standard springs. For that reason most rowers needed a research assistant to help with the return phase.
- Most rowers, especially the taller ones, were slumped in their seat. The strapping arrangement prevented the rowers from falling sideways or forward, but it also pushed the shoulders of the rowers down.

Physiological limitations could also have played a role since rowers had to adhere to an interval-training programme to prevent muscular fatigue in the leg muscles. Finally, motivational factors might have played a role in some rowers for missing training sessions and consequently achieving a lower exercise volume. Future research should address these issues and if adequate solutions are found, it is expected that higher exercise intensities and volumes are achievable.

4.6. Conclusion

FES-rowing training did not result in statistically significant improvement in lipid profile of seven paraplegic men. This could have been caused by:

- Underpowered study design, and/or
- Absence of any real improvement in lipid profile.

Future studies should determine the exact underlying reasons, however the correlations between exercise volume and improvement in lipid profile that were found in this pilot study, suggest that larger improvements can be expected in exercise volume if further increased. A time effective method of increasing exercise volume is increasing the exercise intensity. This pilot study has identified limitations in the design of the FES-rowing machine and FES-rowing training, in particular:

- The inadequate return phase of the rowing motion caused by the inability to accurately assist the hamstrings action
- The extra rolling resistance caused by the rocking of the seat carriage system over the monorail.
- The problem around using two separate switches for controlling quadriceps and hamstrings stimulation and the subsequent risk for simultaneous stimulation of knee flexors and knee extensors.
- The early onset of muscular fatigue in the electrically stimulated muscles.
- The lack of motivation of some rowers to row for prolonged periods of time.

Future studies should address these issues and it is expected that clinically more relevant results can be achieved with an improved FES-rowing machine.

Chapter 5

The effect of FES-rowing training on risk factors for obesity and non-insulin dependant diabetes mellitus in men with paraplegia: a pilot study

5. The effects of FES-rowing training on risk factors for obesity and non-insulin dependant diabetes in men with paraplegia: a pilot study.

As explained in Chapter 1, obesity and non-insulin dependant diabetes (NIDDM) form a major threat to the health of persons with long-term spinal cord injury. The study explained in Chapter 2 provided a unique opportunity to look at the effects of a whole body exercise regime on risks factors for obesity and NIDDM.

In this chapter I will present the results of the analysis of the effects of FES-rowing on leptin, glucose and insulin levels.

This chapter has in adapted form been submitted for publication as follows:
Jeon JY, Hettinga DM, Steadward RD, Wheeler GD, Bell G, Harber V. Reduced plasma leptin levels and improved insulin sensitivity after 12 weeks of exercise training in people with spinal cord injury.

Abstract

Six paraplegic subjects participated in a FES-rowing training study to investigate the effect of high intensity and high volume exercise training on glucose, insulin and leptin. On average the subjects used 614 kcal·week^{-1} over 12 weeks. Plasma leptin and glucose decreased significantly by 35% and 10% respectively. Insulin sensitivity, as measured by HOMA, improved significantly by 31%. The results suggest that FES-rowing training can significantly improve risk factors for obesity and non-insulin dependant diabetes mellitus in SCI. This is of great importance since both these conditions are more common in SCI than in the able-bodied population.

5.1 Introduction

Body weight is tightly regulated by a complex homeostatic feedback loop (Flier and Maratos-Flier, 2000, Flier, 2004). Identification of the ob gene and the characterization of the hormone leptin have greatly increased the understanding of body weight control (Zhang et al., 1994). Leptin is produced by adipose tissue and affects food intake, energy expenditure, and neuroendocrine status (Ahima and Flier, 2000). Leptin deficiency, as seen in ob/ob mice and humans with congenital leptin deficiency, causes obesity and the administration of leptin to ob/ob mice and children with congenital leptin deficiency decreases feeding, normalizes body fat and body temperature, and also corrects neuroendocrine abnormalities (Farooqi et al., 1999, Halaas et al., 1995). Although leptin deficiency results in morbid obesity in some animals and humans, most obese humans generally have elevated circulating leptin levels, which suggests that in general, human obesity is related to leptin resistance rather than leptin deficiency (Flier and Maratos-Flier, 2000, Considine et al., 1996). Individuals with SCI have significantly higher plasma leptin levels compared with the able-bodied group (Jeon et al., 2003a, Jeon et al., 2003b). Moreover, a large proportion of the spinal cord injured population is overweight or obese. However, to what extent the abnormal levels of leptin actually causes obesity in SCI is unknown.

From animal models it is known that the effect of leptin on metabolism is primarily through its action on glucose uptake in the heart, brown adipose tissue and skeletal muscle, independent of changes in plasma insulin (Haque et al., 1999). However, the action from leptin on glucose uptake in peripheral tissues is abolished after surgical or chemical sympathectomy (Minokoshi et al., 1999). Also, leptin's effect on glucose uptake was blocked by preventing the release of noradrenaline from sympathetic nerves with guanethidine treatment. Leptin administration also suppresses glucose-induced insulin secretion and stimulates hypoglycemia-induced glucagon secretion through activation of the sympathetic nervous system (Mizuno et al., 1998). This suggests that an intact sympathetic nervous system is required in order for leptin to impact glucose uptake (Minokoshi et al., 1999, Haque et al., 1999).

Moreover it also shows that body weight homeostasis is closely related to carbohydrate metabolism. Recently, this interaction has received a great deal of attention since obesity, impaired glucose tolerance, hypertension and dyslipidaemia are increasingly seen in combination. This so-called metabolic syndrome is a major threat to the health of individuals all over the world and prevalence rates as high as 20 to 50% have been reported.

Many persons with long-term SCI have dyslipidaemia, high body fat content, and impaired glucose tolerance (Bauman et al., 1999b). It is therefore of interest to investigate the metabolic syndrome in this population and possible intervention programmes, such as FES-rowing.

Previously, the effects of FES-rowing on lipid profile in SCI have been described (Chapter 4). The aim of the present study was to investigate the effects of FES-rowing training on glucose tolerance and leptin.

Exercise programmes can result in improved glucose tolerance in able-bodied persons, especially when exercises of high intensity (>6 MET) are included. In SCI however, glucose tolerance has been improved with less strenuous exercise programmes such as FES-cycling. The effect of exercise on leptin is less clear. Most studies in able-bodied subjects report a decrease in leptin after training, but in many cases this is not independent from a decrease in body fat. No data is available on the effect of exercise on leptin in SCI. The hypothesis of this study is therefore:

- FES-rowing training improves glucose tolerance in persons with SCI.
- FES-rowing training decreases leptin in persons with SCI.

5.2 Methods

The methodology for VO_2peak testing and the design of the training programme are similar to the methodology and programme explained in Chapter 2. The six subjects in this pilot study also participated in the studies presented in Chapter 3.

This study has been approved by the Ethics Committee of the Faculty of Physical Education and Recreation of the University of Alberta, Edmonton, Canada. All subjects gave their written informed consent before participating.

Subjects

Six healthy male subjects with paraplegia participated in the study (age 48.6±6, weight 70.06 ±3.28, injury levels between T4-T5 and T10). Complete inclusion and exclusion criteria are given in Chapter 2. Subject characteristics are summarized in Table 5.1.

Table 5.1: Subject Characteristics

Subject	Age (years)	Body weight Pre-training (kg)	Body weight Post-training (kg)	Time since injury (years)	Level of lesion	ASIA
1	49	76.4	75.1	21	T5	A
2	56	79.4	75.6	36	T4	A
3	24	64.5	65.5	1.5	T5	B
4	53	66.8	65.5	21	T4	A
5	47	63.2	62	31	T5	A
6	46	84.2	81.4	15	T10	A
Average (±SD)	45.8 (±11)	72.4 (±8.7)	70.9 (±7.6)	20.9 (±12)		

Materials and protocols

A detailed description of the materials, testing and training protocols used in this study is given in Chapter 2. In brief: a Concept 2 rowing ergometer was adapted to enable use for paraplegic subjects. Leg movement was induced by electrical stimulation of the quadriceps and hamstrings muscle. The rower controlled the timing of the stimulation with a switch on the handle bar of the rowing machine. This technology enabled paraplegics to exercise with their whole body.

If necessary, a leg muscle strengthening programme was conducted to ensure sufficient strength and endurance in the leg muscles. After two or three introductionary FES-rowing sessions, the training programme commenced. Training was performed 3-4 times per week for at least 12 weeks. Exercise volume was 800 $kcal \cdot week^{-1}$ and intensity was set at 80% VO_2peak. Regular (every 3-4 weeks) physiological max and sub-max tests were conducted to monitor oxygen consumption during training sessions and VO_2peak tests.

Body Composition.

Dual Energy X-ray Absorptiometry (DEXA) was used to assess body composition before and after the FES-rowing program. With the subject in supine position a whole body scan was made by an experienced technician. The scan revealed body fat, lean mass and fat percentage for the individual body parts and summated for total body composition.

Insulin sensitivity

The homeostasis model assessment (HOMA) index was calculated and used as an insulin sensitivity index by using the following formula: fasting plasma glucose ($mmol \cdot L^{-1}$) x fasting plasma insulin ($\mu U \cdot mL^{-1}$) (Matthews et al., 1985).

Blood collection

Two blood samples were drawn (before and after completion of 12 weeks of FES-rowing training). All blood samples were drawn from an antecubital vein after overnight fasting between 8:00am to 10:00am. For each sample, 21 ml of blood was drawn and collected in chilled vacutainers containing EDTA (noradrenaline assay) and heparin (insulin, leptin and glucose assay). Blood samples were separated by centrifugation at 4°C for 12 min at 3,000 rpm. Plasma was transferred to a storage vial and stored at –80°C until. Plasma samples were sent off to an experienced technician for analysis of leptin, glucose, insulin, and noradrenaline.

Analytical procedures

Blood samples were sent of for analysis. An experienced technician analysed all plasma samples from each subject in duplicate in a single assay to eliminate between-assay variation. Plasma leptin (ng·dL·) and insulin ($\mu U \cdot mL^{-1}$) were measured by RIA (human leptin RIA, human insulin RIA, Linco Research, Inc, St. Charles, MO). The intra-assay coefficients of variation (CVs) were 3.4% and 6.1% respectively. Glucose levels were measured by the enzymatic method (Glucose Analyzer II, Beckman, Irvine, CA). Plasma noradrenaline ($nmol \cdot L^{-1}$) levels were measured by HPLC with electrochemical detection (electrochemical detector model 1045, Hewlett-Packard Co., Waldbronn, Germany). The intra-assay CV for this assay was 4.0% for noradrenaline.

Statistical analysis

Since the data was not normally distributed, nonparametric statistics, Wilcoxon matched-paired signed rank test were used to determine the effects of FES-rowing on each variable. P-value was set at 0.05.

5.3 Results

Subjects expended an average of 200 ±16 kcal per training session for 36 ±3 exercise sessions. Over 12 weeks, they expended a total of 7374 ±671 kcal during exercise training (614 kcal·week^{-1} on average).

Plasma leptin (-35%), glucose (-10%) and HOMA (-31%) decreased significantly after FES-rowing training. Insulin, noradrenaline and body composition did not change significantly, although the increase in noradrenaline and decrease in insulin were considerable. Full details are given in Table 5.2.

Table 5.2: Body composition, metabolic and hormonal parameters before and after FES-rowing training in six paraplegic men.

	Pre-training	Post-training	Change
Body weight (kg)	72.4 ±3.6	71.0 ±3.0	-2%
Lean Mass (kg)	51.1 ±1.9	51.8 ±1.4	1%
Fat Mass (kg)	18.5 ±2.0	17.5 ±1.7	-5%
Body fat percentage (%)	25.4 ±1.7	24.5 ±1.5	-4%
Glucose (mg·dL^{-1})	103.2 ±6.8	92.5 ±3.4	-10% *
Insulin (μU·mL^{-1})	13.7 ±2.1	11.2 ±1.7	-18%
HOMA	3.6 ±0.8	2.5 ±0.4	-31% *
Leptin (ng·dL^{-1})	6.9 ±1.7	4.5 ±0.8	-35% *
Leptin / fat mass (ng·dL^{-1}·kg^{-1} body weight)	0.35 ±0.06	0.26 ±0.03	-26% *
Noradrenaline (nmol·L^{-1})	1.4 ±0.6	2.0 ±0.5	43%

Data are the mean ±standard error

* Statistically significant at $p<0.05$

5.4 Discussion

The aim of this study was to investigate the effect of FES-rowing training on risk factors for obesity and NIDDM in SCI. FES-rowing training resulted in a significant decrease in leptin (-35%) and a significant increase in glucose tolerance (+31%) in six paraplegic men.

Although fat mass did not change significantly, the small five per cent decrease could have influenced the change in leptin, since leptin is associated with fat mass. However, even when controlling for fat mass, leptin decreased significantly by 26%. No training studies have studied the effect of exercise on leptin in SCI before. However in able-bodied subjects, conflicting results have been reported. When weight loss occurs with training, reduction in plasma leptin levels were observed. Halle et al. (1999) studied plasma leptin levels in 20 men with NIDDM before and after six weeks of training (2,200kcal·week^{-1}). They reported that their exercise program caused a 4% weight loss and a 30% reduction in plasma leptin levels. Kohrt et al. (1996) also reported a 5% loss in body mass and a 28% reduction in plasma leptin levels after nine months of training. In the current study, we observed that a 1.93% reduction in body weight and a 5% reduction in FM result in 28% reduction in plasma leptin levels. These results are not unexpected, as leptin is known to be produced and secreted by adipose tissue (Ahima and Flier, 2000) and it is well documented that plasma leptin correlates with fat mass (Considine et al., 1996), also in SCI (Jeon et al., 2003a, Jeon et al., 2003b).

However, leptin has also been shown to change after exercise training without associated weight loss. Hickey et al. (1997) reported a reduction in plasma leptin levels in females after 12 weeks of training (4days·week^{-1}, 1200 kcal·week^{-1}) despite stable fat mass. Pasman et al. (1998) also reported a reduction in plasma leptin levels in obese males after 10 months of exercise training, independent of changes in fat mass. Therefore, the results from these studies combined with the current study suggest the existence of another factor, which influence the exercise training induced reduction in plasma leptin levels other than fat mass changes.

Noradrenaline has been suggested as such a factor since noradrenaline is known to decrease both ob gene expression and plasma leptin levels (Commins et al., 1999, Gettys et al., 1996, Pinkney et al., 1998). However in the present study noradrenaline did not increase significantly after training, which is expected in persons with high spinal lesions (Schmid et al., 1998a, Schmid et al., 1998b, Mathias et al., 1979, Frey et al., 1997).

Studies suggest that glucose metabolism is partly responsible for leptin regulation (Mueller et al., 1998, Wang et al., 1998) and glucose infusion prevents the fasting-induced leptin decline (Sonnenberg et al., 2001). Segal et al. (1996) reported that insulin resistance is associated with an elevated plasma leptin concentration in males. It is therefore possible that the improvement in insulin sensitivity found in this study has resulted in lower leptin levels after training.

It should be noted though that glucose tolerance and insulin sensitivity has been measured using HOMA, which has few limitations (Yeni-Komshian et al., 2000). HOMA is a less invasive, inexpensive, and less labor-intensive method to measure insulin resistance as compared with the golden standard; an euglycemic clamp test (Wallace et al., 2004, Keskin et al., 2005). However the results of the present study are in agreement with other FES-exercise studies in SCI. Improvements in glucose tolerance and insulin sensitivity have been reported after FES-cycling training by at least three research groups (Jeon et al., 2002, Chilibeck et al., 1999, Mohr et al., 2001). It is of interest that participants in these FES-cycling studies most likely did not achieve the threshold exercise intensity and volume needed to significantly lower the risk for NIDDM in able-bodied. This suggests that persons with SCI could benefit from exercise programmes of lower intensity and volume. However it also implies that benefits of at least similar magnitude can be achieved with programmes of higher intensity and larger volume.

5.5 Conclusion

Leptin and insulin resistance were significantly decreased after FES-rowing training in men with paraplegia. Since no changes in fat mass or noradrenaline were observed, the decrease in leptin could have been caused by the increased insulin sensitivity and decreased plasma glucose levels. However future studies need to assess this with more reliable instruments (e.g. euglycemic clamp test) in larger groups of subjects.

Nevertheless this study shows that FES-rowing could have a significant effect on risk factors for obesity and NIDDM in SCI. This is of importance since both conditions are increasingly common in the ageing SCI population.

Chapter 6

The effect of FES-rowing training on body composition in the lower body of men with paraplegia: a pilot study

6. The effect of FES-rowing training on body composition in the lower body of men with paraplegia: a pilot study

The DEXA scans used to assess body fat percentage for the previous analyses, also gave detailed information on fat mass, fat free mass and bone mineral density in the various body parts of the seven subjects. Of particular interest is bone mineral density in the lumbar spine and hip and the lean and fat mass in various body parts, since it has been suggested that many of these parameters are abnormal in the majority of the persons with long-term SCI.

Central in this chapter are the hypotheses:

- FES-rowing training improves body composition in persons with paraplegia
- FES-rowing training improves bone mineral density in the lower extremities of persons with paraplegia.

Abstract

Body fat percentage, bone mineral density in hip and lumbar spine and body composition in the lower extremities of five paraplegic volunteers were measured before and after 32-48 FES-rowing sessions. The group average did not change significantly for any of these parameters, although individual changes were considerable. One outlier could have disturbed the statistical power of the results.

Changes in fat mass were positively correlated with training volume, suggesting high volume exercise training is essential if health benefits are to be achieved. Technological limitations of the RowStim II FES-rowing machine could have negatively influenced the exercise intensity and volume that could have been achieved.

6.1 Introduction

Long-term immobilisation after spinal cord injury (SCI) is associated with a series of adverse changes in the fat mass, fat-free mass and mineral content in the paralysed body parts (Uebelhart et al., 1995, Wilmet et al., 1995, Kocina, 1997). The lower extremities of persons with paraplegia show a decreased bone mineral density (BMD) and lean mass (mainly muscle mass) and increased fat mass. Secondly, high total body fat content is more common in SCI than in able-bodied (Kocina, 1997), even when total body weight appears to be in the normal range SCI (George et al., 1988, Jones et al., 1998) or individuals are physically active (Bulbulian et al., 1987, Ide et al., 1994). These changes in body composition put the SCI population at elevated risk for bone fractures, coronary heart diseases, obesity and non-insulin dependant diabetes mellitus (Bauman et al., 1992a, Bauman et al., 1999a, Kocina, 1997, Freehafer, 1995). Exercise appears, however, to be able to at least reduce some of these abnormalities in body composition.

Long-term electrical stimulation of paralysed muscles results in hypertrophy of those muscles (Scremin et al., 1999, Baldi et al., 1998) and indeed muscle hypertrophy has been reported after FES-cycling training (Hjeltnes et al., 1997, Mohr et al., 1997a). Decreases in whole body fat content have also been associated with similar FES-cycling training in tetraplegics (Hjeltnes et al., 1997). Changes in BMD after FES-cycling have only been reported after long-term (>1 year) FES-cycling training and even then improvements were only reported in the proximal tibia and not in the femoral neck or lumbar spine (Mohr et al., 1997b). Studies monitoring BMD in shorter FES-cycling programmes have not shown significant changes in BMD (BeDell et al., 1996, Eser et al., 2003a).

Weight bearing seems an important factor in bone health, as can be derived from space flight and extended bed rest experiments (Kocina, 1997, Uebelhart et al., 1995). Nevertheless passive standing or assisted walking in paraplegia has not resulted in improvements in leg BMD (Ogilvie et al., 1993). It has also been suggested that neuronal and vascular abnormalities in SCI play a role in the negative bone balance (Kocina, 1997, Griffiths et al., 1972), in particular venous stasis (Bergmann et al., 1977, Chantraine, 1978). Obviously weight-bearing is absent in cycling, but the electrical stimulation might improve venous return and reduce blood pooling in the lower extremities (Phillips et al., 1998). At this moment in time the magnitude of the mechanical forces in the legs during FES-cycling or FES-rowing are unknown although it is likely that these forces are smaller than during weight-bearing.

Since FES-rowing training uses electrical stimulation that is similar to most FES-cycling programmes, the changes in lean mass and fat mass in the lower extremities of persons with paraplegia might be similar to that seen after FES-cycling training (Hjeltnes et al., 1997, Mohr et al., 1997a, Jacobs and Nash, 2001). Both exercises mainly stimulate the quadriceps and hamstring muscles for an average of 3-4 times per week for 30 minutes.

In addition to these changes in local body composition, exercise training can also impact on total body fat content. High total body fat content, in particular body fat percentage and visceral obesity, are risk factors for Coronary Heart Diseases and Non Insulin Dependant Diabetes Mellitus (Buchholz and Bugaresti, 2005, Bauman and Spungen, 2001). Besides a healthy and balanced diet, high levels of physical activity are an important mechanism for controlling body fat (Jakicic et al., 2001). The latter can be difficult for persons with extensive paralysis because the limited amount of active muscle mass leads to low levels of energy expenditure (Mollinger et al., 1985). Increasing energy expenditure by increasing the activity of that limited amount of muscle mass (for example pushing a manual wheelchair) might increase the risk of musculoskeletal overuse (Dyson-Hudson and Kirshblum, 2004). A preferred option would be to increase the amount of active muscle with the use of FES. FES-rowing is a whole body exercise and this could enable persons with paraplegia to achieve higher energy expenditure values, and subsequently the effect on body fat mass might be more pronounced than after exercise programmes of smaller volumes.

It is anticipated that FES-rowing might offer at least the same level of benefits as FES-cycling due to the many similarities between the two types of exercise. However, the difference in exercise intensity and volume that can be achieved with FES-rowing might give superior results. Therefore the hypothesis of this study is: FES-rowing training leads to:

- decreased total fat mass and fat mass in the legs and trunk.
- increased lean mass in the legs
- increased bone mineral density in the hip and lumbar spine.

The 'gold standard' for measuring body composition is hydrostatic weighing, however this can be difficult in persons with limited mobility. Dual Energy X-ray Absorptiometry (DEXA) has been suggested as a suitable alternative, that has proven to be an accurate tool in SCI (Kocina, 1997, Jones et al., 1998). The advantage of a DEXA scan over hydrostatic weighing is that regional distributions of fat mass and lean mass can be assessed and the same technique also allows for accurate measurement of bone mineral density (Watts, 2004).

6.2 Methods

Five subjects participated in this pilot study, their characteristics are given in Table 6.1. These five subjects also participated in the pilot studies presented in Chapter 2-5. Full inclusion and exclusion criteria are given in Chapter 2.

Table 6.1: Subject characteristics and training stimulus.

Subject	Level of lesion	ASIA Scale	Time since injury (years)	Age (years)	Average weekly energy expenditure (kcal)	Total energy expenditure during training period (kcal)
1	T5-T6	A	21	49	457	5554
2	T4-T5	A	36	56	526	9466
3	T10-T12	B	2	46	685	8909
4	T4-T5	A	2	23	277	6372
5	T5-T6	B	2	24	349	6989
Ave ± SD			12.6 ±15.5	39.6 ±15.1	459 ±159	7458 ±1670

Materials and protocols

A detailed description of the materials, testing and training protocols used in this study is given in Chapter 2. In brief: a Concept 2 rowing ergometer was adapted to enable use for paraplegic subjects. Leg movement was induced by electrical stimulation of the quadriceps and hamstrings muscle. The rower controlled the timing of the stimulation with a switch on the handle bar of the rowing machine. This technology enabled paraplegics to exercise with their whole body.

If necessary, a leg muscle strengthening programme was conducted to ensure sufficient strength and endurance in the leg muscles. After two or three introductionary FES-rowing sessions, training programme commenced. Training was performed 3-4 times per week for at least 12 weeks. Exercise volume was 800 kcal·week^{-1} and intensity was set at 80% VO_2peak. Regular (every 3-4 weeks) physiological max and sub-max tests were conducted to monitor oxygen consumption during training sessions and VO_2peak tests.

Body composition

Body composition was determinded using Dual Energy X-ray Absorptiomertry (Hologic Model QDR 4500A), which has been suggested as a reliable and valid method of determining body composition in persons with paraplegia (Jones et al., 1998). All scans were conducted by the same, experienced technician. Subjects were asked to transfer to an examination table and lie still for the duration of the scan. Subjects were asked not to wear any metal objects, although some subjects had metal rods in their spine. A whole body scan was performed to determine fat mass, lean mass and bone mineral content in the various body parts. A second scan was made to determine BMD at the lumbar spine (L1-L4) and left hip (neck, trochanter and intertrochanter regions). BMD is expressed as absolute value ($g \cdot cm^{-2}$) and as a Z-score. This Z-score was calculated by the Hologenic DEXA scanner software, which used data from age, gender and ethnicity matched controls as collected in the US National Health and Nutrition Examination Survey (NHANES).

Differences in pre and post values for the group average were tested using non parametric Wilcoxon tests. Correlations between training stimulus (average weekly energy expenditure) and changes in body composition were calculated using Spearman rank order correlation coefficients. Changes in body composition were expressed as percentage of baseline values to control for variation in baseline values. All tests were conducted at $p<0.05$.

6.3 Results

Average weekly energy expenditure ranged from 277 to 685 kcal·week^{-1} (Table 6.1). None of the changes in average body composition values reached statistical significance ($p<0.05$). Lean mass in the legs increased from 7189 ±798 to 7779 ±818 (+8.5%) (Figure 6.1), fat mass decreased from 3083 ±205 g to 2961 ±323 g (-4.1%) (Figure 6.2), and mineral content remained stable (pre: 349 ±117 g, post: 341 ±95 g; -0.6%) (Figure 6.3). Total body fat percentage decreased from 27.1 ±2.9% to 26.0 ±3.5% (Figure 6.4). Fat mass in the trunk, as indicator for visceral obesity decreased from 11577 ±3089 g to 11288 ±3698 g (-3.8%) (Figure 6.5).

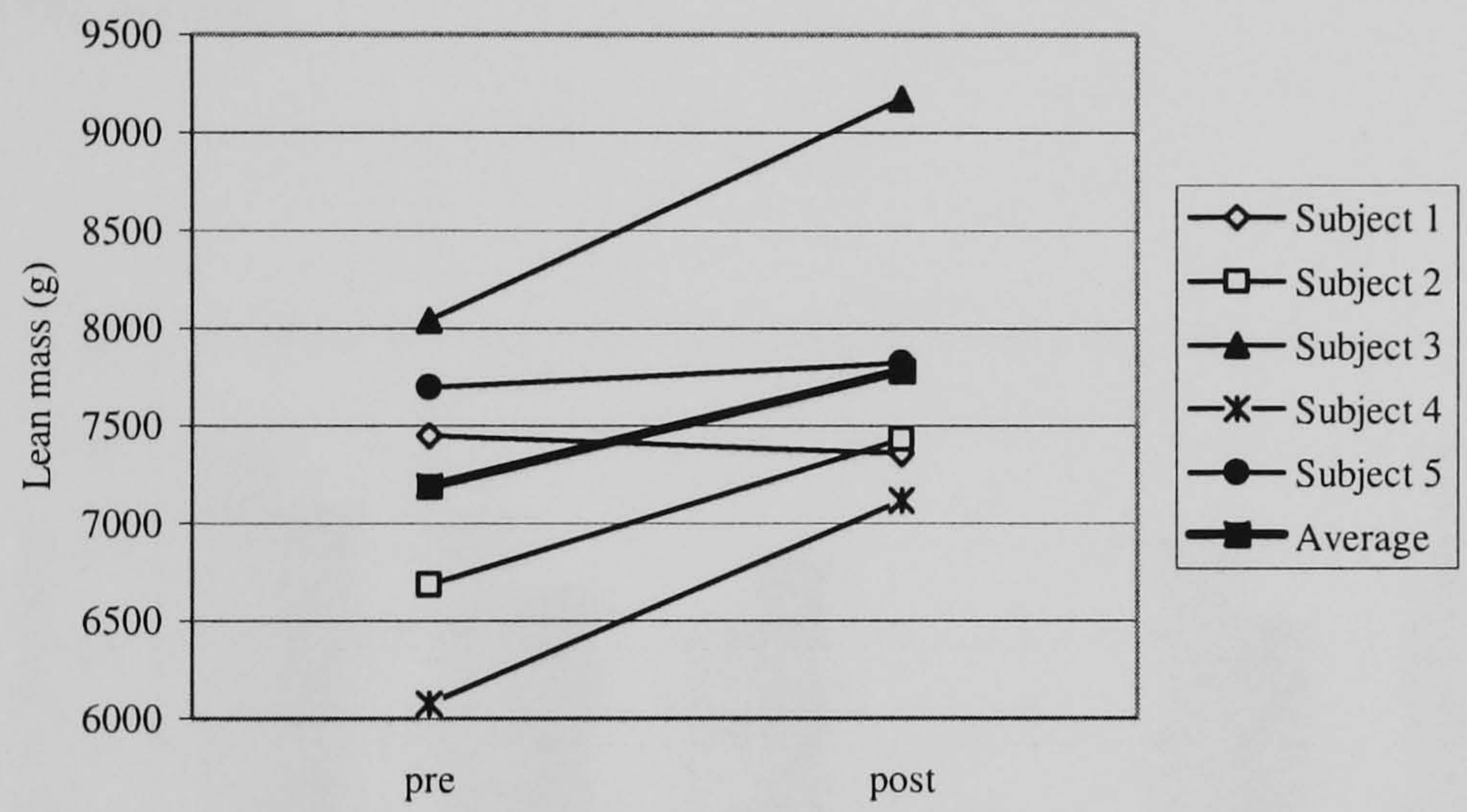


Figure 6.1: Lean mass in the legs of five paraplegics before and after FES-rowing training.

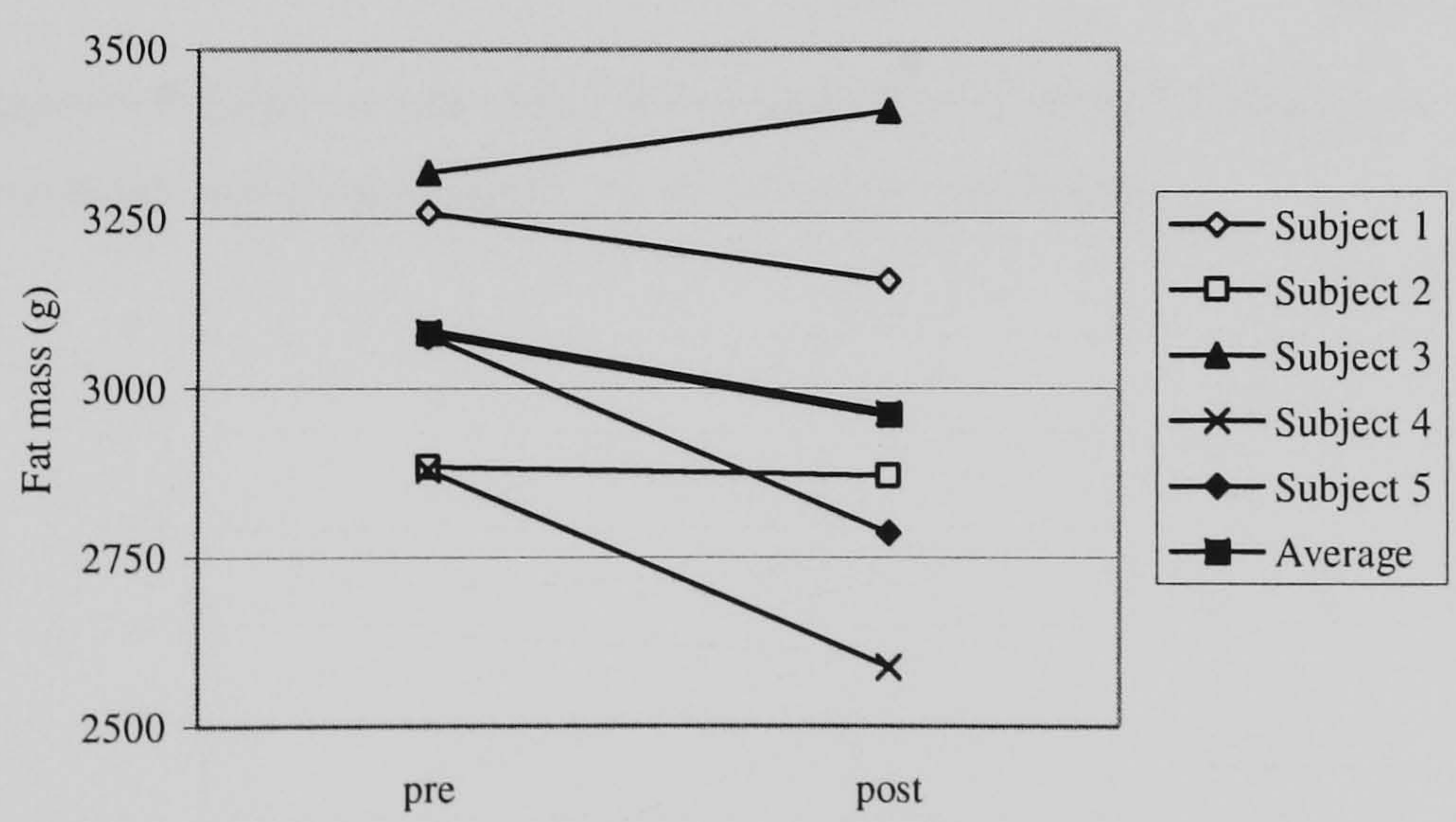


Figure 6.2: Fat mass in the legs of five paraplegics before and after FES-rowing training.

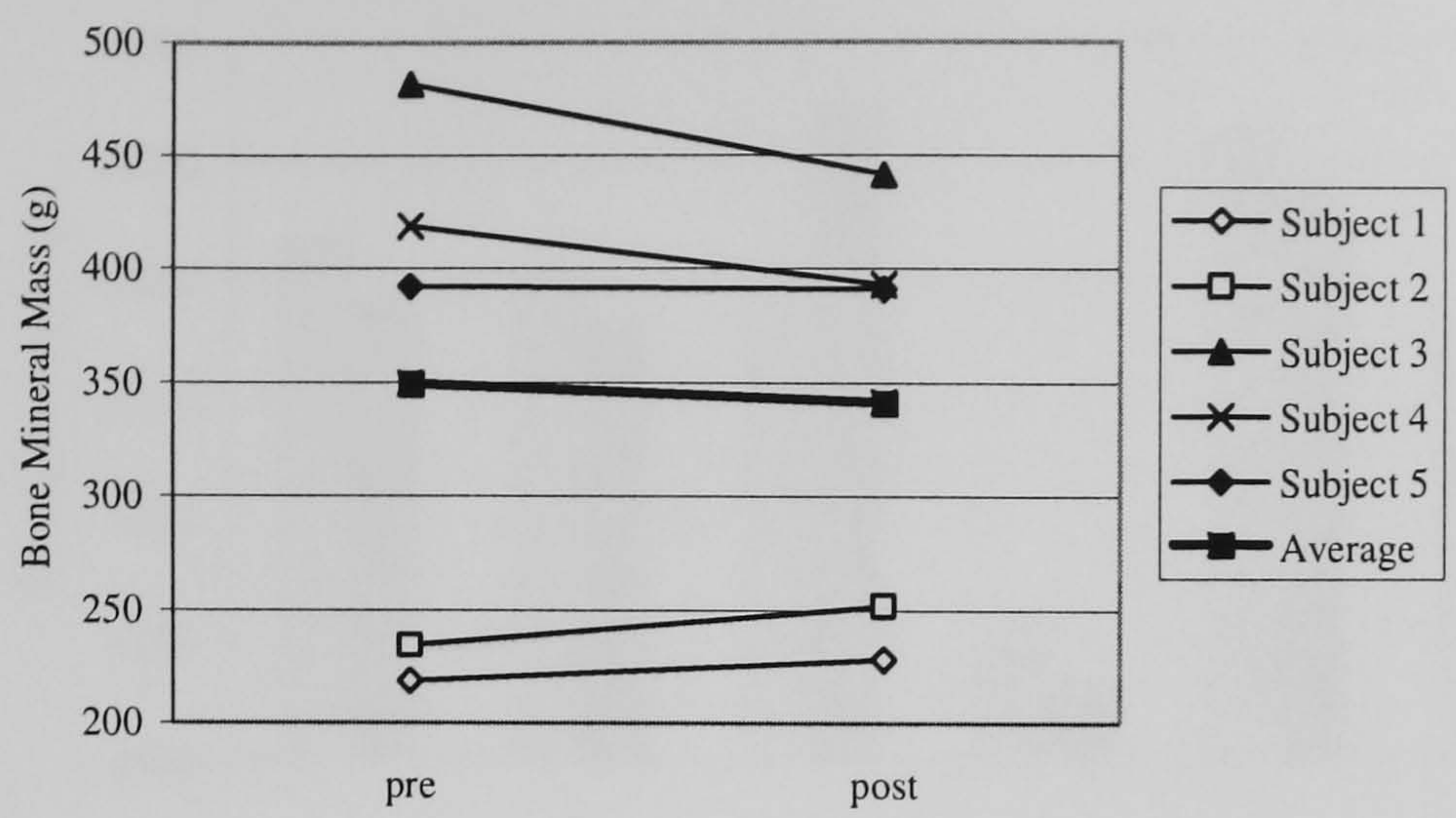


Figure 6.3: Bone mineral mass in the legs of five paraplegics before and after FES-rowing training.

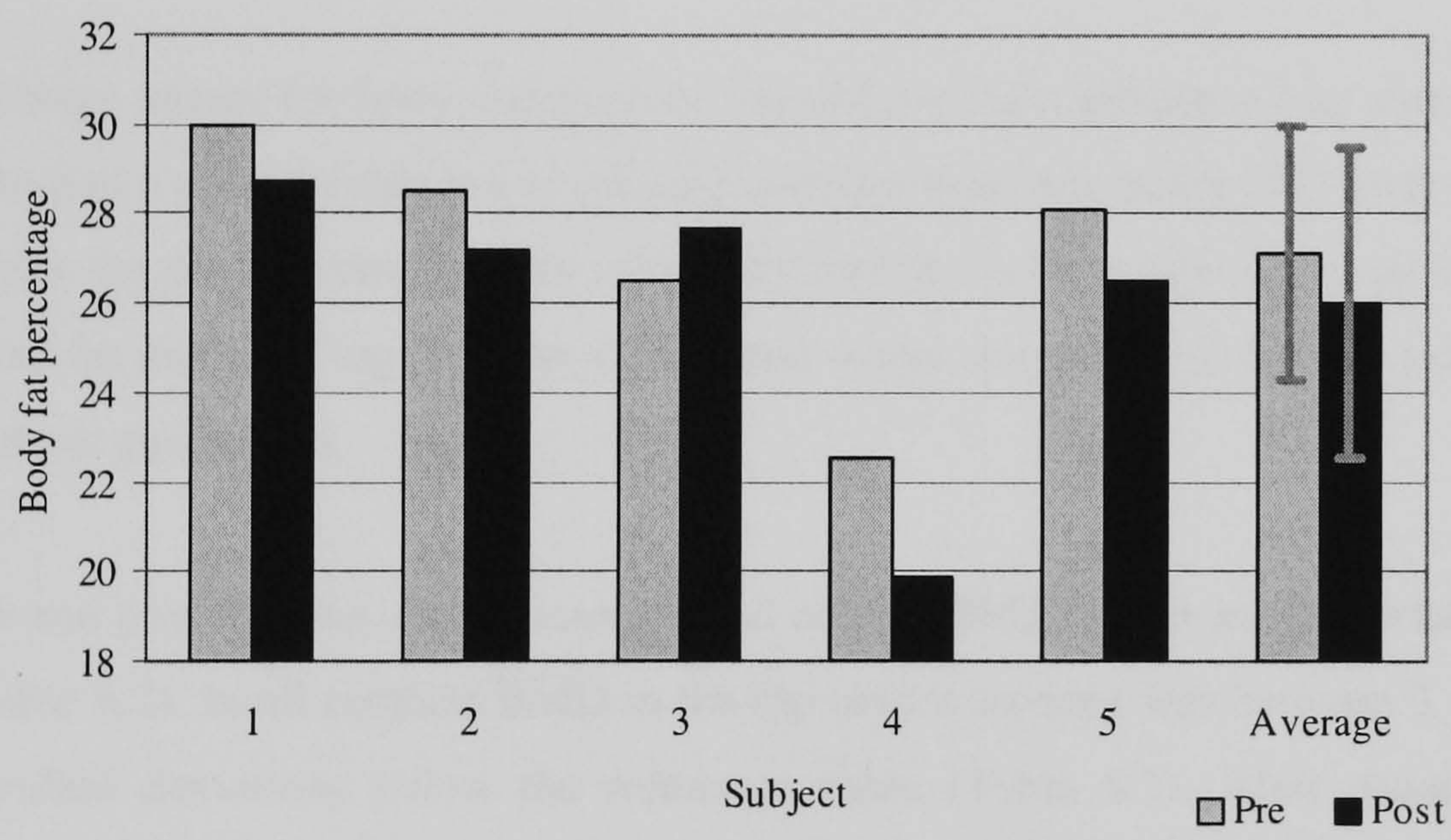


Figure 6.4: Body fat percentage before and after 12 weeks of FES-rowing training in five paraplegics and group average (mean ± standard deviation).

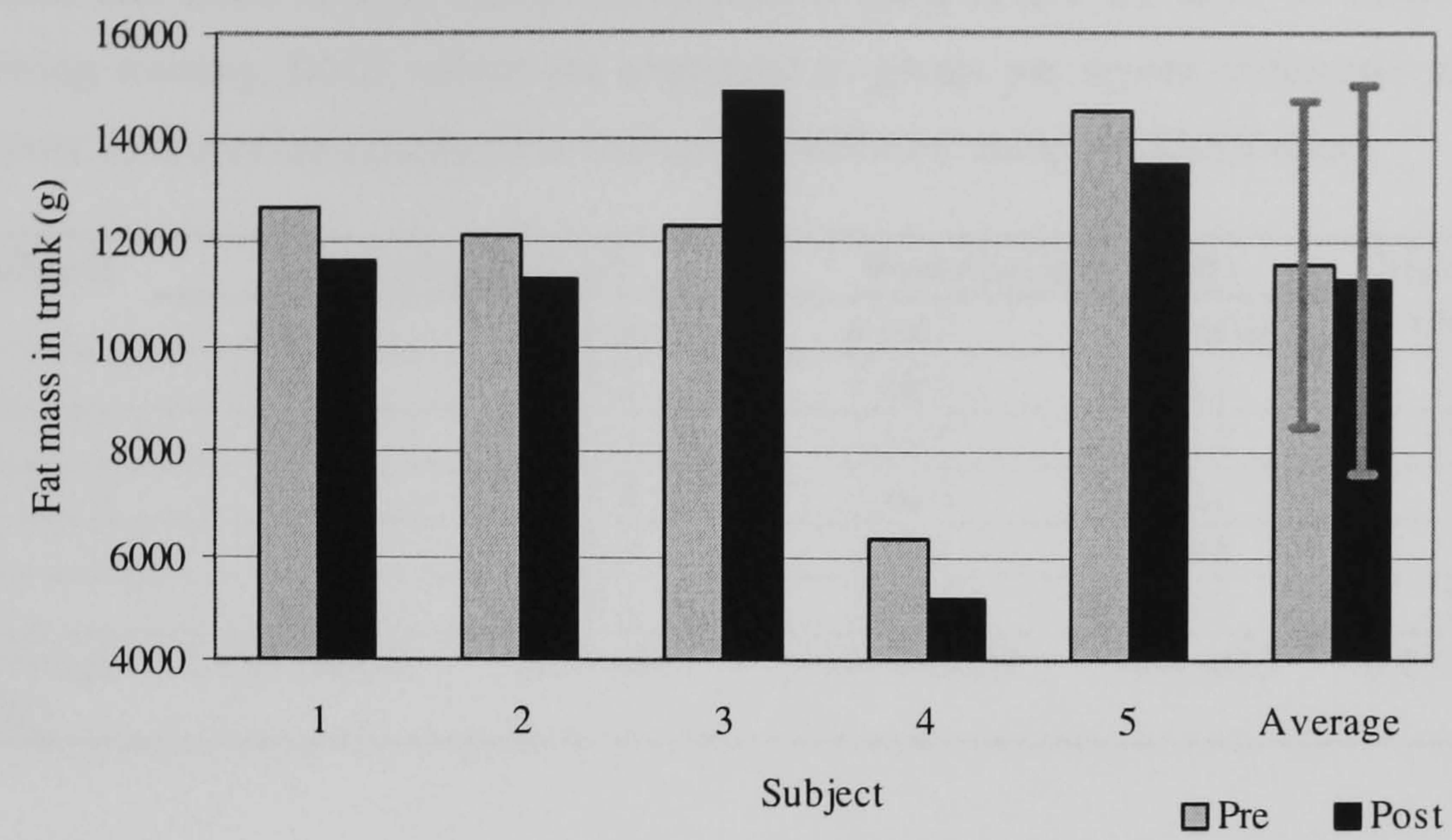


Figure 6.5: Trunk fat mass before and after FES-rowing training in five paraplegics and group average (mean ± standard deviation).

Average values for body composition could have been influenced by one subject who had a considerable lower training stimulus than the others (277 kcal, 1.4 SD below the group average). This subject showed an increase in body fat percentage, trunk fat mass and leg fat mass while other others showed considerable reductions in these parameters.

Pre and post training, all participants had normal BMD values in the lumbar spine (Table 6.2). In all subjects BMD in the hip before training was between 1 and 2.5 standard deviations below the reference value (Table 6.3). After training one subject's BMD had declined to below 2.5 SD from the reference value, all others remained in the –1 to –2.5 SD range. BMD in the lumbar spine remained stable (pre: 1.039 ±0.035 $g{\cdot}cm^{-2}$, post: 1.044 ±0.029 $g{\cdot}cm^{-2}$, +0.6%) while BMD in the hip decreased significantly by 5.3% (pre: 0.728 ±0.095 $g{\cdot}cm^{-2}$, post: 0.688 ±0.085 $g{\cdot}cm^{-2}$).

Table 6.2: Bone mineral density in the lumbar spine before and after 12 weeks of FES-rowing training. BMD values are expressed in grams per square centimeter and as Z-scores. Z-scores are calculated by Hologenic software using NHANES data.

Subject	Pre-training BMD		Post-training BMD		Percentage change
	$g{\cdot}cm^{-2}$	Z-score	$g{\cdot}cm^{-2}$	Z-score	
1	1.040	-0.5	1.066	-0.2	2.5%
2	1.063	-0.3	1.072	-0.2	0.8%
3	1.020	-0.6	1.020	-0.6	0%
4	0.991	-0.9	1.008	-0.8	1.6%
5	1.079	-0.1	1.056	-0.3	-2.1%
Average ±SD	1.039 ±0.035	-0.5 ±0.3	1.044 ±0.029	-0.4 ±0.3	0.6% ±1.7%

Table 6.3: Bone mineral density in the hip before and after 12 weeks of FES-rowing training. BMD values are expressed in grams per square centimeter and as Z-scores. Z-scores are calculated by Hologenic software using NHANES data.

Subject	Pre-training BMD		Post-training BMD		Percentage change
	$g{\cdot}cm^{2}$	Z-score	$g{\cdot}cm^{2}$	Z-score	
1	0.699	-2.2	0.677	-2.4	-3.1%
2	0.579	-3.0	0.566	-3.1	-2.2%
3	0.796	-1.6	0.783	-1.7	-1.6%
4	0.816	-1.4	0.752	-1.9	-7.9%
5	0.752	-1.9	0.663	-2.4	-11.8%
Average ±SD	0.728 ±0.095	-2.0 ±0.6	0.688 ±0.085	-2.3 ±0.5	-5.3% ±4.4%

Pearson correlation coefficients were statistically significant for average weekly energy expenditure and the change in body fat percentage ($r=0.98$ $p=0.005$) and trunk fat ($r=0.90$ $p=0.037$). All other correlation coefficients for average weekly energy expenditure or total energy expenditure and the change in body composition were not statistically significant.

6.4 Discussion

The changes in body composition seen in this group of subjects undergoing FES-rowing training were not statistically significant. However, this could have been be a consequence of the small number of subjects and the inclusion of one outlier. Subject four had a considerably lower average weekly energy expenditure (277 kcal·week^{-1} while target was 800 kcal·week^{-1}). Therefore results will be described qualitatively.

Four out of the five showed considerable reductions in body fat percentage (1.3-2.6%), trunk fat mass (821-1128 grams, 6.8-17.8% of baseline value) and leg fat mass (13-292 grams, 0.5-10.1% of baseline value). The ideal body fat percentage for adult men is 15%, while percentages above 25% would be defined as obese (Kocina, 1997). Four out of the five subjects were well above the 25%, even after completion of the exercise programme. The high body fat percentages seen in these subjects confirm earlier findings that persons with SCI have elevated body fat contents (Spungen et al., 2000, Spungen et al., 2003, Nuhlicek et al., 1988). FES-rowing training seems to be able to reduce body fat considerably, but the group average did not reach statistical significance. This is in line with other exercise studies in SCI that have found improvements in body composition, some statistically significant (Hjeltnes et al., 1997), others non statistically significant (Duran et al., 2001). The improvements in body fat found in the four subjects were not only local (leg) but also in other (non-exercising) parts of the body (trunk) and whole body.

Lean mass in the legs of four subjects increased by 1.7-17.1%, which most likely indicates muscle hypertrophy. The one subject who showed a small decrease in leg lean mass had been involved in a FES-cycling programme and thus further muscle hypertrophy might not be expected. It should be noted however that DEXA scans do not distinguish between various types of tissue classified as lean mass. Connective tissue, muscle and water all contribute to lean mass and therefore differences in hydration before and after the training period might have confounded the analysis on lean mass changes after FES-rowing training (Kocina, 1997). Modlesky et al. (2004) conducted a small study in which they investigated the correlation between muscle mass (as determined by MRI) and fat free soft tissue mass (as determined by DEXA) in the upper leg of SCI indivuals and able-bodied controls (Modlesky et al., 2004). They reported that muscle mass was a significantly smaller proportion of fat free mass in SCI (0.80 ±0.09) than in able-bodied (0.91 ±0.10). However fat free mass and muscle mass both in SCI (r=0.99) and able-bodied (r=0.91) were strongly related. Therefore they concluded that muscle mass in SCI can be estimated using DEXA. This would validate the use of DEXA to determine muscle mass pre training, however post training the muscles mass might contribute more to fat free mass due to hypertrophy. In which case the 1.7-17.1% increases in lean mass reported in this study might be an underestimate for the muscle hypertrophy taking place during the training phase.

Despite the low compliance of subject 4 and the increases in fat mass seen in this subject, lean mass in his legs increased (1127 g, 14% of baseline value). This can be explained by the fact that he previously had not used any FES and consequently his leg muscles responded very well to the training, even though the training stimulus was much lower than for the other subjects.

To compare BMD with normal (able-bodied) values matching for age, gender and ethnicity, Z-scores for all BMD values were calculated using the Hologenic DEXA scanner software. BMD in the lumbar spine before starting the training programme was in all five subjects within the 95% confidence interval for the average value for their (able-bodied) peer group, which confirms similar findings by other authors (Wood et al., 2001, Mohr et al., 1997b, Zehnder et al., 2004). Surprisingly three subjects showed a further increase in BMD in the spine after training (0.8-2.5%), which has also been reported after 9 months of FES-cycling training (Bloomfield et al., 1996). Since all these values were in the normal range, the clinical relevance of these findings is limited.

Before and after the training programme, BMD in the hip for all subjects was well below the average for their reference group; three subjects had a hip BMD below the 95% confidence interval for the average of the reference group (based on age, gender and ethnicity). BMD in the hip decreased significantly for the group, although it was more pronounced in the subjects with a shorter time since injury

(<2 years). It appears that in the first year after a spinal lesion a rapid loss in bone mass takes place and that a new, although lower, equilibrium in bone formation is established two to five years post injury (Hancock et al., 1979, Biering-Sorensen et al., 1988). Two out of the three individuals who were approximately two years post injury showed considerable reductions in hip BMD after the programme, while one individual did not show such rapid decrease in BMD. No plausible explanation can be found for this phenomenon, but it would be of interest to conduct a similar intervention study in a larger group of subjects to see if these effects can be replicated.

BMD in the lower extremity after FES-cycling training has been investigated in five studies. Only one of these found significant changes in BMD and that was after long-term cycling (one year) and a significant increase was only found in the proximal tibia (Mohr et al., 1997b). Hangartner et al. (1994) compared BMD in the tibia of 15 newly injured subjects after completion of a 14-week FES-cycling programme with the value they had predicted if no intervention had taken place (and thus BMD had further declined). They found higher BMD values than predicted, but absolute increases in BMD were not statistically significant. The fact that one year (2.3 sessions per week) of FES-cycling results in significant increases in BMD but not 14 weeks of FES-cycling (3 sessions per week), confirms the slow response in bone growth (Mohr et al., 1997b). Also, a decrease in training frequency to one weekly session after the one year programme was not sufficient to maintain the elevated BMD values in the tibia, indicating a dose-response relationship (Mohr et al., 1997b). No improvements in BMD in the hip (femoral neck) have been reported after FES-cycling intervention (Hangartner et al., 1994, Sloan et al., 1994, Pacy et al., 1988).

The results of this study and the FES-cycling studies implies that changes in BMD are hard to achieve with exercise programmes, especially in the hip. Therefore future FES-exercise studies should monitor BMD over longer training periods and measure BMD in various parts of the lower extremity. BMD in the lumbar spine seems to be normal in most persons with SCI and the potential effect of exercise on spine BMD is therefore less relevant.

More positive changes after FES-rowing training were found on whole body parameters. There was a significant positive correlation between the exercise volume (as measured by average weekly energy expenditure) and the change in body fat percentage (r=0.98) and trunk fat mass (r=0.90). Changes in body composition were not associated with total energy expenditure (energy expenditure over the full training period). This implies that high exercise volumes are more effective in improving body composition than lower exercise volumes, confirming able-bodied guidelines on weight loss through exercise (Jakicic et al., 2001, Saris et al., 2003). This is an important finding since persons with SCI have difficulties in reaching high exercise volumes due to the low oxygen consumption values seen during most types of exercises in this population (Davis, 1993)(see also Chapter 1). Further improvements in the FES-rowing might augment oxygen consumption during FES-rowing and optimise health benefits.

6.5 Conclusion

This FES-rowing training study did not result in significant improvements in body fat percentage, lean mass in the legs, fat mass in the legs or BMD in the hip or lumbar spine in a group of five paraplegics. Nevertheless individual improvements in fat mass and lean mass were considerable and the group average is mostly likely disturbed by one subject who showed low compliance with the training programme.

Changes in fat mass were positively associated with training volume, confirming the health benefits of high volume exercise training. It is anticipated that further improving the FES-rowing system will result in higher oxygen consumption values and reduce the time needed to achieve high exercise volumes. The results of this study implies that FES-rowing has potential but further improvements in technology are needed and studies need to include larger numbers of subjects.

Chapter 7

The limitations of the RowStim II as identified in the pilot studies

7.1. Introduction

The results of 12 weeks of FES-rowing training presented in Chapter 2-6 are promising but are of limited statistical value. As indicated in these chapters one subject showed a low compliance to the training programme and since the sample size was already small (5-7 subjects), this one outlier had a big impact on group averages. The secondary analysis of looking at the correlation between training stimulus and change in the parameters supported the benefits of high volume exercise training. In addition, improvements in lipid profile and body composition seen in individuals with good adherence to the training programme implied that FES-rowing has the potential to impact health of individuals with SCI.

The fact that the effects in the pilot studies did not reach the level of statistical significance, could have been caused by either too small a sample size or the absence of a true effect. The first option is explored in this chapter by conducting a power analysis based on the results of the pilot studies.

7.2. Power analysis

Statistical power is the probability of rejecting the null hypothesis when the null hypothesis is false (e.g. detecting a real difference) (Thomas and Nelson, 2001). The power is dependant on:

- The effect size, which is an expression of the size of the difference that is being studied.
- The level of alpha, which determines the probability of making a type I error (rejecting a true null hypothesis).
- The level of beta, which determines the probability of making a type II error (accepting a false null hypothesis).
- The sample size.

This concept can be used to estimate the number of subjects needed to obtain a statistically significant difference between two variables. The results of the pilot study presented in Chapter 3-6 can be used to estimate the number of subjects needed in a second study that would test the statistical significance of the findings found in the pilot study. This is discussed below.

Making a type I error when investigating the (potential) health benefits of FES-rowing (rejecting true benefits) is just as undesired as making a type II error (accepting non-existing benefits), which is why both alpha and beta are set at 0.05. Also the data from the one outlier presented in chapter 2 and 3 is not included in the power calculation.

The following formula can be used to determine sample size for parametric unpaired t-tests:

$N_1 = N_2 = (z_{1-\beta} + z_{1-\alpha/2})^2 * (\sigma_1^2 + \sigma_2^2) / ((\mu_1 - \mu_2)^2)$

N_1 = sample size in population 1

N_2 = sample size in population 2

$z_{1-\beta}$ = Z-score of $1-\beta$

$z_{1-\alpha/2}$ = Z-score of $1-\alpha/2$

σ_1^2 = true variance in population 1

σ_2^2 = true variance in population 2

μ_1 = true average in population 1

μ_2 = true average in population 2

In this study non parametric tests for paired observations were used, which meant that the above formula needs to be adjusted for this different type of test. This is done by multiplying N by (1-ρ) in which ρ is the estimated correlation between the 2 samples (pre and post). As a guideline in the case of repetitive measurements a $\rho = 0.50$ can be used (Van Breukelen, 1997).

In case of Wilcoxon tests, the sample size will be approximately 5% larger than that calculated above. Therefore the results are multiplied by 1.05. The results of the analysis to determine sample size needed to obtain statistically significant changes for various outcome parameters are displayed in Table 7.1. Only those outcome parameters that showed promising but no significant improvements in the pilot study have been displayed. Using the other parameters with smaller effect sizes would have resulted in even larger sample sizes needed to obtain statistically significant results.

Table 7.1: Sample size needed to show statistical significance of the effects of a selection of outcome parameters.

	Total Cholesterol	**Free Fatty Acids**	**Triglycerides**	**VO_2 peak**	**Body Fat Percentage**
Effect size	0.38	0.78	0.32	0.59	0.27
Desired sample size	76	24	81	39	170

The large number of subjects needed to investigate the statistical significance of the health benefits of FES-rowing would cause difficulties in subject recruitment and management of such a study. Therefore instead of increasing statistical power by selecting a large sample size, the effect size is to be increased.

The significant correlations found between training volume and the improvements in lipid profile and body composition suggest that a larger effect can be reached if training volume is further increased. This is supported by numerous studies in able-bodied on exercise volume and health benefits, as presented in Chapter 1. The results of the FES-rowing pilot study showed that the threshold volumes identified in able-bodied, were not achieved. This could be a reason why no statistically significant improvements were found in the pilot study.

Increasing training volume to optimise health benefits, can be achieved by either extending the exercise time or increasing the exercise intensity. Extending the exercise time might be feasible for some subjects, but not everyone is willing to spend long periods of time exercising. Therefore the preferred option would be to increase the oxygen consumption during FES-rowing. This would also have the benefit of ensuring that the exercise intensity is well above the thresholds identified in able-bodied on optimal exercise intensities for health benefits.

7.3. Conclusion

The results of the power analysis show that an impractical number of subjects would be needed to test the statistical significance of the health benefits of FES-rowing. Since this was beyond our capacities, an alternative approach is suggested. The pilot studies suggest that larger benefits can be achieved if oxygen consumption during FES-rowing is further increased. This would not only increase the chances of achieving recommended exercise intensities, it would also decrease the time needed to obtain optimal exercise volumes. In the following chapters two strategies to achieve this are presented:

- Further developing the FES-rowing technology that would address the limitations identified in the pilot studies.
- Improving adherence to the training programme by introducing a competitive element to FES-rowing training.

7.4 Hypotheses

The literature review presented in Chapter 1 concluded with the hypotheses:

H 1 FES-rowing is a high intensity exercise and an effective cardiovascular training for persons with paraplegia.

H 2 FES-rowing training will affect cholesterol and blood lipids in persons with paraplegia.

H 3 FES-rowing training will affect leptin levels and insulin sensitivity in persons with paraplegia.

H 4 FES-rowing training will affect body composition in persons with paraplegia.

H 5 FES-rowing will affect bone mineral density in the lower extremities of persons with paraplegia.

The results presented in Chapter 3-6 showed that FES-rowing is indeed a high intensity exercise but the pilot studies do not confirm the hypotheses on health benefits. However, the power analysis presented in Chapter 4 showed that this was most likely a result of the small sample size and the inclusion of one outlier. In addition, a number of limitations in the design of the rowing machine have been identified. It is likely that technological improvements will enhance the exercise intensity and the associated health benefits. Therefore the aim of the next study was to further develop the FES-rowing technology, in particular:

- The mechanical augmentation during the return phase
- The man-machine interface control switch.
- The stability of the seat carriage system and trunk constraints.
- Sagittal constraint of leg motion.

Tests were performed to determine if the new generation FES-rowing system will enable paraplegics to row at higher intensities and for longer than with the RowStim II system.

With an improved FES-rowing machine, an additional hypothesis could be tested, namely:

H 6 Introducing a competitive element to FES-rowing will improve training compliance and enable larger training intensities and volumes to be achieved.

Although the therapeutic benefits of FES-rowing will motivate some individuals to participate, it is expected that offering the full range from therapeutic exercise to competitive sport would stimulate more persons to take up FES-rowing. Moreover, FES-rowing as a competitive sport would present challenges for the proposed technological developments.

The technological developments will be discussed in Chapter 8. The feasibility of FES-rowing as a competitive sport will be presented in Chapter 9.

Chapter 8

Technological development of FES-rowing

8. Technological development of FES-rowing

The pilot studies presented in Chapters 2-6 showed promising results, but it also identified limitations in the RowStim II FES-rowing technology that could have had a negative influence on the physiological parameters. In this chapter these limitations are detailed and the solutions described.

Abstract

The first generation FES-rowing machines, the RowStim II, had a number of limitations that restricted the exercise intensity and volume that could have been achieved by the participants. The main limitations were the unstable seat-carriage system, the impaired return phase, the leg stabilisers, the stimulation control and the end stops. A new prototype has been developed that addressed these shortcomings and the RowStim III appears to allow participants to row harder and for longer.

8.1 Introduction

Paraplegics using the FES-rowing machine are able to achieve high oxygen consumption values and this enables them to participate in high intensity and high volume exercise training. Subsequently, larger health benefits may be expected since a dose-response relationship has been identified in able-bodied (Tanasescu et al., 2002). However, during the FES-rowing pilot studies limitations have been identified in the design of the rowing machines and this might have had a negative effect on the FES-rowing performance.

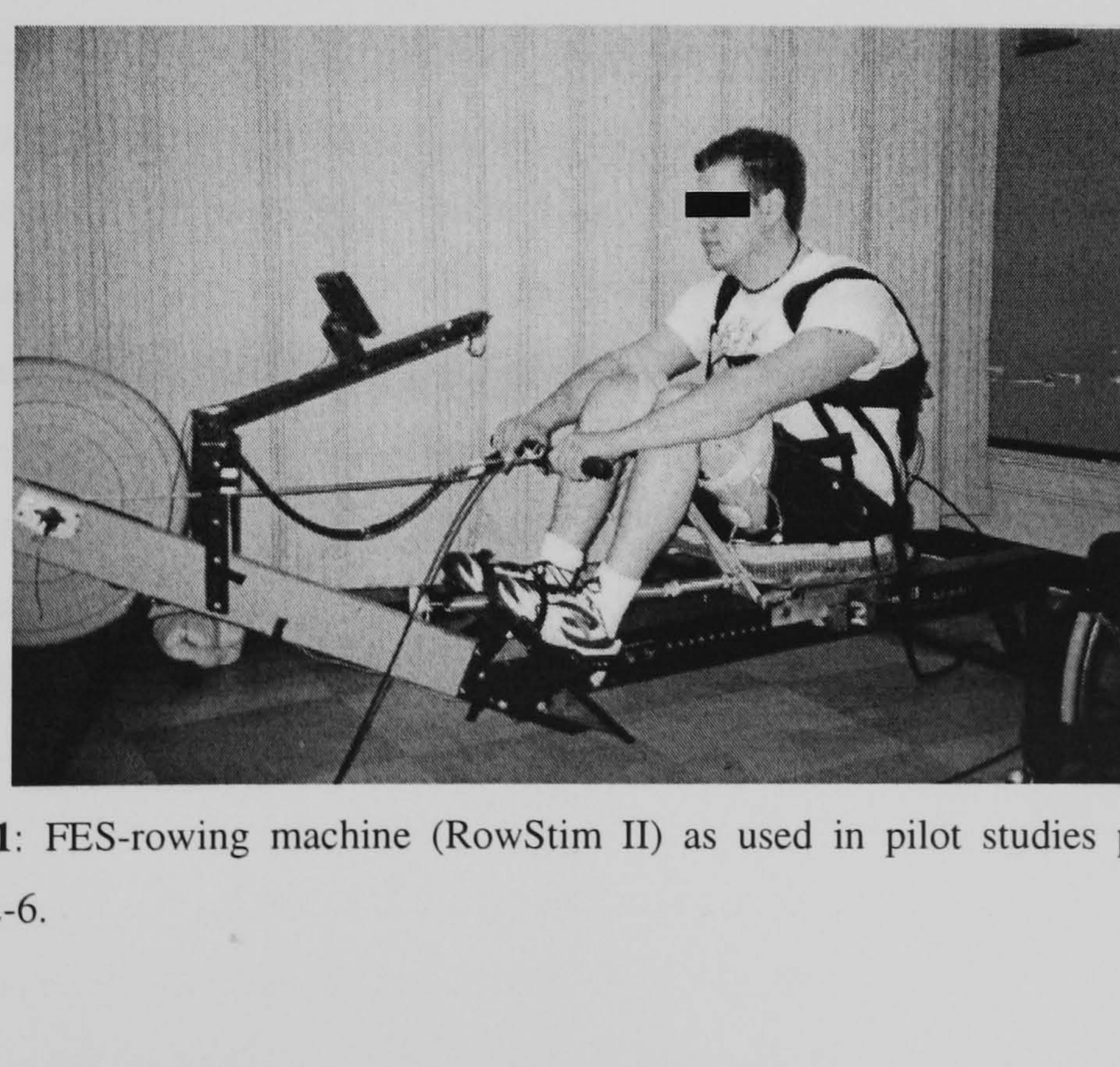


Figure 8.1: FES-rowing machine (RowStim II) as used in pilot studies presented in Chapters 2-6.

The main shortcoming identified in the pilot studies included:

- The high rolling resistance and unpredictable jamming of the seat carriage system caused by the rocking of the seat-carriage system. The high backrest has resulted a long moment arm that results in large torsion forces on the rollers carriage that locates the seat on the monorail. These large force actions caused the carriage to deform, jamming the rollers and rapidly wearing the bearings. The rollers were in contact with the upper lip of the 'I' section monorail. The large torques transmitted through the underside roller to the monorail lip caused permanent deformation of the lip, which further increased roller resistance and jamming.
- The inability to adjust the return forces needed to support the hamstring action in the recovery phase of the rowing motion. The spring or bungee cord that was attached to the seat and the front end of the rowing machine could not be easily adjusted to suit each rower on each occasion and consequently the spring was either too strong, which puts additional stress on the quadriceps during the drive phase, or too weak, which limits the forward motion. This made it difficult to reliably set up the rower for the same conditions from session to session.
- The pelvis/trunk/shoulder harness system was overly complicated and constricting. The over shoulder straps were located too low. This was found to pull down on the shoulders causing skin chaffing when more vigorous rowing was attempted.
- The travel range of the seat over the monorail was limited by using pneumatic cylinders at the end of the monorail, which acted as end-stops. However these cylinders were found to be unreliable and consequently the seat could travel too far back and result in overextension of the knee joint.
- The interference of the leg stabiliser with the electrodes on the upper leg. The leg stabiliser was a three jointed bar that was attached to the seat and around the upper leg of the rower. The three joints resulted in an unstable configuration and the straps around the leg interfered with the placement of the electrodes.

- The coordination needed to switch from hamstring stimulation to quadriceps stimulation. Since both were controlled independently, it was possible that hamstrings and quadriceps were stimulated simultaneously.

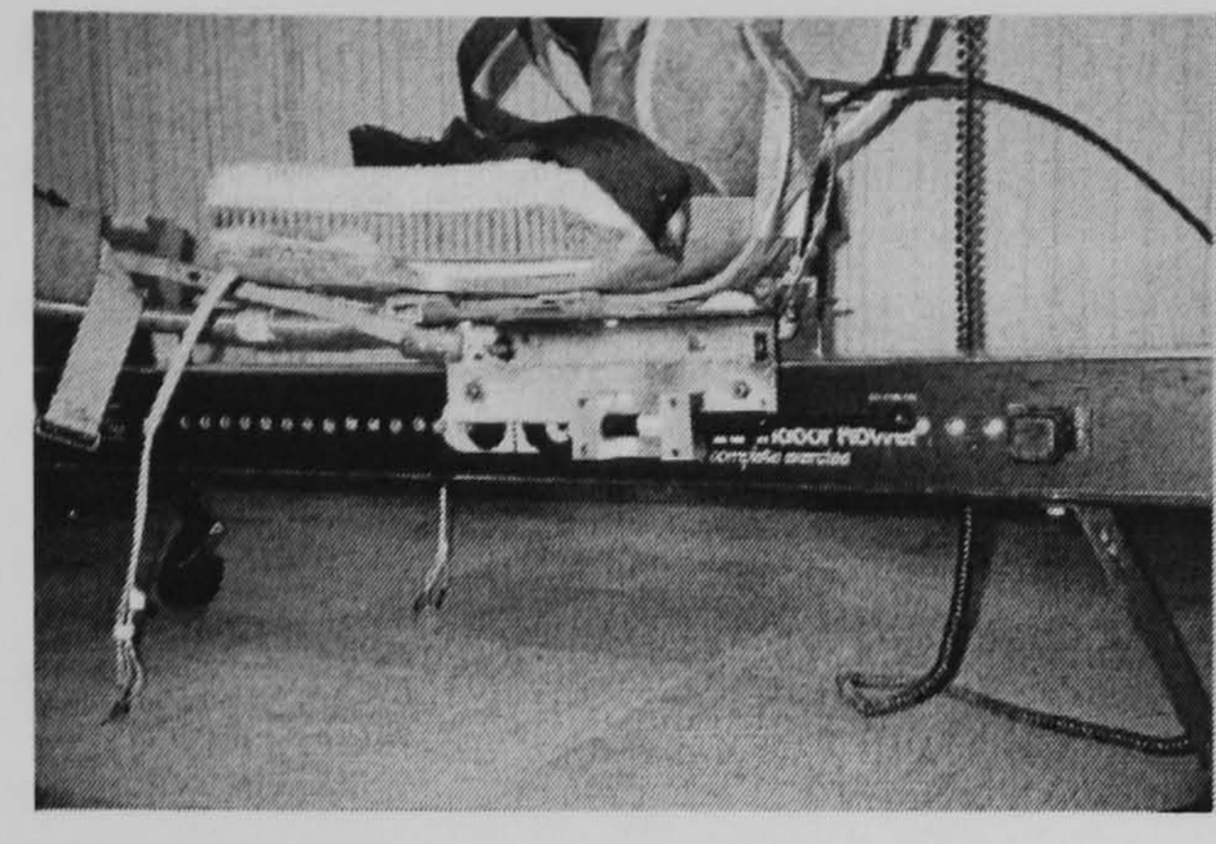
In this chapter I present solutions for the above- mentioned limitations.

8.2 Seat carriage system

In able-bodied rowing, power generated by the leg muscle results in the seat sliding over the monorail with minimal forces in the vertical plane or perpendicular to the monorail. Therefore the Concept 2 seat carriage system consists of two rollers sliding over the top flange of the monorail (to take the body weight of the rower) and one roller on the bottom on the flange (to prevent the seat from falling off the monorail) (see Figure 8.2). However the forces through the seat in FES-rowing are in different directions as can be concluded from the deformed bearings displayed in Figure 8.3. The cause of these deformities is the backrest used on the FES-rowing seats. As explained in Chapter 2, a backrest has been mounted on the Concept 2 seat to provide additional postural support for paraplegic rowers. Rowers with high thoracic lesions (the majority of the FES-rowers) use a strapping system that keeps their shoulders close to the back rest, while rowers with lower lesions can use a lap belt instead (note: all rowers in the pilot studies used a shoulder strap). The forces applied on the backrest are transferred to the bearings of the seat and since the backrest acts as a long momentum arm, the forces at the bearings are considerable.

The forces on the backrest are in two directions; parallel to the monorail and perpendicular to the monorail. The forces parallel to the monorail result in rocking action of the seat (the whole seats pivots around the rollers), while the perpendicular forces result in misalignment of the rollers on the monorail (the rollers come off the monorail). In both instances rolling resistance increases and consequently the movement of the seat over the monorail is impaired.

The Concept 2 carriage system has not been designed to cope with the above described forces since in able-bodied rowing these forces are minimal. It appeared that the carriage system had to be re-designed specifically to suit FES-rowing.



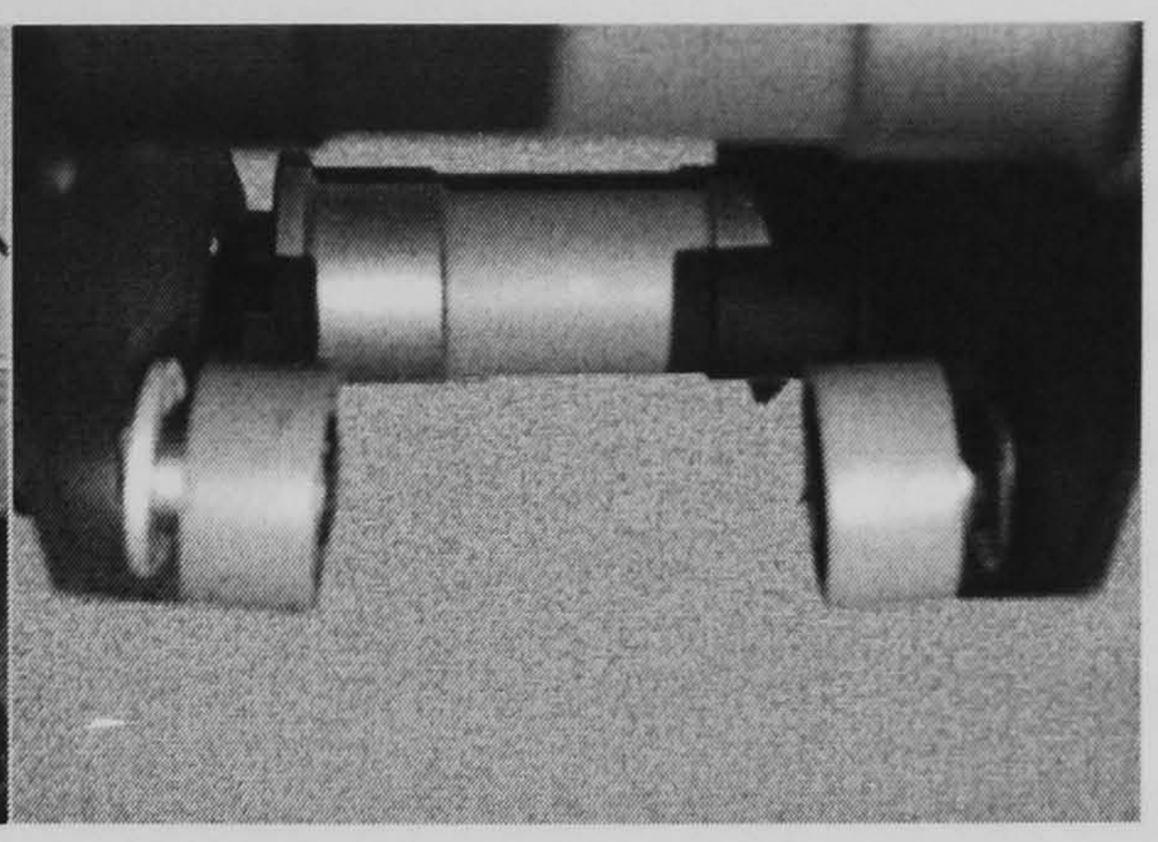


Figure 8.2: Mounting of seat- carriage system on top flange of monorail with standard Concept 2 rollers arrangement.

Figure 8.3: Standard top and bottom Concept 2 (rollers (rollers have been Dismounted from monorail). The left bottom roller is clearly bent.

This has been achieved by designing a box section that slides around the monorail (see Figure 8.4). The distance between the two top rollers of the Concept 2 system has been extended and two rollers have been added to slide along the bottom of the monorail. This gives a much more stabile platform for the seat and back rest, since it uses the full strength of the 'I' shape of the monorail instead of only the top flange.

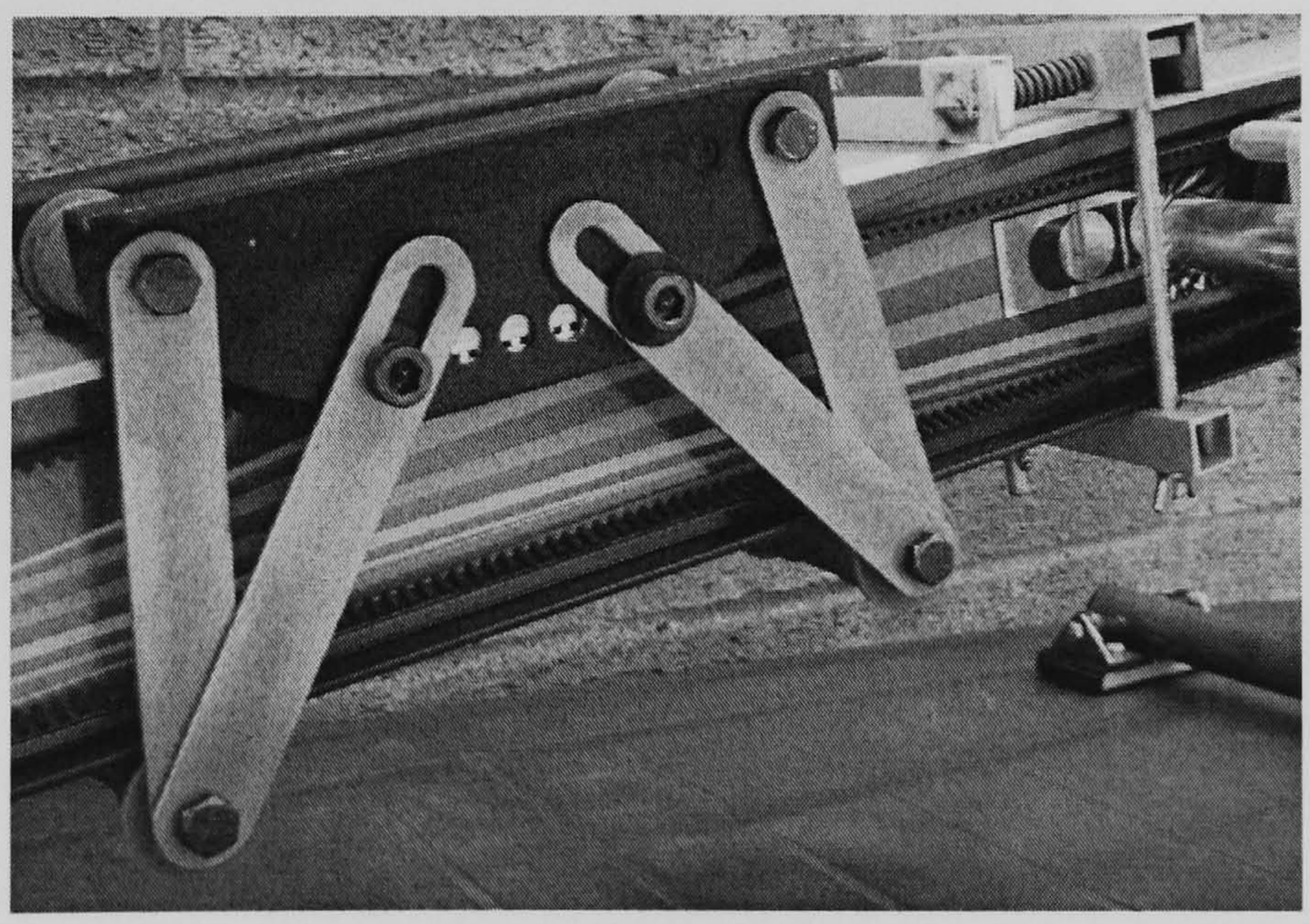


Figure 8.4: Redesigned seat carriage system with box-section. The seat has been taken away to show the box section with rollers sliding on top and at the bottom of the monorail.

In addition, the box section allows a strong brake to be fitted to the seat carriage system. Such a brake is useful when the rowers are transferring on and off the machine and when they wish to alternate between FES-rowing and arms only rowing. In the pilot studies presented in Chapters 3-6, the subjects used an interval training consisting of FES-rowing and short rest periods. However the exercise volume can be increased by replacing the rest intervals with arms only rowing. This would give the leg muscles the necessary time to recover, but still continue the exercise.

The brake consists of a braking pad on the bottom of the monorail that can be clamped with a lever on the side of the seat (see Figure 8.5). The lever is positioned high enough to allow the rower to operate the brake, which ensures a fast switch over from FES-rowing to arms only rowing. The strength of the brake can be adjusted by changing the distance of the braking pad to the monorail using a single bolt.

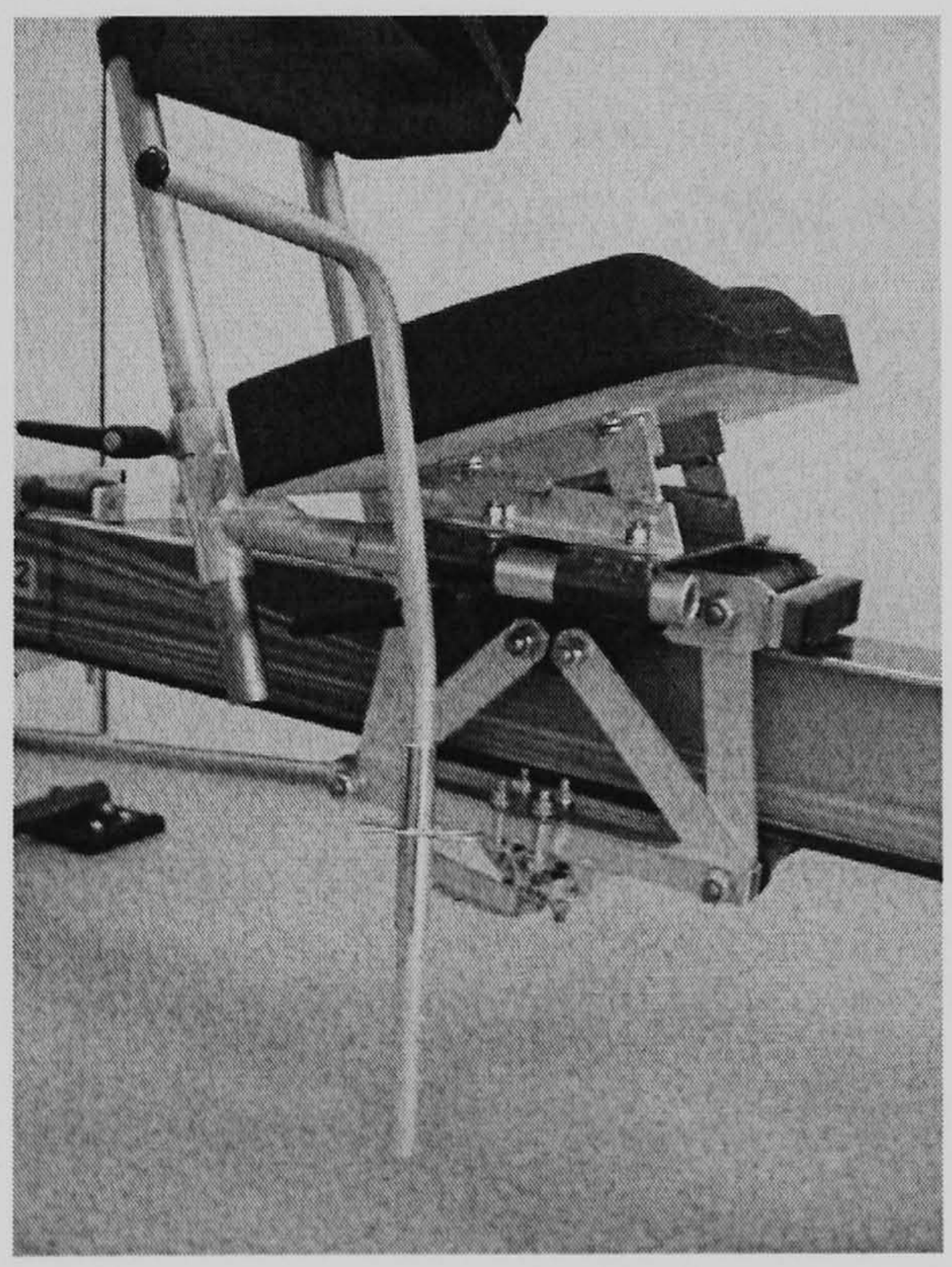


Figure 8.5: Brake and handle of the RowStim III.

This improved seat carriage system with brake has resulted in less rolling resistance as visible by the diminished rocking of the seat and more stable positioning of the rollers on the monorail. The brake has given the additional advantage that rowers can now alternate between FES-rowing and arms only rowing.

8.3 Return phase and harness system

The return phase (also called recovery phase) of the rowing cycle (during which the seat comes forward) is achieved by flexing the knees using electrical stimulation of the hamstrings. However the hamstrings are bi-articular muscles with an action in the knee (flexion) and hip (extension). The hip extension is counter-productive during the return phase since hip flexion is visible during the return phase. Therefore alternative strategies are needed to achieve a fluent return phase. In the experiments described in chapters 2-6 an Odstock 4 channel stimulator was used which excluded the possibility to simultaneously stimulate additional muscle groups (e.g. calf muscles) to achieve a fluent return phase. As a result, at that stage, only mechanical solutions could be considered. The FES-rowing machine used for the studies presented in Chapter 2-6 was equipped with a spring that stored energy generated by the quadriceps muscles during the drive phase. This energy was released when the quadriceps were relaxed and the return phase was initiated. However it was often difficult to find the right spring; too strong springs gave unnecessarily strain on the quadriceps while too weak springs failed to adequately support the hamstrings.

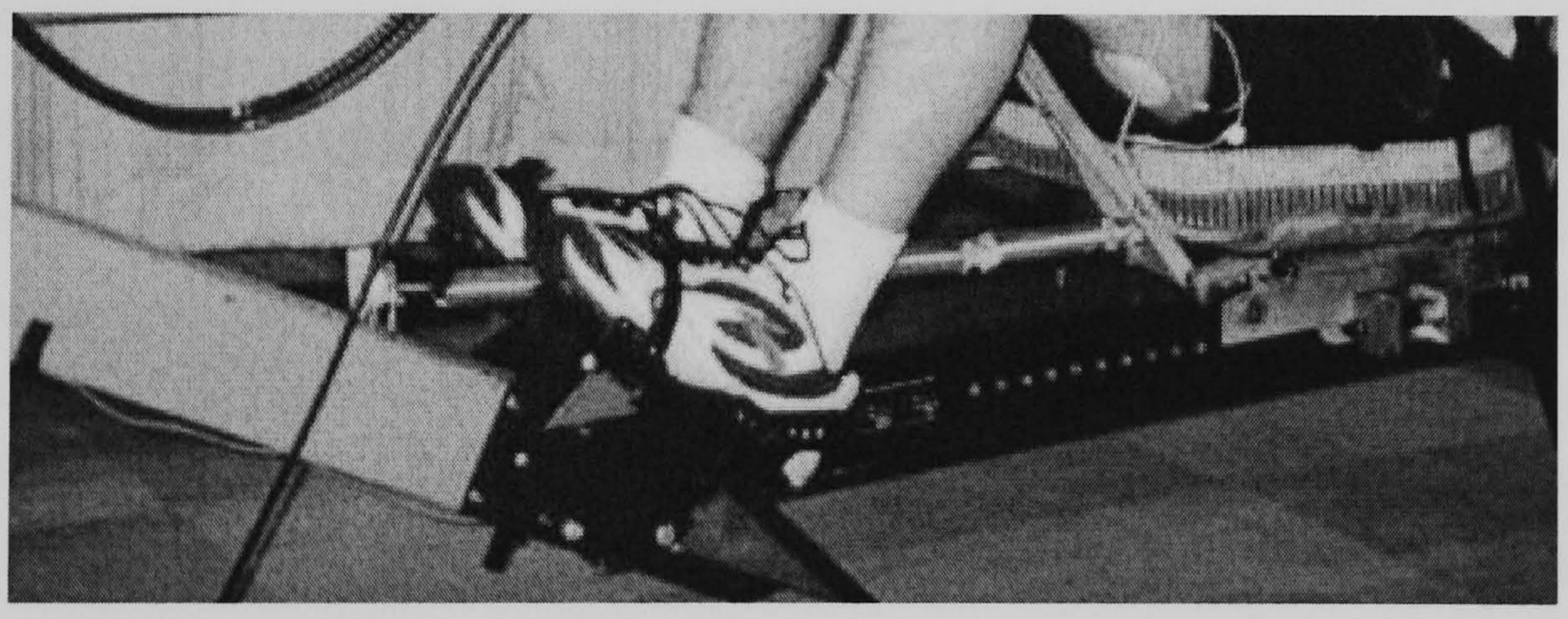


Figure 8.6: The spring is attached at the front end of the seat and on the front end of the rowing machine.

An attempt was made to replace the springs with elastic cords, but problems arose around the reproducibility of strength of these cords. Continued use and aging resulted in weakened and / or damaged elastics with altered strength characteristics. A second attempt was made using gravity as an assisting force. Creating an inclined monorail whereby the front end is lower than the rear end would assist the return phase. This has been achieved by replacing the standard rear foot of the rowing machine with a jockey wheel construction (Figure 8.7). This allows simple and accurate adjustment of the inclination and prevents overstraining the quadriceps or under-supporting the return phase.

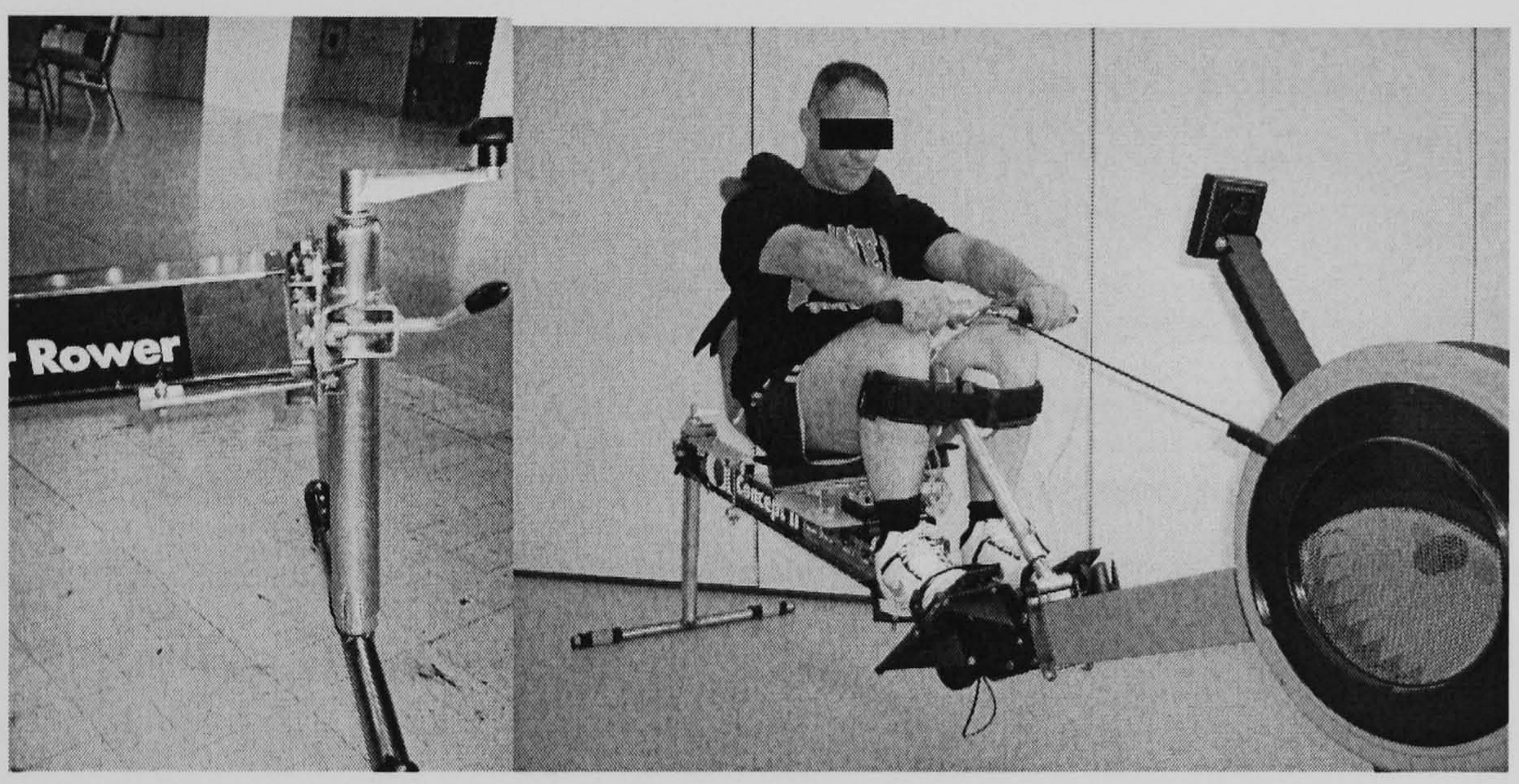


Figure 8.7: Re-designed back foot of the rowing machine with adjustable height enabling a rower to use an inclined monorail to assist with the return phase.

The foot displayed in Figure 8.7 had the tendency to slide over the floor with every stroke. This is mainly caused by the sudden stop of the seat against the end stop on the monorail. Therefore a foot was designed that absorbs some of this energy and prevent the machine from moving across the room during rowing (see Figure 8.8). This was done by mounting the foot on a small platform. The bottom of this platform consisted of a high resistance anti-slip surface. The foot was mounted with rubber brackets on this platform. Any forward or backward movement from the rowing machine would be absorbed by these rubber brackets. This new foot prevented the machine from moving across the room although on some surfaces additional tape was necessary.

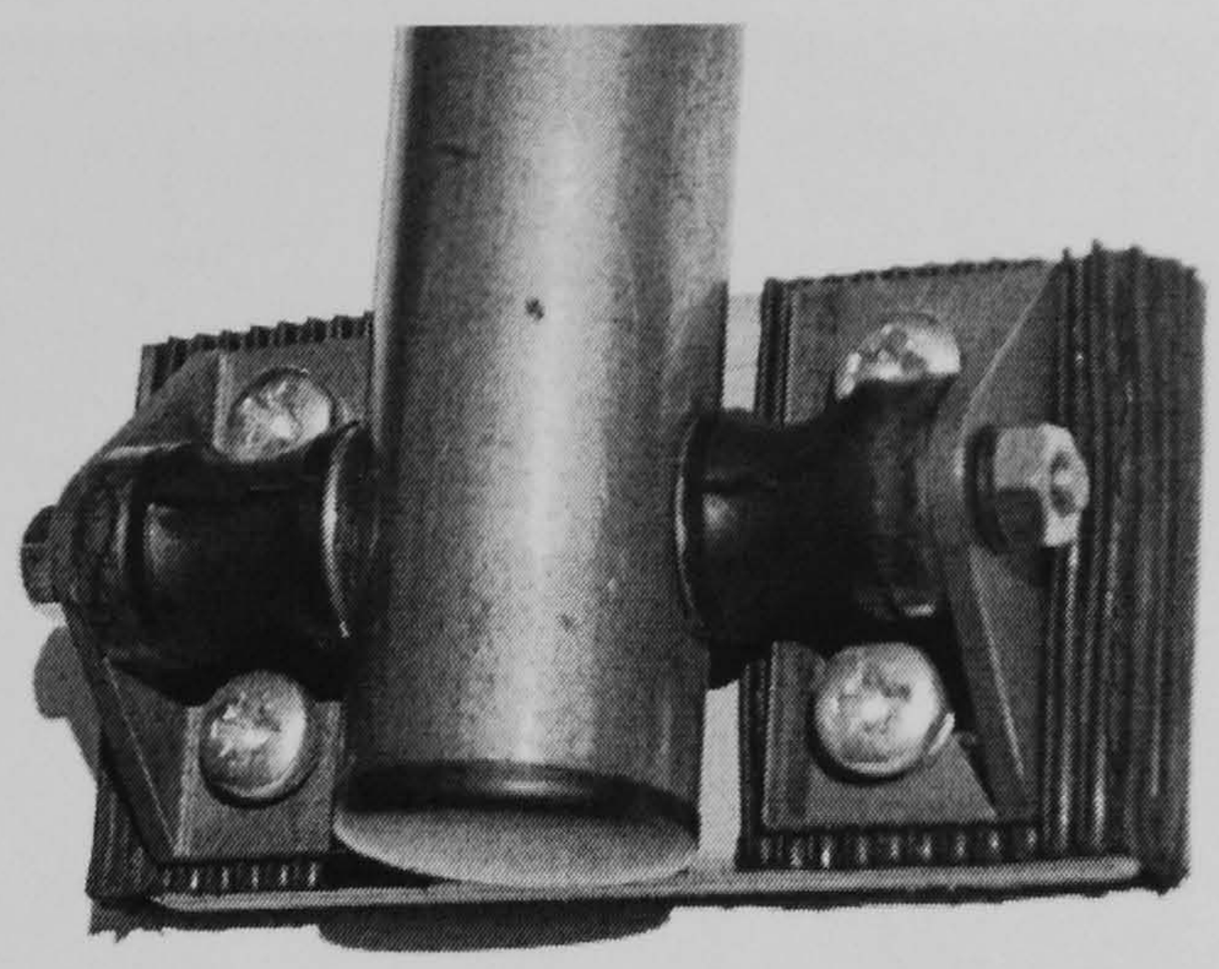


Figure 8.8: Foot of rowing machine with anti-slip surface and rubber brackets.

As a consequence of the inclination in the monorail, the seat and backrest are also tilted forward. This is an uncomfortable position for the rower since the rower now hangs more in the straps. Therefore the seat and backrest were tilted back to compensate for the inclined monorail (see Figure 8.9). Although the inclination of the seat and backrest are non adjustable, rowers have mentioned that they prefer to have the seat and back rest tilted back more than strictly necessarily to compensate for the inclined monorail. This has the added benefit that a simple shoulder strap gives sufficient postural support since the rower by default leans more against the backrest. Moreover, the inclination in the seat prevents the rower from sliding of the seat and this meant that the lap belt used on the RowStim II is now obsolete. The higher backrest that was made possible with the more stable seat carriage system (as explained in section 8.2), also meant that the shoulder straps could be attached higher than on the RowStim II. This new arrangement meant that when the straps were tightened, the shoulders were pulled back and not down.

This inclination in the seat and backrest and the high backrest with shoulder straps resulted in a more upright rowing posture as can be seen by comparing Figure 8.9 (RowStim III) and Figure 8.10 (RowStim II). The rowers noted that this posture was more comfortable.

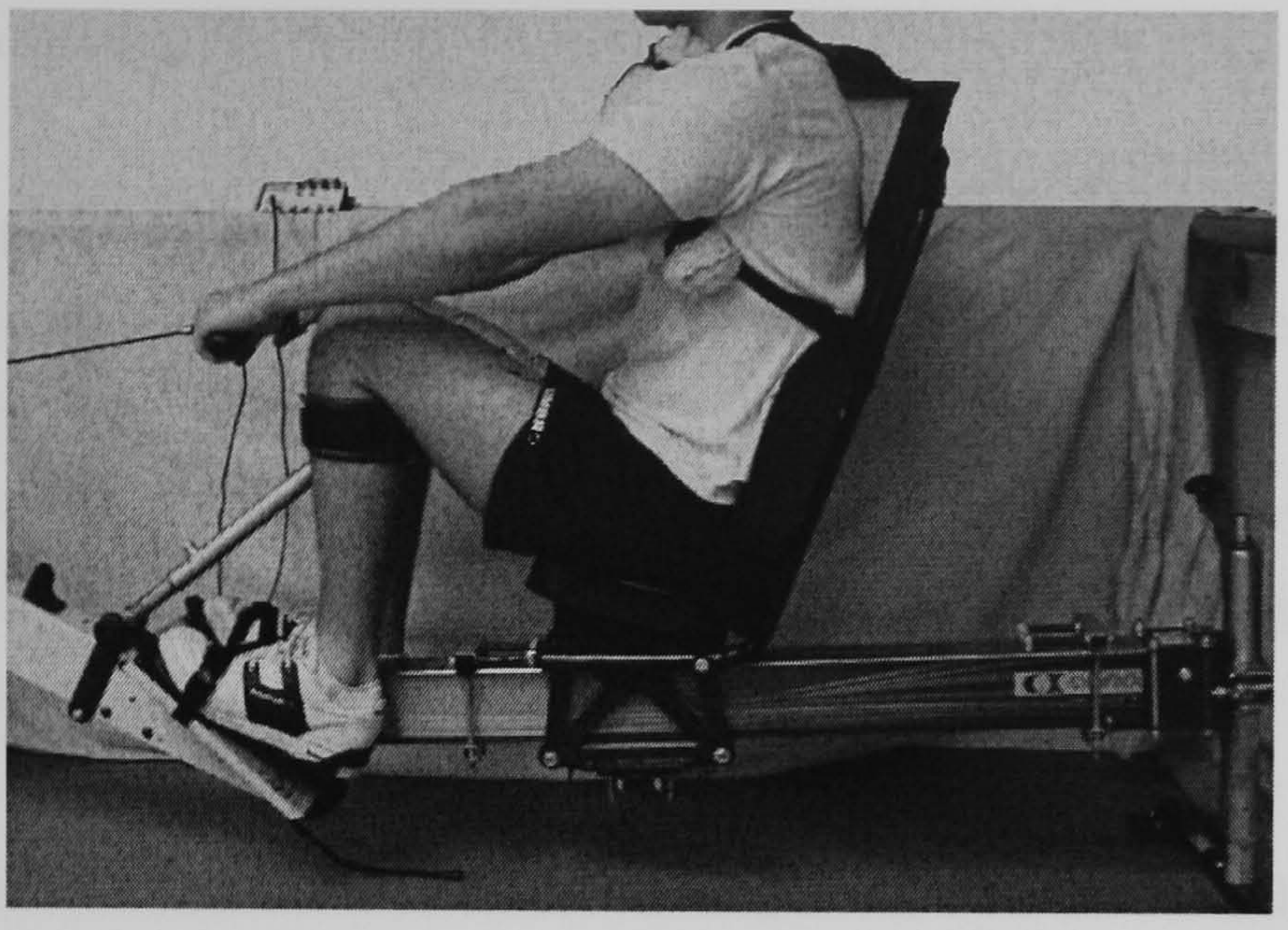


Figure 8.9: Tilted seat and high backrest of the RowStim III resulting in an upright rowing posture.

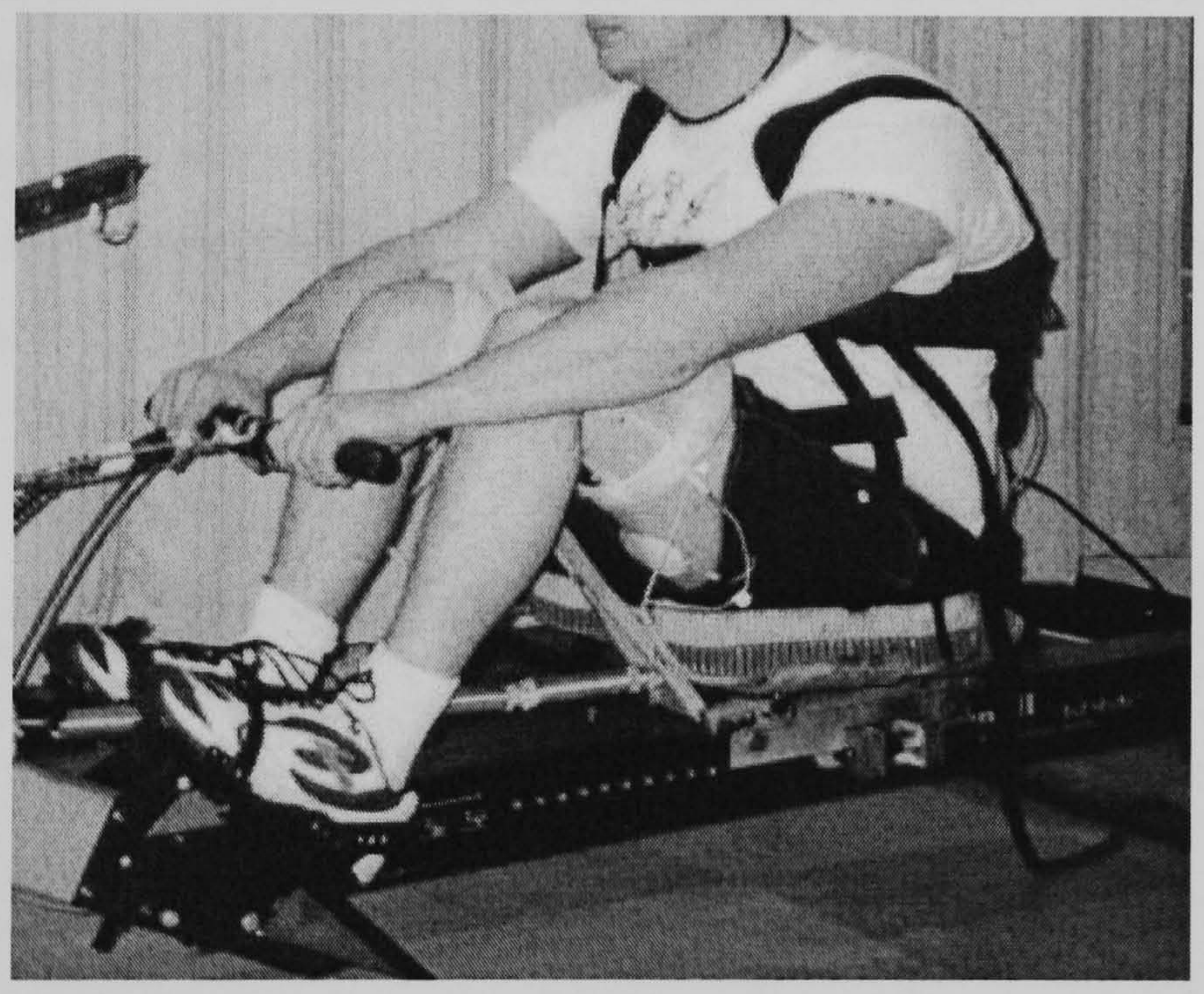


Figure 8.10: Flat seat and low backrest of the RowStim II resulting in a slumped rowing posture.

8.4 Leg stabilisers

Extreme hip adduction or abduction impairs the leg action during the rowing cycle. To prevent this from happening, leg stabilisers have been designed that keep the legs in the sagittal plane. The leg stabilisers of the RowStim II consisted of a three jointed bar attached to the seat and the upper leg of the rower (Figure 8.11). However, there were two significant disadvantages to this arrangement:

- The three joints in the leg stabiliser impaired the stability
- The strap that kept the leg stabiliser on the upper leg of the rower, interfered with the electrodes resulting in the electrodes coming loose or disconnected.

The new design of the leg stabilisers consisted of a telescopic tube attached to the front end of the rowing machine and the calves of the rower (see Figure 8.12). This resulted in a much more stable system and no interference with the electrodes on the upper leg. Moreover, the leg stabiliser was attached to the front end of the rowing machine and not the seat which decreased the weight of the seat carriage system.

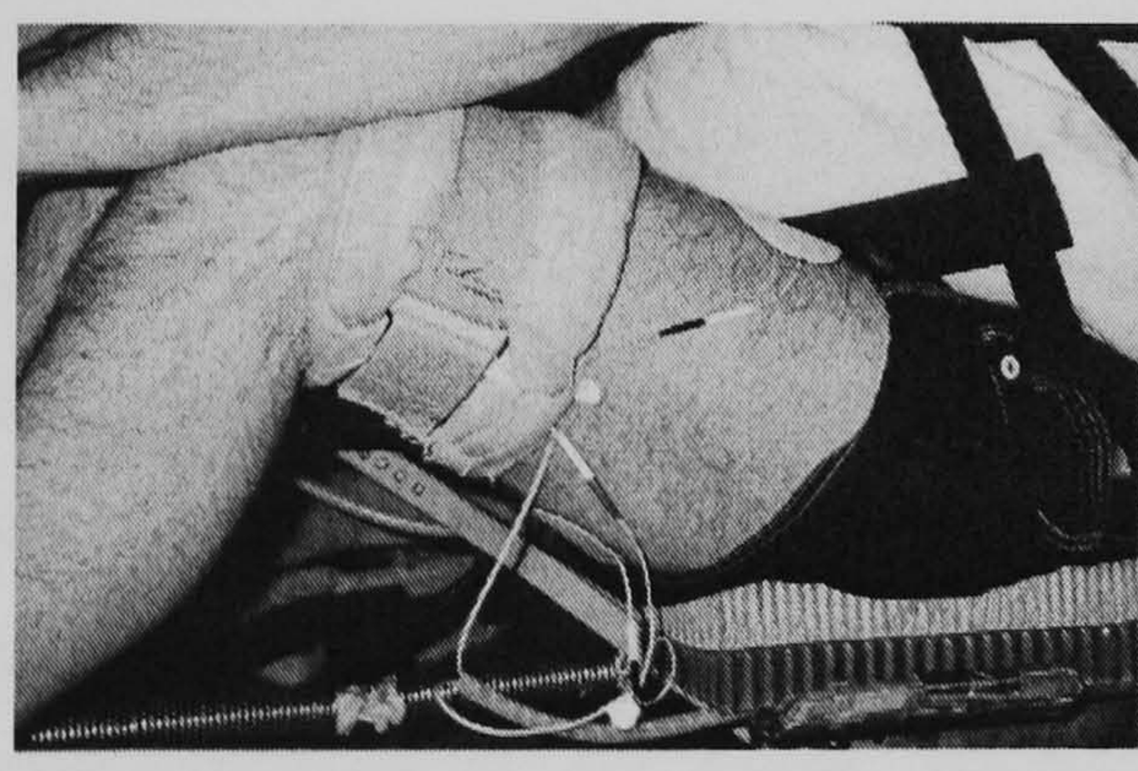


Figure 8.11: Leg stabiliser of the RowStim II

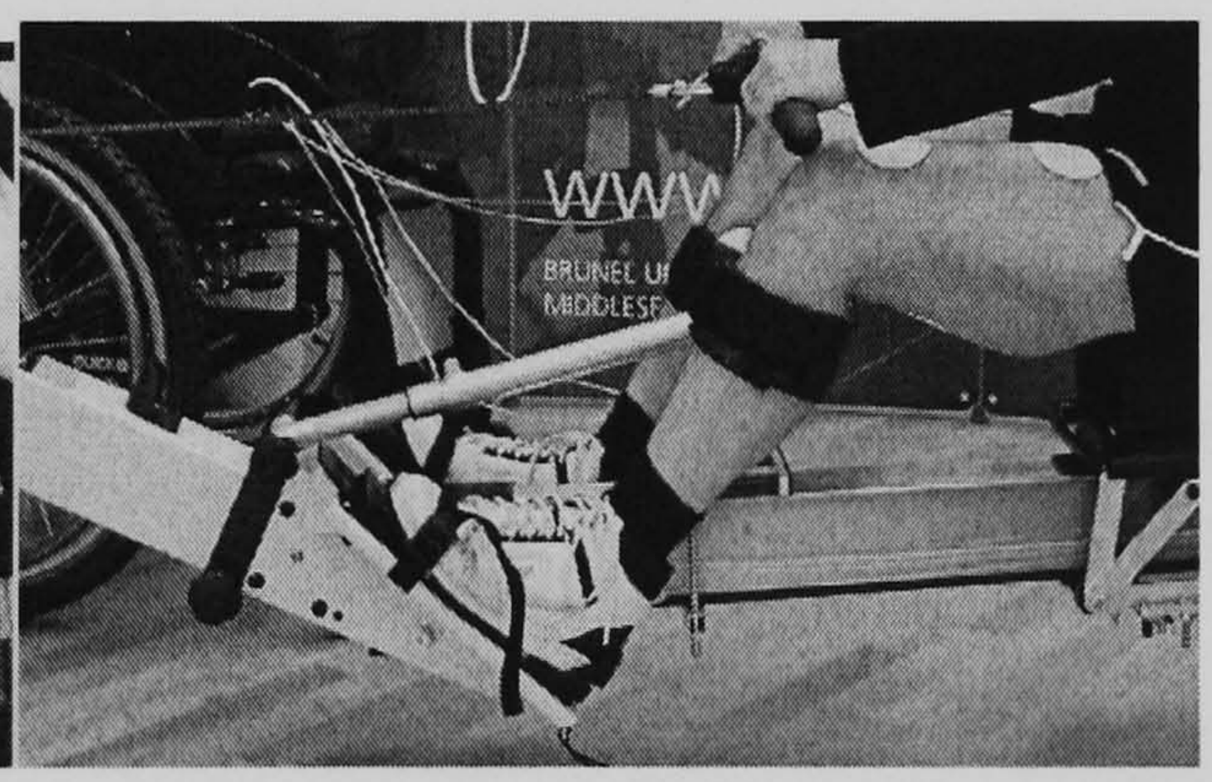


Figure 8.12: Leg stabiliser of the RowStim III.

8.5 Stimulation control and end stops

Using two separate switches to control hamstrings and quadriceps stimulation can result in simultaneous stimulation of these two muscle groups. Obviously this impairs the rowing movement and theoretically it could damage the muscle (if high powers are generated). Therefore a new two-way switch was developed for the FES-rowing machine. The Odstock stimulator is set to two by two stimulation (channel 1 is coupled to channel 2, channel 3 is couples to channel 4). If the switch is now pressed, two channels are active. Releasing the switch results in the other two channels to be active.

Although this has solved the problem with simultaneous stimulation, a new problem arose that two channels are always on when the stimulator is in use. This is not desirable during for instance arms-only rowing intervals. However the Odstock stimulator has a function whereby all four channels can be coupled together, using two switches on the stimulator. Since two channels are inactive when the switch is not pressed, the other two channels can be coupled to these two inactive channels to achieve zero stimulation on all four channels. Consequently rowers could still switch swiftly between FES-rowing and arms-only rowing with no stimulation.

Even with this improved switching mechanism, rowers still have only a split second to change stimulation channels. If the quadriceps are being activated too long, the knees will go to over-extension and lock out. This could not only damage the knee joint, it also impairs the return phase. The RowStim II used pneumatic cylinders to slow the seat down at the end of the stroke and prevent over-extension of the knees. However, these cylinders were unreliable and difficult to position along the monorail. Therefore the end-stops of the RowStim III consisted of springs attached with clamps around the monorail. This allowed for precise adjustment of the distance the seat could travel over the monorail. A similar stop was also attached to the front, since the inclined monorail could result in the seat coming forwards too much and consequently over-pressurising the knee joint.

8.5 Conclusion

The main limitations in the FES-rowing machine used in the studies presented in Chapter 3-6 were:

- The high rolling resistance and unpredictable jamming of the seat carriage system caused by the rocking of the seat-carriage system.
- The inability to adjust the return forces needed to support the hamstring action in the recovery phase of the rowing motion.
- The pelvis/trunk/shoulder harness system was overly complicated and constricting. The over shoulder strap located too low.
- The unreliable pneumatic cylinders used to limit the travel range of the seat over the monorail.
- The interference of the leg stabiliser with the electrodes on the upper leg and the impaired stability of this configuration.
- The coordination needed to switch from hamstring stimulation to quadriceps stimulation.

The technological development described in this chapter (see also Figure 8.13) have shown to be an improvement to the previous design and the above limitations have been solved or controlled. The new box section with extra rollers on the bottom of the monorail give more stability to the seat carriage system and less rocking. The height-adjustable rear-end of the rowing machine allows accurate and simple adjustment of the support needed for the return phase without putting excessive strain on the quadriceps. Moreover this inclination has resulted in less pressure on the straps during rowing, which is more comfortable for the rowers. The newly designed leg stabilisers do not interfere with the electrodes on the upper leg and provide more stability to the system. And finally, the new two-way switch prevents simultaneous stimulation of the hamstrings and quadriceps muscles.

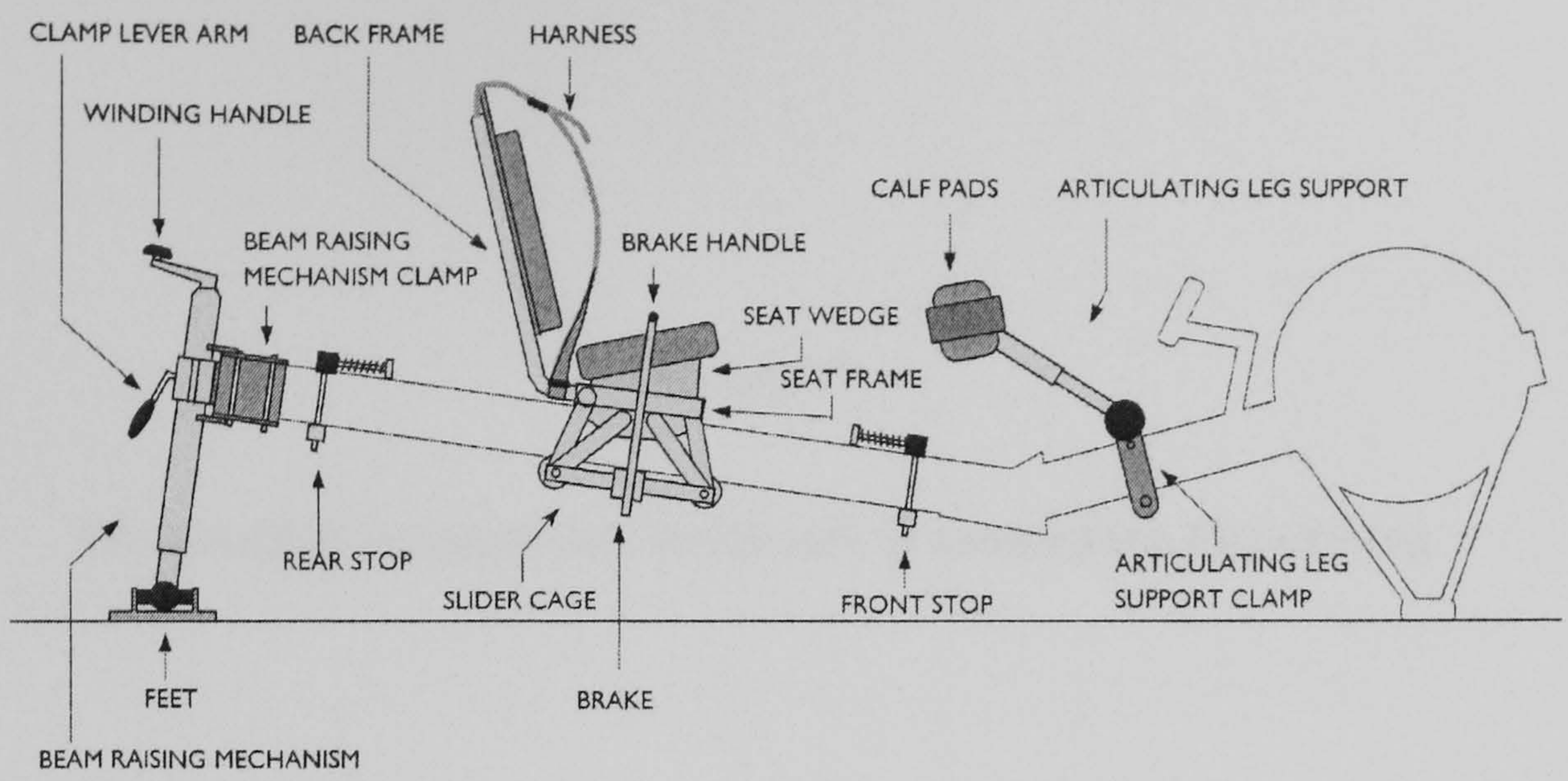


Figure 8.13: The RowStim III.

This new prototype, known as RowStim III, was a significant improvement from the previous version and to fully test the reliability of the machine, FES-rowers were encouraged to compete in indoor rowing events. This allowed the following hypothesis to be tested:

H 6 Introducing a competitive element to FES-rowing will improve training compliance and enable larger training intensities and volumes to be achieved.

This is discussed in Chapter 9.

Chapter 9

Physiological demands and limitations of competitive FES-rowing

9. Physiological demands and limitations of competitive FES-rowing

The previous chapter reported on the improved design of the FES-rowing machine, which has solved the limitations of the RowStim II. To fully test the reliability of this new prototype, the RowStim III was used for indoor rowing competitions, namely the British and World Indoor Rowing Championships. Moreover, such a competitive challenge could motivate FES-rowers to train harder and for longer. The following hypothesis is central in this chapter:

H 6 Introducing a competitive element to FES-rowing will improve training compliance and enable larger training intensities and volumes to be achieved.

During the training towards these competitions, a number of observations were made that could indicate physiological limitations to long-term high intensity FES-rowing, in particular:

- Blood circulation in the muscle during electrical stimulation.
- Prolonged pressure on the ischial tuberosity leading to an increased risk for pressure sores.

This will also be discussed in this chapter.

Abstract

High exercise intensities and large exercise volumes are more likely to be achieved by those FES-rowers who are motivated to spend long periods of time training. To facilitate this, FES-rowing has been included in the British and World Indoor Rowing Championships. The FES-rowers training for these events achieved very high exercise intensities (VO_2sub-peak: 26.8 – 31.0 $mL \cdot kg^{-1} \cdot min^{-1}$) and large volumes (1,150 $kcal \cdot week^{-1}$). Moreover the newly developed prototype, the RowStim III, was proven to be reliable.

Preliminary data suggests that blood flow in the quadriceps during FES-rowing could have been a limiting factor in some rowers. The risk for pressure sores appears to be minimal since body weight is taken off the seat for a short period during the rowing cycle due to a pivoting action on the edge of the seat.

FES-rowing is now a well-established sport that provides a competitive element to those who would like to test their daily training. This might facilitate achieving optimal exercise intensities and volumes that have significant health benefits.

9.1. Introduction

Since the pioneering work of Sir Luttwig Guttmann at Stoke Mandeville Hospital on including physical activity and sport in the rehabilitation of spinal cord injured persons, disability sport has seen continuous growth (Guttmann, 1976). Sir Guttmann was an advocate of sport due to its therapeutical effects in the rehabilitation of his patients, but nowadays the high-performance side of sport is just as important for many. However in both instances, optimal benefits would be achieved by participating in exercise programmes of sufficient intensity and volume.

FES-rowing pilot studies have suggested that the reported intensity is not high enough to obtain optimal health benefits (Chapters 3-6). Moreover, trained spinal cord injured athletes are able to achieve higher intensities using upper body exercise (section 1.5.2), which implies FES-rowing is of limited value for cross-training for spinal cord injured athletes. The pilot studies also revealed a number of mechanical limitations in the rowing machine, which could have been the reason why the participants did not reach higher intensities. Therefore a new FES-rowing prototype has been developed in order to achieve higher intensities (Chapter 8). This new design will hopefully enable paraplegic rowers to participate in high intensity and high volume training programmes and competitions.

Indoor rowing has seen a steady increase in able-bodied participants over the years. Since the first British Indoor Rowing Championships in 1991, the number of athletes competing each year has grown to well above 2,500. The popularity of indoor rowing can be explained by the following factors:

- For recreation, indoor rowing offers a social dimension. It can be undertaken in a club setting or in a virtual environment in which rowers are connected together via the internet (eROW by Concept 2 Inc, Vermont, USA and RowPro by Digital Rowing Inc, Boston, USA).
- For health maintenance, indoor rowing is associated with high exercise intensities due to the large amount of active muscle mass involved in rowing. These high intensities and consequently large training volumes have resulted in superior health benefits (Durstine et al., 2001, Tanasescu et al., 2002).
- For cross-training i.e. cardiovascular workout for training in a wide range of other sports such as rowing on-water or other sports whereby a large aerobic capacity is important. Indoor rowing offers a convenient form of cardiovascular workout that can be undertaken in the club or home environments.
- For competition, there are many levels of competition including national and international events.

These indoor rowing competitions form for many a goal for training that challenges them to improve. This factor was absent in the previous FES-rowing pilot studies and perhaps therefore participants were less motivated to achieve high exercise intensities and high exercise volumes. It is anticipated that competitive FES-rowing would appeal to more people if it would not only allow FES-rowers to compete FES-rowers, but also able-bodied rowers. To achieve this, technology and training will have to be optimised.

Halliday et al. (2004) published a biomechanical analysis of FES-rowing and compared the data with experienced able-bodied rowers. The power output for the FES-rower (an experienced FES-rower with a T2 complete lesion) at the handle peaked at 320 N, while the five male able-bodied rowers showed on average a peak force of 1000 N. The peak force at the foot plate for the FES-rower was approximately half of the peak forces seen in the able-bodied rowers (400-500 N). Of interest was the fact that the force on the foot plate peaked twice for the FES-rower (of approximately the same magnitude), while the able-bodied rowers had only one peak, suggesting that the upper body action of the FES-rower was not fully integrated with the FES-induced leg drive. The correct rowing technique is illustrated in Figure 9.1. Although Figure 9.1 shows the rowing technique in a boat, the same technique should be used on the rowing machine.

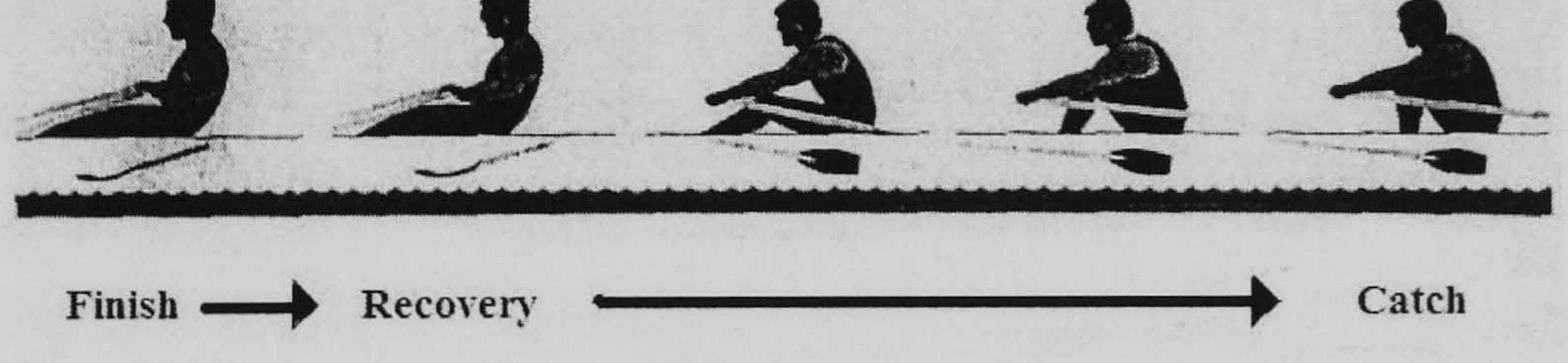


Figure 9.1: Rowing technique in able-bodied rowers.

Starting at the catch position (or front-stops), the arms of the rower are fully extended, the legs flexed (with the lower legs vertical) and the trunk slightly leaning forward. The first part of the stroke is conducted with the legs (the drive phase). When the legs are almost fully extended, the trunk extends from an 11 o'clock position to a 1 o'clock position. Finally the arms are flexed until the hands are just in front of the chest. This is the finish position (or back-stops). The return phase starts when the hands are brought forward, followed by trunk movement. When the hands go over the knee, the knees should flex and the whole body should go back towards the catch position (McArthur, 2005). In able-bodied, this arms-trunk-legs action should be a very fluent movement, but the results from Halliday et al. suggest that in the FES-rower, the power generation from the legs is not very well timed with the power generation of the arms. Halliday concluded that FES-rowing is not able to reproduce a race-winning stroke as seen in able-bodied varsity rowers (members of the 2002 Oxford-Cambridge Boat Race winning crew). It should be noted though, that this comparison group consisted of young world-class athletes and that the vast majority of the able-bodied population would not be able to achieve the forces reported in these varsity rowers. Also, the rowing machine used by Halliday et al. (2004) is similar to the one used in the pilot studies presented in Chapters 2-6. The aim of the technological improvements discussed in Chapter 8 was to develop a rowing machine that would allow for a fluent and efficient rowing movement. It would therefore be of interest to evaluate this new design in a competition context.

In addition to evaluating FES-rowing as a competitive sport, the resulting higher exercise intensity and volume would also optimise health benefits. The average VO_2peak achieved in previous FES-rowing studies (Wheeler et al, 2002, Verellen et al, 2007, and the study presented in Chapter 3) is 1.81 $L \cdot min^{-1}$, although values up to 2.66 $L \cdot min^{-1}$ have been reported by Verellen et al. (2007). Average relative VO_2peak reported in the above three studies is 23.6 $mL \cdot kg^{-1} \cdot min^{-1}$. Subjects in the pilot study presented in Chapters 2-6 were instructed to aim for an exercise volume of 800 $kcal \cdot week^{-1}$ although all rowers achieved considerably less than that (277-683 $kcal \cdot week^{-1}$). It would be of interest to explore if competitive FES-rowers can achieve higher intensities and volumes. The technological improvements will have solved some of the limitations in the rowing machine and consequently higher VO_2 values are expected with the re-designed machine.

However, during FES-rowing training, remarkable differences in the fatigue resistance of the leg muscles between individuals were observed. This might be explained by the nature of FES-contractions and the long-term adaptations needed. In able-bodied, blood flow is reduced during muscle contractions and elevated during muscle relaxation, whereby the intensity and duration of the contraction influences the magnitude of the blood flow increase during these relaxation periods (Hoelting et al., 2001, Wesche, 1986, Walloe and Wesche, 1988). FES provokes tetanic muscle contractions, which could consequently restrict blood flow to a large extent. Butler et al. (2004) found that high blood pressure is associated with an improved fatigue resistance during FES-induced contractions, which implies that muscle perfusion during FES could indeed be a limiting factor (Kralj and Bajd, 1989). And this could also explain the high blood lactate levels seen in persons undertaking FES-exercise as the restriction in blood flow forces the muscle to use anaerobic energy sources (Kim et al., 1995). It would therefore be of interest to monitor blood flow in the quadriceps during FES-rowing.

During this training period concerns were raised on the effect of prolonged FES-rowing training on the risk for pressure sores on the ischial tuberosity (buttocks). Although a gel-pad (Akton Action, 0.25" thick) prevents excessive stress on the tissue, no data is available on the pressure present on the ischial tuberosity during FES-rowing. Evidence based clinical guidelines from the National Institute of Clinical Excellence (NICE) state the following risk factors for pressure sores (National Institute for Clinical Excellence, 2001):

- Reduced mobility
- Sensory impairment
- Acute illness
- Level of consciousness
- Extremes of age
- Vascular disease
- Severe chronic or terminal illness
- Previous history of pressure damage
- Malnutrition and dehydration

The majority of the spinal cord injured population has at least two of the above risk factors, putting this population at elevated risk for pressure sores. In addition

NICE recommends minimising prolonged pressure on bony prominences, friction and shear stress. FES-rowing is likely to result in pressure and shear stress on the ischial tuberosity, but the magnitude of these forces is unknown. Although the gluteii muscles are not being stimulated during FES-rowing, radiation of the electrical current and reflex activity in these muscle groups might have resulted in muscle hypertrophy. Such hypertrophy and FES use have been recommended in the prevention and treatment of pressure sores (Ferguson et al., 1992). Nevertheless a pressure mapping study should be performed to assess the effect of FES-rowing on the pressure distribution under the ischial tuberosity.

The aim of the pilot study presented in this chapter is to explores three parameters during competitive FES-rowing with the new prototype:

- Oxygen consumption, exercise intensity and volume.
- Muscle blood flow in the quadriceps
- Pressures on the ischial tuberosity

Although the small sample size will not be able to show without doubt the safety and efficacy of FES-rowing, it will be used to compile hypotheses for future studies.

9.2. Methods

This study was approved by an institutional ethics committee and all subjects gave written informed consent before participation. Three men with complete thoracic lesions (T4-T8) participated in this project. All three participants were experienced FES users and were involved in some other kind of regular physical activity (e.g. swimming, wheelchair basketball, rowing, strength training).

FES-rowing equipment

A full description of the FES-rowing machine has been described in Chapter 8; in brief: a standard Concept 2 rowing ergometer has been equipped with a special seat with backrest and leg stabilisers to give paraplegic rowers sufficient postural support. Quadriceps and hamstrings were stimulated with an Odstock 4-channel stimulator (Salisbury District Hospital, Salisbury, UK). Stimulation (frequency: 50Hz, pulsewidth: 450μs, amplitude: max 115 mA) is controlled by a switch on the handle bar of the rowing machine (pressing switch results in quadriceps stimulation for the drive phase, releasing the switch gives hamstrings stimulation for return phase). To assist the forward motion triggered by the hamstrings contraction, the monorail could be inclined.

FES-rowing training

Before starting the FES-rowing programme, two FES-rowers (9 and 11) used FES to increase strength and endurance of the quadriceps muscle. This was done with dynamical knee extensions, while the subject was seated in his wheelchair. Stimulation parameters of the Odstock 4-channel stimulator (Salisbury District Hospital, Salisbury, UK) were set to 50 Hz, 450 μs pulsewidth, un-ramped stimulation with a four seconds on-time and 12 seconds cycle time. Amplitude was started at a level resulting in full knee extension and increased if 180 degrees extension was no longer achieved. In the first week of muscle strengthening, three to four 15-minute sessions were performed. This was quickly built up to five to six 30-minute sessions in week four. Subject 9 used ankle weights after approximately four weeks, but no clear benefit was visible. That is why for rower 11 a pragmatic approach was used; he started short FES-rowing sessions in week four, supplemented with continuous muscle strengthening on the days he was not rowing. Subject 10 had been using a FES-cycle for over a year before entering this project, which is why no muscle conditioning phase had been included for him.

When starting the FES-rowing training, most FES-rowers started with an interval training consisting of FES-rowing and arms only rowing intervals. The ratio is very different from individual to individual and depends on to what extent the leg muscles are able to contract forcefully over prolonged periods of time and the time needed to recover from these (tetanic) contractions (typically 30 seconds FES-rowing, 30 seconds arms-only rowing). Further FES training would lead to longer FES-rowing intervals and after some time arms only rowing intervals were no longer necessary. FES-rowing training was performed at home or at a local rowing centre for three to five sessions per week. Initially rowers aimed for 2,000 meters, which took 12-20 minutes. When rowers were able to row 2,000 meters, training time was increased to approximately 30 minutes per session. In addition all rowers continued to use FES muscle strengthening and/or FES-cycling.

Subject 9 kept a detailed training log during the months before the 2005 BIRC. This gave information on the number of training sessions, the distance covered in these sessions and the performance (time per 2,000 and 5,000 meters).

Oxygen consumption testing

Two FES-rowers came to the lab in the weeks after competing in the British Indoor Rowing Championships for a simulated 2,000 meter race. During this test oxygen consumption (Oxycon Pro 500), heart rate (Polar heart rate monitor), power output, stroke rate (both read from display Model D Concept 2 rowing ergometer) were monitored. After a two minute warm up period, the subject was instructed to complete the 2,000 meter as fast as he could. The subject decided on their own racing strategy, but both rowers aimed for level race with a spurt towards the final 500 meter.

Blood flow testing

Two subjects participated in Near-Infrared Spectroscopy (NIRS) testing (Hamamatsu NIRO 500). An infrared laser and sensor was placed over the

Quadriceps muscle of the rower and covered with a bandage to prevent any other light coming through to the sensor. The rower conducted a normal rowing session, while NIRS, due to the difference in light reflection, revealed the dynamics of the blood circulation and oxygenated hemoglobin (HbO_2) and reduced hemoglobin (Hb-) concentration in a part of the quadriceps muscle.

Pressure mapping

One rower (subject 9) participated in pressure mapping experiments. Pressure mapping was performed using a Tekscan ConformMAT (Tekscan Inc, Boston , USA). The Tekscan mat was placed on the seat of the rowing machine without any other interface materials. Since the main interest was changes in pressure during rowing, no calibration was used and the results show relative pressures. Two experiments were conducted; static and dynamic. The static testing was done in two position, end stops (with the legs extended and seat at the rear of the monorail) and front stops (with the legs flexed and seat in forward position). The dynamic testing was conducted during a single rowing stroke from front stops to front stops.

9.3. Results

In 2004, the winning FES-rowing time at the British Indoor Rowing Championships over the official 2000 meter race was 12 minutes and 2 seconds. In 2005 the winning time was 11 minutes and 11 seconds. Full details of the performance of the individual rowers is given in Table 9.1.

Table 9.1: Subject characteristics and performance

Subject	**9**	**10**	**11**
Age (years)	50	34	44
Body weight (kg)	70	65	77
Level of lesion and ASIA scale	T4, ASIA A	T8, ASIA A	T6, ASIA A
Time since injury (years)	5	5	6
FES-rowing training duration	18 months	12 months	3 months
FES before FES-rowing	3 months of muscle strengthening	>1 year FES-cycling and muscle strengthening	1 month of muscle strengthening
BIRC results	2004: 12:02 2005: 11:11	2004: 13:59 2005: 13:58	2004: na 2005: 11:38
Steady state VO_2 during simulated race	31.0 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ (2.17 $L{\cdot}min^{-1}$)	unknown	26.8 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ (2.07 $L{\cdot}min^{-1}$)

Training and competition

The results of the physiological tests are displayed in Table 9.1. Steady state oxygen consumption values for the two FES-rowers (9 and 11) was 26-31 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ (2-2.2 $L{\cdot}min^{-1}$). The Respiratory Exchange Ratio (RER) after reaching a steady state was, in both rowers, above 1.0. Heart rate showed, in both rowers, a steady state around 160 bpm.

Figure 9.2 is a detailed graph with heart rate and VO_2 during the full 2,000 meter session in rower 9. After 2-3 minutes heart rate and VO_2 had reached a steady state and this was similar to the VO_2 and heart rate dynamics of the other rower.

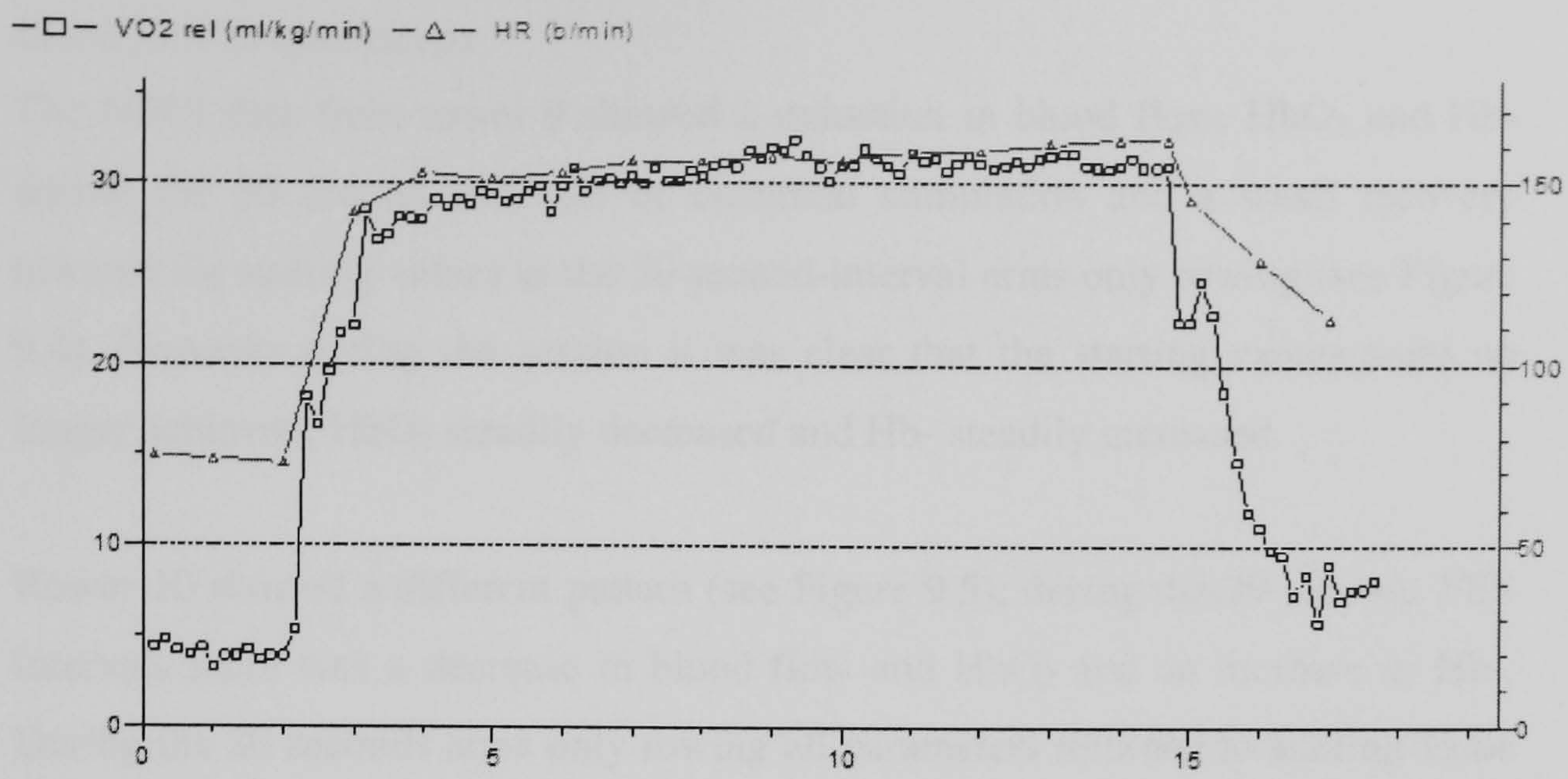


Figure 9.2: Oxygen consumption and heart rate of subject 9 during 2,000 meter FES-rowing race.

Figure 9.3 gives a detailed presentation of the times rower 9 did in training over the year 2005. The majority of his training sessions consisted of 2000 meters followed by a short rest to monitor performance and heart rate, and then an additional 3000 meters. The total 5000 meters took him on average 30-35 minutes. The training log from rower 9 revealed that in the period January 2005 - November 2005, he rowed on average 106 minutes per week (split over 3-4 sessions).

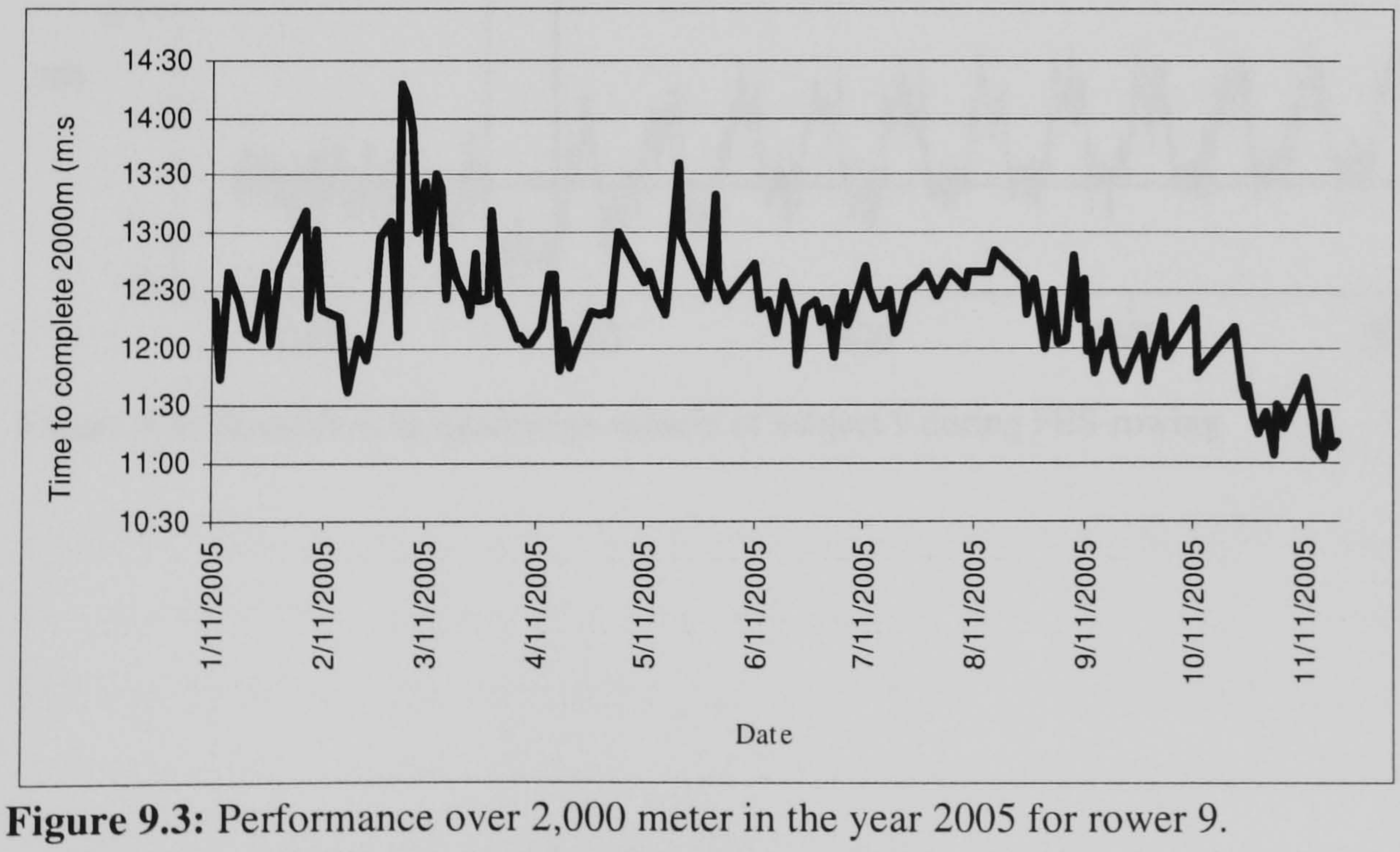


Figure 9.3: Performance over 2,000 meter in the year 2005 for rower 9.

Blood flow in quadriceps

The NIRS data from rower 9 showed a reduction in blood flow, HbO_2 and Hb- during the 30 second intervals of electrical stimulation and a small recovery towards the starting values in the 30 second-interval arms only rowing (see Figure 9.4). However during the session it was clear that the starting values were no longer achieved; HbO_2 steadily decreased and Hb- steadily increased.

Rower 10 showed a different pattern (see Figure 9.5); during the 30 seconds FES intervals there was a decrease in blood flow and HbO_2 and an increase in Hb-. During the 30 seconds arms only rowing all parameters returned to starting value and there was no long term decrease in blood flow and HbO_2 and increase in Hb-. After 5-6 minutes blood flow was not disturbed much from the starting values.

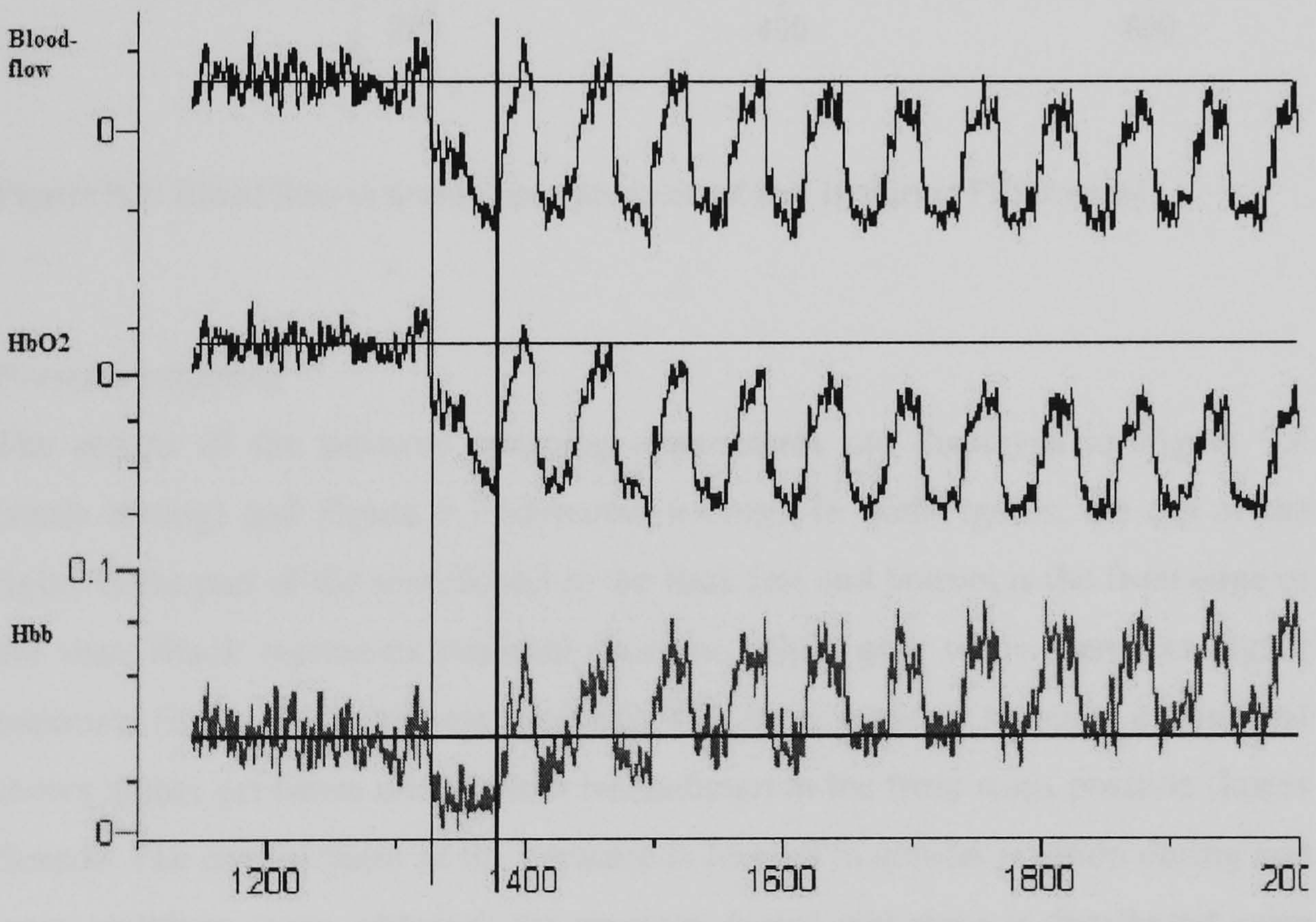


Figure 9.4: Blood flow in quadriceps muscle of subject 9 during FES-rowing.

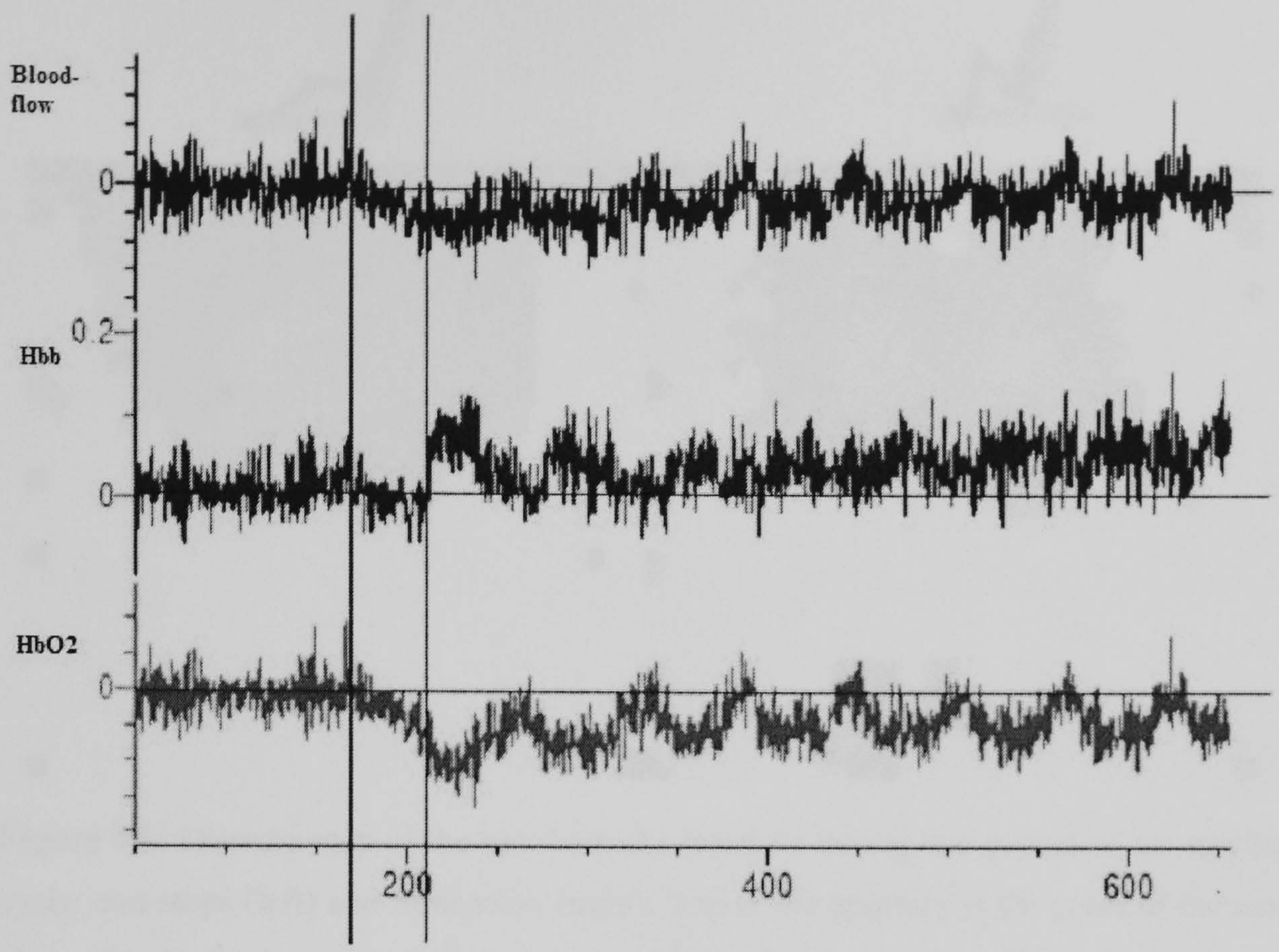


Figure 9.5: Blood flow in quadriceps muscle of subject 10 during FES-rowing.

Pressure mapping

The results of the pressure mapping experiments are displayed in Figure 9.6 (static testing) and Figure 9.7 (dynamic testing). In both figures, the top of the figure is the part of the seat closest to the back rest and bottom is the front edge of the seat. Black represents minimal pressure, while grey tones represent higher pressures (light grey is highest pressure). The static pressure mapping experiment shows higher pressures on the tuber ischiadicum in the front stops position (knees flexed). The central point of the pressure is located in similar position during end stops and front stops, although the pressure during end stops is distributed more evenly. This is more obvious in the dynamic situation whereby minimal pressure is applied to the tuber ischiadicum towards the end of the drive phase (Figure 9.6). The central point of pressure not only shifts during the drive phase, it almost completely disappears at the end the drive phase (situation 5 and 6 in Figure 9.7).

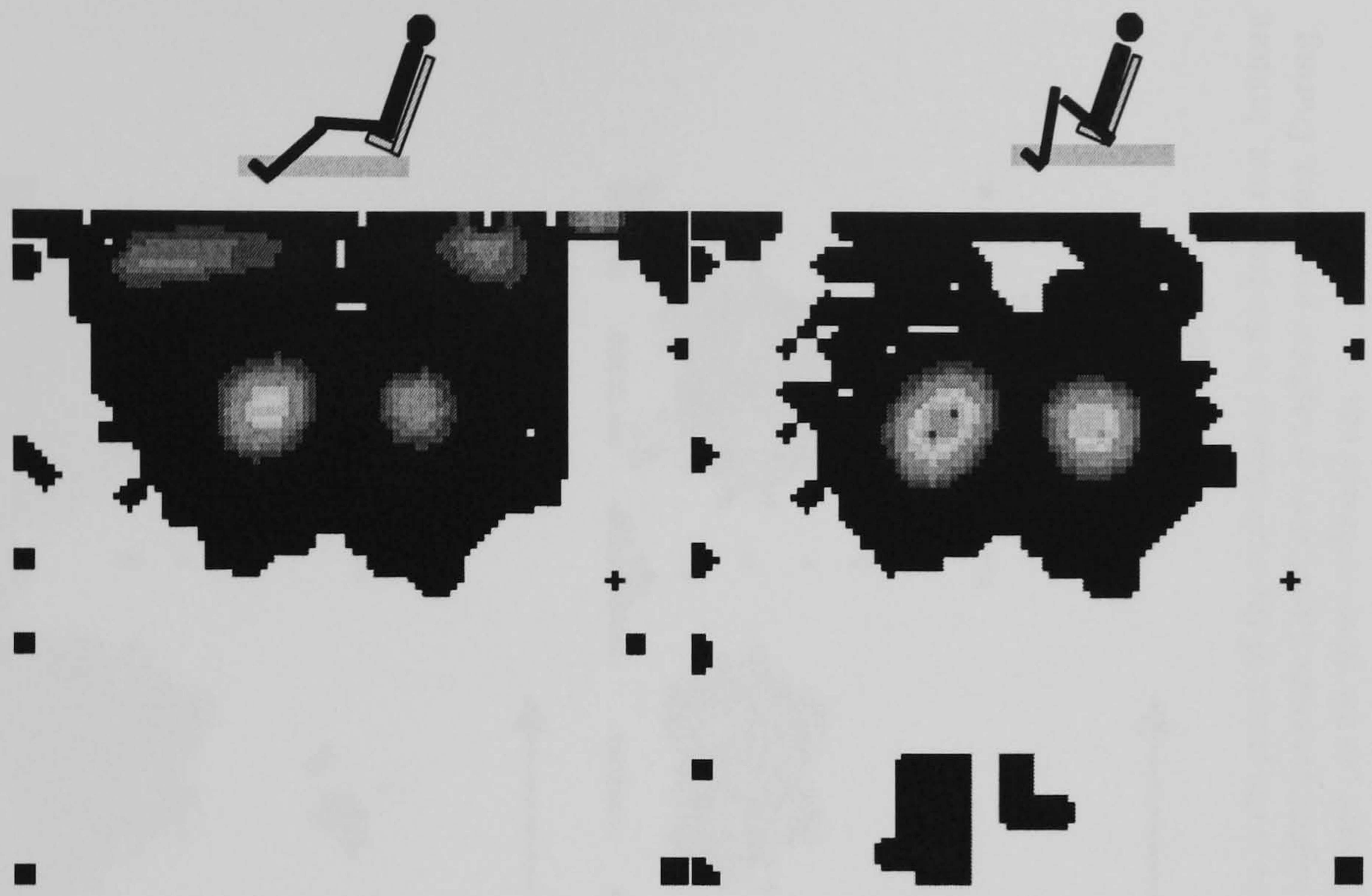


Figure 9.6: Pressure map of the seat-buttocks interface during two phases of the rowing cycle: end stops (left) and front stops (right). Top of the graphics is the point of the seat closest to the back rest, bottom end is the front edge of the seat. White represents no pressure, black minimal pressure and grey tones higher pressure (light grey is highest pressure).

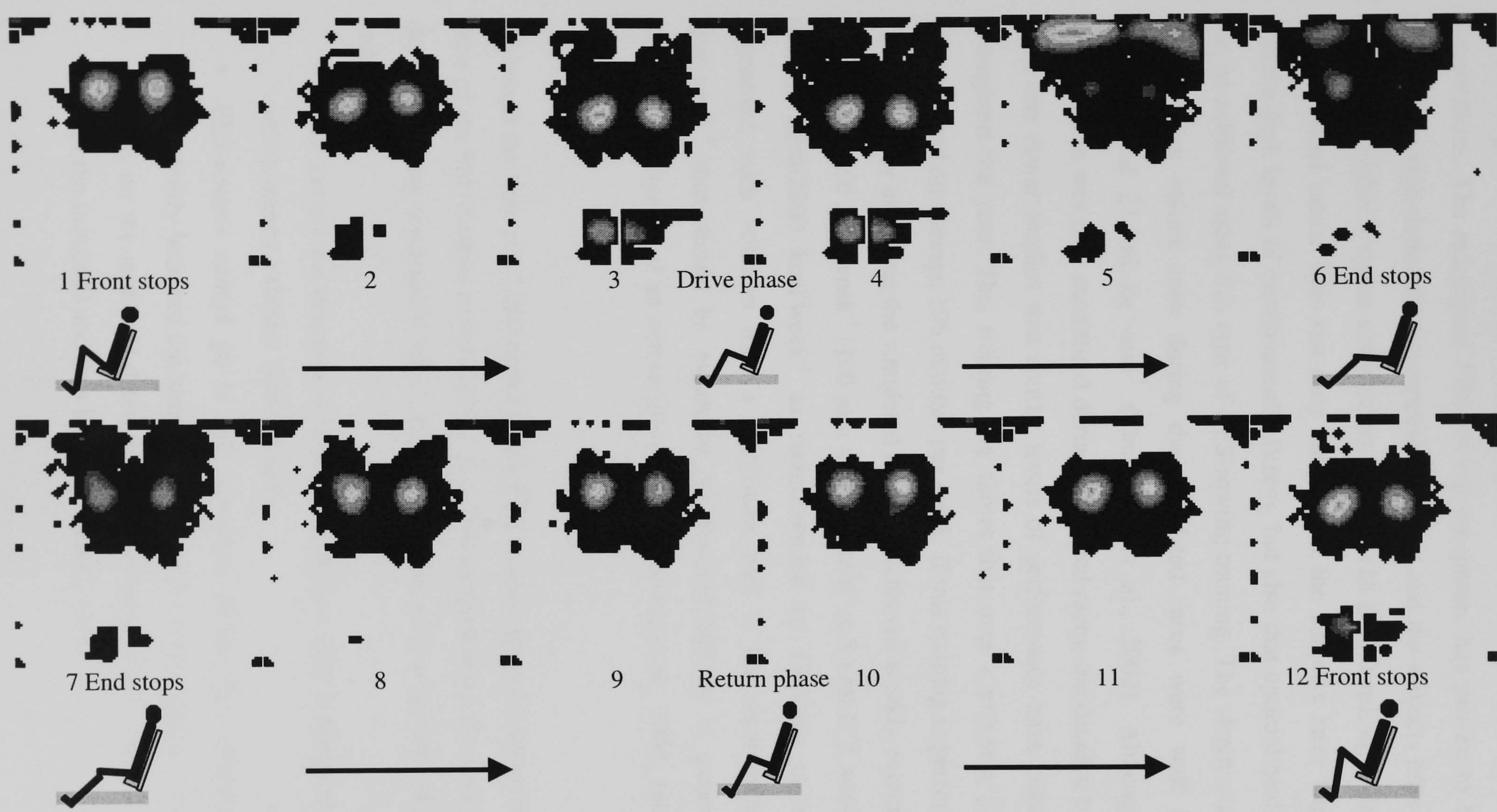


Figure 9.7: Pressure map of the seat-buttocks interface during a FES-rowing cycle. Top of the graphics is the point of the seat closest to the back rest, bottom end is the front edge of the seat. White represents no pressure, black minimal pressure and grey tones higher pressure (light grey is highest pressure). During final stages of the drive phase (5-6) the upper leg pivots on the edge of the seat and this relieves the pressure on the tuber ischiadicum.

9.4. Discussion

FES-rowing has successfully been integrated with mainstream indoor rowing competitions. The redesigned FES-rowing equipment has proven to be reliable under these high-demanding competitive settings and the subjects have been able to achieve higher oxygen consumption values (26.8-31.0 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$) during the simulated races. This not only shows that the subjects have been able to achieve high levels of cardiovascular fitness, but also that optimal health benefits can be achieved using this type of FES-rowing training. The steady state oxygen consumption values seen during the simulated races were well above the recommended 21 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ (Tanasescu et al., 2002). Although oxygen consumption was only monitored during simulated races, the detailed training log from one rower implies that similar levels of performance have been achieved throughout the year. This training log shows that over a one-year period, this rower rowed on average 106 minutes per week. If this training is performed at the same intensity as during the simulated race, the achieved weekly exercise volume would be 1,150 $kcal{\cdot}week^{-1}$ (106 min x 2.17 $L{\cdot}min^{-1}$ x 5 $kcal{\cdot}L^{-1}$), which is close to the 1200-2200 $kcal{\cdot}week^{-1}$ as recommended by Durstine et al. (2001). Moreover, such volumes form a significant part of the recommended 2,000 $kcal{\cdot}week^{-1}$ that should be expended on physical activity in general (which includes all aspects of an active lifestyle) (Tanasescu et al., 2002, Jakicic et al., 2001).

Although the time per 2,000 meter of the FES-rowers was well above the winning time of the able-bodied rowers (11:11 and 5:46 respectively), the performance of the rowers was remarkable since they had to deal with a number of significant restrictions:

- FES-rowers are strapped in their seat and have only minimal trunk swing, which means a shorter stroke length.
- FES-rowers cannot go to full extension of the legs since this would effectively lock out the knees and impair the return phase. Front and end stops on the monorail determine the maximum travel of the seat system over the monorail and thus limit the stroke length.

- Instead of using a full set of leg muscles, FES-rowers only use the quadriceps and hamstring muscles in their legs. Clearly this puts a higher metabolic stress on these muscles and muscular fatigue shows up sooner.
- FES induced muscular contractions are less efficient than voluntarily controlled contractions (Mizrahi, 1997).
- Long-term FES training is needed to achieve a highly fatigue resistant muscle.

This latter point can be derived from the NIRS experiments. The NIRS data showed that the blood flow in the quadriceps muscle of rower 9 did not recover in the 30 seconds arms only rowing intervals. On the contrary, the 30 seconds were sufficient time for the blood flow of rower 10 to recover to starting values, which suggests that blood flow is a limiting factor in the FES-rowing performance of rower 9. At the time of the NIRS experiments rower 9 was not able to continuously FES-row but had to adhere to a 30 seconds FES-rowing- 30 seconds arms only rowing protocol to complete the 2,000 meters. Rower 10 was able to FES-row for 2,000 meters continuously. The differences between subject 9 and 10 might be explained by the difference in duration of FES training. Subject 10 had been involved with FES-cycling for over a year, while subject 9 had only been using FES for a number of months. Possibly the long-term training of subject 10 had resulted in better vascularisation of the quadriceps and therefore he was better able to cope with the tetanic contractions during FES-rowing.

The NIRS data from subject 9 showed another remarkable feature; during the FES intervals blood flow, HbO_2 and Hb- all decreased. This is unexpected as during a contraction blood flow will decrease, HbO_2 decrease (oxygen is being used) and subsequently Hb- will increase (as visible in the data from subject 10). Possibly this is a result of severe restriction in blood flow whereby all blood is squeezed out of the muscle during FES and subsequently [HbO_2] and [Hb-] are both reduced.

Finally, the results of the pressure mapping experiments suggest that FES-rowing sessions do not increase to the risk for pressure sores since the centre point of pressure shifts during the rowing cycle. Towards the end of the drive phase, the power generated by the quadriceps results in a pivoting action over the front edge of the seat, consequently the pressure of the ischial tuberosity is decreased. In addition, when the seat hits the end-stops on the monorail, the continued power generation by the quadriceps results in the subject being pushed against the back rest and the point of pressure shifts towards to rear of the seat. Although the magnitude of the pressure is unknown the result of both the above described actions is that every rowing cycle includes a brief pressure relief. Long term follow up should ascertain the clinical value of these findings, but to date none of the rowers who participated in the studies presented in this thesis have experienced any pressure sores as a consequence of their rowing. This could be explained by the findings of the pressure mapping experiments.

These findings suggest that FES-rowing could play a role in optimal prevention of cardiovascular diseases but it also indicates that FES-rowing could be a valuable and safe cross-training tool for SCI athletes. Cardiovascular training in SCI has traditionally been restricted to upper body exercises, whereby a small amount of muscle mass creates a high oxygen consumption/ energy expenditure. FES-rowing would give similar high oxygen consumption values, but spread this over a larger muscle mass. As well, the movement pattern of rowing is distinctively different from wheelchair propulsion (a commonly used type of cardiovascular training in SCI). This results in different muscle groups being used or muscles being used differently. For example, an imbalance between protractors and retractors around the shoulder could be an underlying mechanism for shoulder complaints in long term wheelchair users (Burnham et al., 1993). Earlier work has shown that the EMG pattern of rowing is similar to a special retractor exercise, which might counteract the chronic loading of the protractor muscles during wheelchair propulsion (Olenik et al., 1995).

9.5. Conclusion

The results from this pilot study suggest that the redesigned FES-rowing prototype gives paraplegic rowers the opportunity to compete in mainstream indoor rowing competitions and participate in high intensity and high volume exercise training. Besides superior levels of cardiovascular fitness, participating in these training programmes can also result in optimal reduction in the risk for cardiovascular diseases, non-insulin dependant diabetes mellitus and obesity.

Participating in such FES-rowing programmes requires sufficient strength and endurance in the quadriceps and hamstrings. During FES-rowing early signs of muscular fatigue are associated with a restriction in the muscular blood flow. Long-term follow up studies need to further investigate this but the results of this pilot study suggest that long-term electrical stimulation of paralysed muscles is able to improve blood flow during stimulation and postpone fatigue.

Moreover, preliminary results indicate that the pressure on the ischial tuberosity during FES-rowing is no reason for concern. The location of the centre point of pressure shifts during the rowing cycle and a tilting action at the end of the drive phase results in a short period of pressure relief on the ischial tuberosity.

It should be noted however, that all the above results need to be confirmed in larger follow up studies. The results of this pilot study suggest that it is safe and useful to continue to study the role of FES-rowing in sport and health for persons with spinal cord injury.

Chapter 10

Overall discussion

10. Overall discussion

The overall aim of this thesis was to test the feasibility of FES rowing for sport and health in persons with spinal cord injury. In this chapter I will present all the initials aims and hypotheses and the conclusions of the studies that addressed these aims and hypotheses.

Lit 1. Identify how a spinal cord injury impacts risk factors for cardiovascular diseases, non-insulin dependant diabetes mellitus, obesity and osteoporosis.

The results of the literature review presented in Chapter 1 indicate that a spinal lesion does not have a significant direct effect on risk factors for cardiovascular diseases, NIDDM, obesity and osteoporosis. However, chronic SCI leads to a number of significant changes in body composition, especially below the level of lesion, that initiate a cascade of events that eventually also impact these risk factors. In particular the reduction in amount of active muscle mass results in elevated risk factors for CVD, NIDDM and obesity, since this muscle mass cannot contribute to overall energy expenditure. Consequently exercise programmes for persons with SCI are typically low in intensity and volume. Moreover, the limited amount of muscle mass that can be used for exercise, is at risk for overuse as a result of chronic heavy use. In addition, the absence of weight bearing in the lower extremities results in a considerable decrease in bone mineral density in the legs.

All the above changes start directly after the spinal lesion occurs, however the effects will only be noticeable after many years. Since improved medical care has resulted in an increased life expectancy for persons with SCI, these secondary complications come to light more often than a few decades ago.

Lit 2. Identify from studies in able-bodied subjects what levels of physical activity are required to obtain optimal reduction in these risk factors.

Cardiovascular diseases, NIDDM and obesity form a major threat to the health of able-bodied population. Extensive research has shown that physical activity can result in a significant decrease in risk factors for these diseases, but only if these exercise programmes fulfil certain criteria on exercise intensity and volume. It seems that optimal risk reduction is achieved if the individual:

- Participates regularly in exercises of at least 6 MET, and
- Uses at least 2,000 kcal·week^{-1} during physical activity, and
- Participates in regular weight bearing exercises.

Small variations between recommendation for the various diseases exist, though, as can be seen in Table 10.1.

Table 10.1: Recommended exercise intensity and exercise volume for optimal health benefits.

Disease/ Condition	Recommended Exercise intensity	Recommended exercise volume
Coronary Heart Disease	>6 MET	1,200-2,200 kcal·week^{-1}, or >2,000 kcal·week^{-1}
Non Insulin Dependant Diabetes Mellitus	4-6 MET, or possibly >6 MET	30-45 minutes on 5-7 days·week^{-1}
Obesity	4-6 MET, or possibly >6 MET	30-45 minutes on 5-7 days·week^{-1}, or >2,000 kcal·week^{-1}
Osteoporosis	Weight bearing exercises, preferably high intensity	Wight bearing exercises on 2-5 days·week^{-1}, 30-60 min·session^{-1}

Lit 3. Assess the validity of adopting these recommendations on optimal levels of physical activity to the SCI population.

The literature review revealed no similar studies in the SCI population and therefore similar detailed exercise recommendations cannot be made. However, there is no biologically plausible reason for persons with SCI to have any significantly protective factors. A conservative approach would therefore be to adopt the recommendations identified in the able-bodied population. An exercise intensity of 6 MET and an exercise volume of 2,000 kcal·week^{-1} are therefore also considered to be of key importance for persons with SCI, in addition to weight bearing exercises.

Lit 4. Explore the potential of persons with SCI to follow these optimal exercise programmes.

The literature review has shown that a large proportion of the SCI population is at the lower end of the fitness spectrum; 25% fails to achieve a VO_2peak of more than 15 $mL \cdot kg^{-1} \cdot min^{-1}$. Although some individuals are able to achieve much higher intensities and subsequent large exercise volumes, concerns have been expressed on the role of upper body exercises in the aetiology of overuse syndrome. A better option would be to spread the musculoskeletal load over a larger muscle mass by activating paralysed muscle groups using FES. However, FES-induced lower body exercises such as FES-cycling are also of low intensity (see Table 10.2) and subsequently the optimal exercise intensity and volume are not achieved. Combining a FES lower body exercise with a voluntarily upper body exercise gives considerably higher intensities and volumes (see Table 10.2) and indeed persons with SCI might be able to achieve the optimal intensity and volume using FES hybrid exercise or FES-rowing. However this has not been tested previously.

Table 10.2: Maximal and sub-maximal oxygen consumption during FES-exercise in persons with spinal cord injury.

		FES-cycling	FES-hybrid	FES-rowing
VO_2peak ($L \cdot min^{-1}$)	Average	1.07	1.65	1.98
	Range	0.51-1.43	1.30-1.91	1.81-2.15
	N	194	42	17
VO_2peak ($mL \cdot kg^{-1} \cdot min^{-1}$)	Average	14.7	26.2	24.1
	Range	7.5-19.4	-	22.8-24.1
	N	106	10	11
Sub-max VO_2 ($L \cdot min^{-1}$)	Average	0.99	1.27	1.02
	Range	0.47-2.5	-	-
	N	95	23	8
Sub-max VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	Average	14.0	18.3	16.3
	Range	7.1-34.7	14.0-23.4	-
	N	45	23	8

This poses the question if FES-rowing can be developed to such an extent that persons with SCI can achieve optimal health benefits with an exercise that is safe and well-tolerated. This is the principal aim of this thesis and will be tested using a series of hypotheses that cover multiple areas of health and exercise.

H 1. FES-rowing is a high intensity exercise and an effective cardiovascular training for persons with paraplegia.

This hypothesis can be accepted since exercise intensities well over 14 $mL \cdot kg^{-1} \cdot min^{-1}$ were found in the training study presented in Chapter 3. Commonly an intensity of at least 4 MET (and oxygen consumption of 14 $mL \cdot kg^{-1} \cdot min^{-1}$) is regarded as high intensity. This confirms results of an earlier study by Wheeler et al. (2002) and therefore a more definitive statement on the high intensity of FES-rowing can now be made. The intensities during FES-rowing are well above intensities reported in FES-cycling studies and at least of similar magnitude as arm cranking and hybrid FES-exercise (see Chapter 1 for a full review of intensities reported in SCI exercise studies). It should be noted though that in order to achieve optimal health benefits, 6 MET (21 $mL \cdot kg^{-1} \cdot min^{-1}$) is often regarded as the minimal exercise intensity needed (e.g. (Morris et al., 1953b, Tanasescu et al., 2002, Morris et al., 1953a, Paffenbarger et al., 1986). This implies that VO_2peak should exceed 26.3 $mL \cdot kg^{-1} \cdot min^{-1}$, since many individuals would not be able to sustain intensities higher than 80% of their peak performance. This suggests that only a sub-group of the FES-rowing participants is able to achieve the optimal exercise intensity.

For fitness benefits however, FES-rowing is a valuable training modality as shown by the 10% increase in VO_2peak and 20-70% increase in sub-peak performance. This is of great value to persons with SCI, since the majority of the activities in daily life are performed at sub-peak intensities (Dallmeijer et al., 1996).

H 2. FES-rowing training will affect cholesterol and blood lipids in persons with paraplegia.

FES-rowing training did not result in significantly improved cholesterol or blood lipid levels. This can be explained by the fact that the participants only achieved exercise volumes ranging from 277 to 685 $kcal \cdot week^{-1}$. In able-bodied subjects, improvements in lipid profile have only been reported after participation in exercise programmes of at least 1,200 kcal·week^{-1}. However the significant correlations between exercise volume and changes in lipid profile, such as total cholesterol (r= -0.91), free fatty acids (r= -0.83), triglycerides (r= -0.81), TC/HDL ratio (r= -0.83) and LDL/HDL ratio (r= -0.76), confirm the health benefits of high volume exercise training.

Training programmes using high exercise intensities tend to give more improvements in lipid profile than lower intensities (Hooker and Wells, 1989, de Groot et al., 2003), however the role of exercise volume has not been studied before. It is likely though that since exercise volume was not controlled for in these studies, the high intensity groups also achieved larger volumes. In addition, cross-sectional studies show that individuals at the higher and of the fitness spectrum have advantageous lipid profiles (Dallmeijer et al., 1997, Brenes et al., 1986, Dearwater et al., 1986). This can either be a direct result or via the effects of physical activity such as lower body fat mass (Dallmeijer et al., 1997). Such changes are more likely if optimal exercise intensities and volumes are achieved.

H 3. FES-rowing training will affect leptin levels and insulin sensitivity in persons with paraplegia.

Significant decreases in leptin and significant improvements in insulin sensitivity were found after FES-rowing training. Impaired leptin sensitivity has been associated with obesity, similarly to impaired insulin sensivity and non-insulin dependant diabetes mellitus (Bays, 2004). Both obesity and non-insulin dependant diabetes mellitus are more common in the SCI population than in the general population (Bauman and Spungen, 2001, Bauman et al., 1999b). The improvement in insulin sensitivity, as measured by the HOMA model, is therefore a promising finding and confirms earlier work in FES-cycling (Jeon et al., 2002, Mohr et al., 2001). The role of leptin, which is secreted by fat tissue, in the aetiology of obesity is still topic of much research, but abnormal levels of leptin have been reported in the SCI population before (Jeon et al., 2003a, Jeon et al., 2003b). The present study shows that leptin levels decrease after FES-rowing training. Interestingly, this was largely independent from changes in fat mass. This suggests an improved sensitivity to leptin.

H 4. FES-rowing training will affect body composition in persons with paraplegia.

No significant changes in total body composition (fat mass or fat free mass) were reported after FES-rowing training. However one outlier, who gained more than 10 kg in body weight and achieved a very low training volume (277 kcal·week^{-1}), had a large impact on the group average. Individual changes for the other participants were considerable, and might reach statistical significance if sample size is increased. Lean mass in the lower extremities increased by 8.5% while fat mass in the legs decreased by 4.1%. This illustrates the large local effects FES training can have. Whole body composition is an important element in determining risks for obesity and cardiovascular diseases. Total body fat percentage decreased from 27.1 ±2.9% to 26.0 ±.5%. Visceral fat content decreased by -3.8%. This is an important indicator since visceral obesity has been identified as an independent risk factor for CVD.

Other FES-exercise studies have reported similar changes in fat and fat free mass in the lower extremities (e.g. (Scremin et al., 1999, Hjeltnes et al., 1997)), and whole body composition (Hjeltnes et al., 1997). Exercise volume is not given in these trials which might explain why some studies did not report statistically significant improvements (Duran et al., 2001).

H 5 FES-rowing will affect bone mineral density in the lower extremities of persons with paraplegia.

No significant improvements in bone mineral density in the hips or lumbar spine were reported after FES-rowing training. This confirms other studies that concluded that BMD only increases after long-term and intensive FES-exercise training (Chen et al., 2005, Mohr et al., 1997b) and not after shorter (<6 months) FES-exercise programmes (Eser et al., 2003a, BeDell et al., 1996). The approximately 12 weeks training period in the present study was insufficient to impact BMD and future work should establish if BMD can be influenced with more long-term FES-rowing training.

The results show that FES-rowing enables persons with SCI to participate in exercise programmes that can reduce the risks for a number of health threats, such as cardiovascular diseases, non-insulin dependant diabetes mellitus and obesity. The literature review has revealed that these conditions are increasingly common in the SCI population and these form not only a major cause of death in this population, but they also restrict the quality of life considerably. A similar trend has been observed in the general population over the past decades and extensive research has shown that exercise is a powerful intervener in the physiological processes of these conditions. Moreover, it has been shown that many of the physiological pathways interlink and cross-over, as shown by the diagnosis of the metabolic syndrome. The metabolic syndrome is characterised by obesity and at least two of the following parameters (Zimmet et al., 2005):

- Raised triglycerides levels
- Depressed HDL cholesterol
- Raised blood pressure
- Raised fasting plasma glucose

Although understudied, the metabolic syndrome appears to be very common in the SCI population (Bauman and Spungen, 2001). Exercise recommendations to specifically treat the metabolic syndrome are not available at the present, however exercise recommendations do exist for the cardiovascular diseases, non-insulin dependant diabetes mellitus and obesity.

The fact that not all the changes in physiological parameters after FES-rowing training reached statistical significance, could have been caused by the fact that the optimal exercise intensity and exercise volume were not achieved. The literature review revealed that optimal health benefits can be expected if:

- The exercise programmes includes exercises of at least 6 MET (21 $mL \cdot kg^{-1} \cdot min^{-1}$), and
- Total exercise induced energy expenditure exceeds 2,000 $kcal \cdot week^{-1}$, and
- Weight bearing exercises are included.

The participants in the FES-rowing study presented in Chapters 2-6 achieved a VO_2peak of 21.9 ±4.0 $mL \cdot kg^{-1} \cdot min^{-1}$ pre-training and 24.1 ±3.7 $mL \cdot kg^{-1} \cdot min^{-1}$ after the training period. Training intensity was set at 80% of this peak value, i.e. 17.5 – 19.3 $mL \cdot kg^{-1} \cdot min^{-1}$. This is below the recommended 21 $mL \cdot kg^{-1} \cdot min^{-1}$. Moreover, the participants achieved a weekly training volume of 277 to 685 kcal·week^{-1}. This only forms a small proportion of the total 2,000 kcal·week^{-1} that one should achieve with all physical activity in any one week. This implies in order to achieve optimal health benefits, exercise intensity and exercise volume should be further increased during FES-rowing.

The pilot studies revealed a number of reasons that could have been the reason for the failure to achieve higher intensities and volumes;

- Overloading of the quadriceps muscles and consequent early onset of fatigue in these muscles. Since the hamstrings action was insufficient to provoke a full return phase with powerful knee flexion, a spring was attached from the seat to the front of the rowing machine. During the drive phase energy (generated by the quadriceps) was stored in this spring and released during the return phase. Since a limited number of springs were available, most used rigid springs that ensured a good return phase but consequently put unnecessarily load on the quadriceps. When the quadriceps muscles were unable to generate sufficient power, a rest period had to be included or a research assistant supported the movement of the seat.
- There were moments of simultaneous stimulation of hamstrings and quadriceps due to the switches used. The left hand controlled a switch for the quadriceps and the right hand for the hamstrings (or vice versa). This arrangement meant that both hamstrings and quadriceps could have been activated simultaneous and consequently external power output was decreased and/or the muscles fatigued earlier.
- The seat was attached to the monorail with two small rollers on the bottom of the top flange of the monorail (which is the standard Concept 2 arrangement). However the high back rest resulted in a long momentum arm with a pivoting action at these rollers. This caused additional rolling resistance and will have impaired the full rowing motion. Moreover, the leg muscles would have had to overcome this resistance and as a result fatigued earlier.

Although some of this extra effort from the muscles to overcome the above factors will have been reflected in total oxygen consumption, it will have impaired the rowing motion considerably. Consequently the upper body would not have been able to contribute as much and total energy expenditure would have been lower.

The importance of further increasing intensity and volume of FES-rowing training was confirmed by a power analysis. In order to test the statistical significance of the results presented in Chapters 2-6, an unmanageable number of subjects would have to be included. This implies that the observed benefits were too small, however the results suggest that further increasing the exercise volume would give larger results. The only practical way of achieving large training volumes would be to:

- Ensure the intensity is as high as possible, and
- Ensure the training is challenging and fun in order to get maximal adherence to the programme.

Therefore the aim of the second part of this thesis was to further develop the FES-rowing machine and to explore the potential of FES-rowing as a competitive sport.

The FES-rowing machine has been re-designed to improve in order to reduce the unnecessarily load on the quadriceps muscles. A box section with double rollers has replaced the single rollers under the seat on the monorail. This results in a much more stabile platform for the seat and the rollers remain in the middle of the monorail which reduced the rolling resistance. Secondly, the spring has been replaced by a height-adjustable rear end. This allows accurate adjustment of the amount of force needed to assist the hamstrings in the return phase while avoiding excessive stress on the quadriceps muscles. And thirdly the two switches have been replaced by a single two-way switch, which prevent simultaneous stimulation of quadriceps and hamstrings. This improved FES-rowing machine (RowStim III) has enabled paraplegics to exercise at high intensities and compete in indoor rowing competition.

H 6. Introducing a competitive element to FES-rowing will improve training compliance and enable larger training intensities and volumes to be achieved.

FES-rowing has successfully been included in the British (BIRC) and World (WIRC) Indoor Rowing Championships. In 2004 two FES-rowers competed in the BIRC, with a winning time of 12.01. Every year the number of competitors has grown to a total of four in 2006 with a winning time of 10.30. Preliminary data suggests that the competitors achieved high exercise intensities (26.8-31.0 $mL \cdot kg^{-1} \cdot min^{-1}$) and large exercise volumes (1,200 $kcal \cdot week^{-1}$). Moreover, the risk for ischial pressure sores seems minimal since the centre point of the pressure shifts during the rowing cycle and a brief period of pressure relief is included in every rowing stroke.

A limitation in the FES-rowing training might lie in the ability of the paralysed muscles to adapt to the training. Preliminary results show that a reduction in the blood flow during electrical stimulation is associated with an early onset of muscular fatigue. Secondly, such a reduction was not visible after long-term FES use (>one year). Further research should establish if muscular fatigue during FES-exercise is indeed caused by a restriction in blood flow and the consequent ischemia. If so, strategies should be explored to control this ischemia. Pilot work in FES-rowing suggests that muscular fatigue in the stimulated muscles can be postponed by including short rest intervals.

To date, no other sport allows individuals with severe physical disabilities to compete in mainstream competition against able-bodied peers. This competitive element provides a mental stimulus to the participants to continue or even increase their training. Consequently they are able to achieve high exercise intensities and large exercise volumes that could be of significant value in the fight against cardiovascular diseases, non-insulin dependant diabetes mellitus and obesity. The psychological benefits of participating in FES-rowing training and competitions should however not be forgotten. Although not recorded in a structural way, participants have mentioned that "it is great to see you legs doing something useful" and that "it feels great to be able to participate in an activity on an even basis with able-bodied peers". Future studies should fully establish the effects of FES-exercise on psychological well-being.

Finally, the high intensities of FES-rowing might be of interest to paraplegic athletes. Since they conduct all their training with their upper body, FES-rowing might represent a preferred type of cross-training.

Limitations

Inherently, the studies presented in this thesis are accompanied with limitations. The most significant limitation is the small sample size in all the conducted studies. As a consequence the results are difficult to generalise to the wider SCI community. However the aim was to test the feasibility of FES-rowing for health and exercise in SCI. Testing the efficacy will require more studies with larger numbers of subjects. Adequate statistical power is difficult to achieve in SCI research due to the small number of people with SCI and the wide variance in other (possibly) confounding characteristics of the individuals, such as level of lesion, completeness of lesion, age, etc.

Secondly, the rationale behind the benefits of high intensity and high volume exercise training is based on studies in able-bodied subjects. These studies are open for criticism and some significant limitations of these studies have been discussed in section 1.3.5. The large epidemiological studies that form the basis of these recommendations are large but not without bias. All studies investigated certain sub-groups in the general population such as bus drivers and conductors, Harvard alumni and health care professionals. This certainly does not represent a random sample of the general population. Secondly all these studies rely on the ability of the subjects to accurately report their physical activity habits via structured questionnaires. Not only does this rely on reliable recollection of activities and time, but coding these individual responses into standard replies is a simplification of the true activity pattern. Important details might be lost in this process.

Nevertheless all these studies report similar benefits of high intensity and high volume exercise training and this consistence makes it more plausible that the findings of these studies in very different settings are accurate and true. However, more questions arise when transferring these recommendations to the spinal cord injured population.

No similar large scale epidemiological work has been conducted in the spinal cord injured population. Moreover, there is no reason to believe that a spinal cord injury affects the factors that determine the relationship between exercise and health (section 1.4). Two small studies have reported on superior effects of high intensity exercise in SCI (Hooker and Wells, 1989, de Groot et al., 2003), however the weight of this evidence is insufficient to provide a solid basis for reliable recommendations. In this thesis a conservative approach has been taken to adopt the able-bodied recommendations, however it is possible that benefits can be achieved with lower intensities and volumes. As explained in Chapter 4, some exercise studies in SCI have indeed found significant effects on for example lipid profile, even although it was likely that the intensities of these exercise programmes were lower than those reported for FES-rowing. Future work should establish if significant benefits can indeed be achieved with lower intensities and volumes, however the aim of this thesis was to look for optimal health benefits. Due to the dose-response relation, higher intensity and higher volume exercise programmes would give superior effects and are therefore preferable.

Chapter 11

Conclusions and suggestions for further research

11. Conclusions and suggestions for further research

The overall aim of this thesis was to develop and evaluate FES-rowing for health, exercise and sport for persons with SCI. The studies conducted to date show that FES-rowing is a safe and well-tolerated exercise that enables persons with SCI to exercise at high intensities and volumes. For the first time, paraplegics can now participate in mainstream indoor rowing competitions and experience the health benefits associated with high intensity and high volume exercise training. This is of great importance since this thesis shows that:

- Persons with SCI have elevated risk factors for cardiovascular diseases, non-insulin dependant diabetes mellitus, obesity and osteoporosis. This does not seem to be a direct consequence of the lesion in the spinal cord, but more the result of secondary changes that particularly start to a play a role in the chronic stages of SCI, such as changes in body composition and physical activity patterns.

  (Lit 1, Chapter 1)
- Similar risk factors in the able-bodied population have shown to be reduced as a result of physical activity, especially if:
  - Exercises are included that are of at least 6 MET (21 $mL\cdot kg^{-1}\cdot min^{-1}$)
  - The total energy expenditure from physical activity exceeds 2,000 $kcal\cdot week^{-1}$
  - Weight-bearing exercises are included.

  (Lit 2, Chapter 1)
- There is very limited evidence to support or refute adopting these able-bodied recommendations to the SCI population. In the absence of such research, a conservative approach would be to also use the above recommendations for persons with SCI and explore the effects of high intensity and high volume exercise training.

  (Lit 3, Chapter 1)
- Due to the reduction in active muscle mass, persons with SCI have difficulties in expending large amounts of energy. Therefore a large proportion of the SCI population cannot achieve intensities of 21 $mL\cdot kg^{-1}\cdot min^{-1}$ and/or volumes of

2,000 kcal·week^{-1}. Weight-bearing exercises for the lower extremities are difficult due to the paralysis.

(Lit 4, Chapter 1)

- FES-rowing is a high intensity exercise (>4 MET or >14 mL·kg^{-1}·min^{-1}) and FES-rowing training is an effective cardiovascular training (VO_2peak improves significantly by 10%).

(H1, Chapter 3)

- FES-rowing training has not been shown to significantly improve lipid profile in SCI, although exercise volume was significantly correlated with improvements in lipid profile.

(H2, Chapter 4)

- FES-rowing training significantly improves leptin and insulin sensitivity in SCI.

(H3, Chapter 5)

- FES-rowing training has not been shown to significantly improve body composition in SCI.

(H4 and H5, Chapter 6)

- Technological limitations of the FES-rowing machine (RowStim II) will most likely have restricted the exercise intensity and exercise volume that could have been achieved.
- A new generation FES-rowing machine (RowStim III) has been developed that has addressed the limitations identified above, especially:
    - The instability in the seat-carriage system.
    - The inability to adequately support the hamstrings action during the return phase.
    - The inadequate support given by the harness system.
    - The limitation in using two separate control switches for hamstrings and quadriceps.
    - The movement in the leg stabilisers and the interference of the leg stabilisers with the electrodes.
- This new RowStim III has enabled persons with SCI to achieve higher exercise intensities (27-31 mL·kg^{-1}·min^{-1}) and volumes (1,200 kcal·week^{-1}).

(H6, Chapter 9)

- FES-rowing has successfully been included in mainstream indoor rowing competitions.
- Observations during >5 years of FES-rowing and preliminary data suggest that FES-rowing is a safe and well-tolerated exercise.

Suggestions for future research

Many intervention studies in SCI include small sample sizes and consequently the findings of these studies are difficult to generalise. Unfortunately the studies presented in this thesis are no exception and this needs to be addressed in future projects. Multi-centre trials are required seen the low prevalence of SCI in the community. This not only accounts for FES-rowing studies, but also for more general studies on the relation between health and exercise in SCI. The need for effective and efficient interventions to reduce the suffering from obesity, non-insulin dependant diabetes mellitus and cardiovascular diseases will only become more important with the aging SCI population.

Future research questions for the FES-rowing project should focus on two areas:

- Optimising the stimulation parameters.
- Evaluating the health benefits.

The technological developments of the FES-rowing machine presented in this thesis have resulted in a reliable and effective exercise device. The preliminary results of the evaluation (Chapter 9) suggest that the mechanical limitations that were identified in Chapters 2-6 no longer form a restriction to the exercise intensity and volume that can be achieved with FES-rowing. Moreover, the data suggests that physiological parameters could now be the limiting factor. Previous research has shown that FES induced muscle contractions are significantly different from normal muscle contractions. The all-or-nothing principle of FES contractions results in early fatigue in the muscle and this limits the exercise time. A follow up project is to look at methods to optimise the stimulation parameters in order to get strong contractions over prolonged periods of time. There is evidence from animal models that certain types of stimulation (in particular low-frequency stimulation) (Salmons et al., 1996, Barron et al., 1998, Jarvis et al., 1996) are more effective in provoking sustainable muscle contractions. However only limited data is available on the transfer of this knowledge to paralysed muscles in human (Harridge et al., 2002). Conflicting evidence exists on the optimal stimulation frequency for FES-exercise in SCI (Eser et al., 2003b, Harridge et al., 2002).

Other factors that could play a role in this early onset of fatigue can be derived from the NIRS findings presented in Chapter 8. Although limited in sample size, remarkable differences in muscle blood flow were found between an experienced FES-user and a more novice user. A follow up study on novice FES-users would be required to see if these differences in perfusion really can explain the differences in fatigue resistance.

Perhaps muscle physiology can give more answers to the question of muscle fatigue in FES-exercise. Peripheral fatigue is still an ongoing area of research in able-bodied (Paul and Wood, 2002), but it would be interesting to see what lessons can be learned from peripheral fatigue in paralysed muscles. Blood lactate levels have shown to be high during FES; is this a result of ischemia, muscle fibre type or glucose/glycogen availability? Does lactate contribute to the early onset of fatigue? If yes, are there strategies to improve lactate clearance or reduce lactate production? Is there any merit in alternating between the various muscles of the quadriceps in order to sustain large knee extension forces over prolonged periods of time? This area will be further explored in a follow-up project. Improvements in stimulation efficiency and consequently improvements in fatigue resistance would have a direct impact on the use of FES-rowing as an effective high intensity and high volume type of exercise training.

A second research question should be on the health benefits of FES-rowing. The data presented in this thesis is encouraging but more research needs to be done to fully assess the effect of FES-rowing training on cardiovascular diseases, non-insulin dependant diabetes mellitus and obesity. Such studies should clearly indicate the exercise intensity and exercise volume of the programmes in order to compare different programmes.

In parallel to these health studies, the potential of FES-rowing as a cross-training tool for persons with SCI should be explored. Traditionally there have been a very limited number of options for athletes who are looking for an effective cardiovascular training. FES-rowing might offer such an option.

A final note is one the use of FES-rowing outside a research or clinical setting. If FES-rowing is to be integrated in public health campaigns to promote exercise and health in SCI, then FES-rowing should be available in the mainstream health and fitness industry. Currently two centres (The London Regatta Centre and the Aspire National Training Centre, both in London) have added FES-rowing to the exercise programmes they have on offer. It is of great importance to monitor these developments and make sure that the findings are fed back to the research projects. Great things can be achieved when the research is closely linked with the practical applications of FES-exercise.

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Appendix I: Outcomes of the research project

The findings of the project presented in this thesis have been used to bring FES-rowing into mainstream rowing settings. To achieve this, the project has been presented in various scientific publications, presentations and demonstrations for lay-persons. The press has widely covered the achievements of the FES-rowers and a selection of the press coverage is given below.

Publications

The content of this thesis has, in adapted form, been published as follows:

1. Hettinga DM & Andrews BJ. The feasibility of functional electrical stimulation indoor rowing for high-energy training and sport. Neuromodulation 2007;10(3):291-297.
2. Hettinga D. Adaptive rowing. In: Secher NH & Volianitis SS (eds). Rowing: International Olympic Committee's Handbook of sports medicine and science. Oxford: Blackwell; 2007, p. 141-144.
3. Hettinga DM & Andrews BJ. FES-rowing for spinal cord injury. Journal of Spinal Cord Medicine, 2006;29(3):257.
4. Hettinga DM, Andrews BJ, Wheeler GD, Jeon JY, Verellen J, Laskin JJ, Olenik LM, Lederer R, Burnham R & Steadward RD. FES-rowing for persons with spinal cord injury. In: Wood DE and Taylor P. 9th Annual Conference of the International FES Society, 2004, Bournemouth, UK.

In preparation:

1. Hettinga DM, Andrews BJ, Jeon JJ, Suh M, Lederer R, Steadward RD & Wheeler GD. Risk factors for cardiovascular diseases and Functional Electrical Stimulation assisted rowing in paraplegic men: a pilot study.
2. Jeon JJ, Hettinga DM, Steadward RD, Wheeler GD, Bell G & Harber V. Reduced plasma leptin levels and improved insulin sensitivity after 12 weeks of FES-rowing training in people with spinal cord injury.
3. Hettinga DM, Andrews BJ & Baxendale R. Physiological demands of Functional Electrical Stimulation assisted Rowing; a series of case studies.
4. Hettinga DM & Andrews BJ. Oxygen consumption during functional electrical stimulation assisted exercise in persons with spinal cord injury; implications for fitness and health.

Presentations

The content of this PhD thesis has been presented at the following conferences:

1. Hettinga DM, Andrews BJ. FES-rowing for spinal cord injury. 2nd Joint meeting of American Spinal Injury Association and the International Spinal Cord Society. 24-28 June 2006, Boston, United States of America. Abstract published in Journal of Spinal Cord Medicine, June 2006.
2. Hettinga DM, Andrews BJ, Goodey S. The Paralympic's latest asset: rowing. An introduction to classification, rules and competitions. VISTA 2006 Conference. International Paralympic Committee (IPC). 6-7 May 2006, Bonn, Germany. Abstract published in conference proceedings.
3. Hettinga DM, Andrews BJ, Wheeler GD. Functional Electrical Stimulation rowing for persons with Spinal Cord Injury. 4th BPA Sports Science and Medicine Conference. British Paralympic Association (BPA). 3-4 February 2006, Loughborough, United Kingdom.
4. Hettinga DM. Coaching arms-only rowers with Functional Electrical Stimulation. World Rowing Forum. International Federation of Rowing Associations (FISA). 3-5 November 2005, Istanbul, Turkey.
5. Hettinga DM. Functional Electrical Stimulation assisted exercise for spinal cord injury. 1st International Congress on Adapted Sport. Spanish National Hospital for Paraplegia (HNP). 19-21 October 2005, Toledo, Spain.
6. Hettinga DM, Andrews BJ. FES-rowing for spinal cord injury. 9th Annual IFESS Conference. International Functional Electrical Stimulation Society (IFESS)/ FESnet. 6-9 September 2004, Bournemouth, United Kingdom. Abstract published in conference proceedings: Wood DE, Taylor P (eds). 9th Annual IFESS Conference. 2004. Bournemouth, UK.
7. Hettinga DM, Andrews BJ, Jeon JJ, Suh M, Lederer R, Steadward RD, Wheeler GD. The effects of a Functional Electrical Stimulation assisted rowing training programme on fitness, lipid profile and body composition in paraplegic men; a pilot study. VISTA 2003 Conference. International Paralympic Committee (IPC)/ Swedish Development Centre for Disability Sport (SUH). 11-14 September 2003, Bollnäs, Sweden

Preliminary results of the study looking at the effect of FES-rowing on lipid profile in spinal cord injury have been submitted to Maastricht University, The Netherlands for the title of Master of Science (Health Sciences), May 2003.

Prizes

The presentation 'FES-rowing for spinal cord injury' was awarded the third prize in the Vudovnik Student Competition at the 9th annual meeting of the International Functional Electrical Stimulation Society, September 2004, Bournemouth.

Implementation of FES-rowing

The FES-rowing machines developed in this project has been adopted by the London Regatta Centre (http://www.london-regatta-centre.org.uk) and the Aspire National Training Centre (http://www.aspire.org.uk), where the machines are used to deliver FES-rowing programmes to members of their fitness and rowing clubs. All these rowers now have the opportunity to compete in the yearly British Indoor Rowing Championships, where FES-rowing is fully integrated with the programme (http://www.concept2.co.uk/birc/). In addition, the FES-rowing equipment is included in the permanent collection of the River and Rowing Museum in Henley-on-Thames (http://www.rrm.co.uk).

Media coverage

The FES-rowing project has been covered by the media as follows:

1. 'Style, size and variety at the indoor rowing champs'. World Rowing Federation website, 28 February 2006. (http://www.worldrowing.com/display/modules/news/dspNews.php?newid=309536&pageid=34 accessed 21 July 2006).
2. 'Honours to paraplegic rowers: British Indoor Rowing Championships'. UK Ability Magazine, 2005, winter issue, p 48-49.
3. 'Rowing their way into history'. Inclusive Sport Magazine (English Federation of Disability Sport), March 2005. p 14-15.
4. 'FES rowers medal presentation'. Concept 2 news site, February 2006. (http://www.concept2.co.uk/birc/news.php?redir=1&sid=3eeaccbefa4d7cce98b08134e45cbd4f&story=fes_at_birc accessed 21 July 2006).

5. 'Rowing duo earn recognition'. BBC sport online, 21 December 2004. (http://news.bbc.co.uk/sport1/hi/other_sports/disability_sport/4099805.stm accessed 21 July 2006).
6. 'Dizzy rascals: the pain is worth the gain for these awesome oarsmen'. The Independent on Sunday, 21 November 2004.
7. 'A new type of exercise for persons with spinal cord injuries'. Forward, Spinal Injuries Association newsletter, June 2003.

More information can be found on http://www.fesrowing.org.