The effects of hand cycling on physical capacity in persons with spinal cord injury

Linda Valent
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The effects of hand cycling on physical capacity in persons with spinal cord injury

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Chapter 1

General introduction
GENERAL INTRODUCTION

Introduction

In the past decades the hand cycle has evolved into an important wheeled mobility device used for sports, recreation and daily mobility in persons with lower limb impairments in the Western world. The popularity of hand cycling can be explained by the relatively low energy cost enabling mobility over longer distances outdoors: the mechanical efficiency appears to be considerably higher than in hand-rim wheelchair propulsion (Dallmeijer et al., 2004b; Mukherjee and Samanta, 2001), resulting in higher velocities and a longer endurance time (Oertel et al., 1999). In The Netherlands, many persons with lower limb disabilities use a hand cycle. They profit from the numerous cycle tracks and footpaths present in every village or city in a mainly flat country. Persons with spinal cord injury (SCI) are often wheelchair bound and have to rely on arm and trunk muscles for wheeled mobility. In The Netherlands, persons with SCI are increasingly more often provided with a wheelchair together with an add-on hand cycle for in- and outdoor mobility within the own living environment (Valent et al., 2007a). Today hand cycling is indeed already introduced during clinical rehabilitation (Valent et al., 2007a). This is assumingly, for two reasons: to prepare patients adequately for regular hand cycle use after discharge and to improve fitness during rehabilitation.

The focus in recent literature on training options for persons with SCI has been predominantly on functional electrical stimulated cycling (Jacobs and Nash, 2004; Newham and Donaldson, 2007) and treadmill walking (Herman et al., 2002; Kirshblum, 2004). These options however, may not always be easy accessible and/or used independently. For persons with SCI, other (upper body) exercise options are wheelchair exercise, arm crank exercise, circuit resistance training (Jacobs et al., 2001), and sports like wheelchair tennis, wheelchair basketball, wheelchair rugby (Dallmeijer et al., 1997) or wheelchair racing and swimming. Yet, hand rim wheelchair and arm crank exercise were the most frequently used modes of exercise in previous upper body training studies (Hoffman, 1986; Valent et al., 2007b). Abovementioned options may not always be easy accessible and/or used independently, while an important advantage of hand cycling is the ease of use of this exercise mode for daily mobility.
Introduction

In the current thesis the main focus was on the effects of exercise, training and use of the add-on ‘synchronously’\(^1\) propelled hand cycle on physical capacity, health and quality of life in persons with an SCI during and after clinical rehabilitation. In this introductory chapter, firstly, the consequences of an SCI and, in particular the low physical capacity will be explained. Secondly, the history and (worldwide) use of the hand cycle will be described. A general comparison with other mobility modes is made and finally the main questions and outline of the thesis are described.

**Spinal cord injury rehabilitation**

A spinal cord injury is defined as a disruption of the spinal cord and its spinal nerves, resulting in muscle paralysis and loss of sensation below the level of the lesion. In addition, a disturbed autonomic nervous system may cause impairments of functioning of internal organs. The neurological level and completeness of the lesion determine the degree of impairment. A cervical lesion (tetraplegia) results in impairment of function of the arms, trunk and legs. A thoracic or lumbar lesion (paraplegia) results in paralysis in the legs and, depending on the level of lesion, also the trunk (Figure 1).

\(^1\) Although also used in current thesis, the commonly used definitions ‘synchronous’ and asynchronous are less appropriate. Synchronous refers to the correct definition in-phase (phase-angle of 0°), whereas asynchronous refers to out-of-phase (angle of 180°).
Introduction

The ASIA Impairment Scale (AIS) describes the degree of completeness below the level of a spinal cord lesion on a 5-point scale (AIS A to E, see Table 1) (Marino et al., 2003; Maynard et al., 1997).

Table 1: Asia Impairment Scale

<table>
<thead>
<tr>
<th>AIS</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Complete: No sensory or motor function is preserved in the sacral segments S4–S5, representing the anal sphincter and peri-anal sensation.</td>
</tr>
<tr>
<td>B</td>
<td>Incomplete: Sensory but not motor function is preserved below the neurologic level and includes the sacral segments S4–S5.</td>
</tr>
<tr>
<td>C</td>
<td>Incomplete: Motor function is preserved below the neurologic level and more than half of key muscles below the neurologic level have a muscle grade less than 3.</td>
</tr>
<tr>
<td>D</td>
<td>Incomplete: Motor function is preserved below the neurologic level, and at least half of key muscles below the neurologic level have a muscle grade of 3 or more.</td>
</tr>
<tr>
<td>E</td>
<td>Normal: Motor and sensory functions are normal.</td>
</tr>
</tbody>
</table>

The origin of SCI can be either traumatic (due to falls, traffic or sport accidents) or non-traumatic: as a consequence of e.g. a metastasis, infection, spinal haemorrhage or infarction (Van Asbeck, 2007). The incidence of SCI in The Netherlands is estimated to be within the range of other European countries: 9-16 per million inhabitants/year (Schonherr et al., 1996; Van Asbeck et al., 2000). It is assumed to be lower than the estimated numbers in the USA (30-32 per million/year) and Japan (39 per million/year) (Schonherr et al., 1996). The average age at which persons acquire a spinal cord lesion is relatively low. In The Netherlands the mean age is 40 ± 14 years (Van Asbeck, 2007). Due to good health care, the life expectancy has increased and consequently persons with SCI have a long life ahead of them. McColl et al. (1997) predicted a median survival time of 38 years post-injury in persons who sustained a SCI between the ages of 25 and 34 years.

The mean duration of clinical rehabilitation in The Netherlands is approximately 270 days, which is comparable to Japan, but much longer than in the USA with a mean duration of 60 days (Post et al., 2005). A relative long length of stay can be a disadvantage in terms of costs, but it may offer more time for therapists and patients to do more than practising the basic skills of daily living. Nowadays client-centered clinical rehabilitation focuses on improving functions and especially functionality: meaningful daily activities are trained aiming at independent living and optimal participation in the community.
Introduction

Quality of life of persons with SCI is closely associated with mobility and access to the society (Richards et al., 1999), enabling participation and independent living (Lysack et al., 2007), which in turn is suggested to be closely related to physical fitness (Noreau and Shephard, 1995). Prevention of health complications (e.g. overuse injuries, pain and other complications) is important as they may seriously affect fitness, mobility and quality of life (Lidal et al., 2008; Salisbury et al., 2006). On the other hand, an improved fitness-level is considered to reduce the risk of health complications in persons with disabilities (Cooper et al., 1999; Durstine et al., 2003; Frontera et al., 1999).

The International Classification of Functioning, Disability and Health (ICF) offers a framework to visualize the influence of rehabilitation, exercise and assistive technology (environmental factors) on the domains of body functions & structures, activities and (social) participation. In addition, the relationship between environmental and personal factors and health status e.g health complications is shown (Figure 2) (WHO, 2001).

![ICF model](image)

*Figure 2: ICF-model (WHO, 2001) as applied to persons with SCI (Van der Woude et al., 2006)*

In conclusion, to enable participation in the community with a satisfactory quality of life, persons with SCI, especially those with tetraplegia, should integrate regular exercise in daily life – in other words; adopt an active lifestyle - to maintain health and an optimal level of functioning in the many years post-injury
Introduction

(Cooper et al., 1999; Fernhall et al., 2008; Figoni, 1993; Jacobs and Nash, 2004; Janssen et al., 1996; Manns and Chad, 1999; Nash, 2005; Rimaud et al., 2005). Already in the clinical rehabilitation period, the focus should not only be on functional goals, but also on maintaining physical fitness and a physically active lifestyle (Hjeltnes and Wallberg-Henriksson, 1998).

Physical capacity in persons with SCI

Physical capacity (fitness) can in general be defined as a multi-dimensional construct of inter-related components, such as peak power output ($P_{O_{peak}}$), peak oxygen uptake ($V_{O_{2peak}}$), muscle strength, and cardiovascular and pulmonary function (Figure 3) (Haisma et al., 2006).

These outcomes of physical capacity are within the ICF-domains of body functions & structures and activities (Haisma et al., 2006) in Figure 2. Other factors -not included in the model- that affect physical capacity are mechanical efficiency: the ratio of external power output over metabolic power (Stainbsy et al., 1980) and sub maximal oxygen uptake ($V_{O_{2submax}}$).

Physical capacity is dependent upon personal and environmental factors and health condition as described in the adapted ICF-model by Van der Woude (2006). As a consequence of the paralysis of their (lower) body, most wheelchair-dependent people with SCI have a relatively low physical capacity in comparison with able-bodied persons. Compared to persons with a paraplegia, the physical capacity of those with a tetraplegia is approximately three times
lower, mainly due to the low active and incomplete upper body muscle function and the consequences of autonomic dysfunction (Curtis et al., 1999; Dallmeijer and Van der Woude, 2001).

**Health complications**

In persons with tetraplegia or high paraplegia, different autonomic nervous system symptoms can be seen, such as: bradycardia, orthostatic hypotension, autonomic dysreflexia, thermo-dysregulation and sweating disturbances (Krassioukov et al., 2007). Their presence depends on the location and severity of the lesion. As a consequence of autonomic dysfunction, cardiovascular responses to exercise such as increased blood flow to active muscles and vasoconstriction in relatively inactive tissues, may be disturbed (Glaser, 1989; Krassioukov et al., 2007). The blood circulation is also impaired as a consequence of absence of the venous muscle pump in the lower part of the body. In addition, in contrast to persons with a paraplegia, a low stroke volume can hardly be compensated by a rise in heart rate due to the restricted peak heart rate (100-130 bpm) in complete tetraplegia (Figoni, 1993). Secondary complications like urinary tract infections, spasms, pressure sores, osteoporosis, fractures, venous thrombosis and respiratory infections may also occur (Noreau et al., 2000). Other complications such as upper limb injuries (e.g. shoulder pain and carpal tunnel syndrome) are seen in 35 to 70% of the persons with a chronic SCI and are often attributed to wheelchair propulsion (Bonninger et al., 2005). In wheelchair bound persons who rely entirely on their upper body muscles, these complications may lead to a lower level of activity. If someone is not able to use his non-paralyzed upper body mass, this will lead to a decline in strength and abilities (physical capacity) and a further deterioration in activity and participation. Long term deconditioning may result in complications like obesity, osteoporosis, metabolic syndrome, diabetes, and cardiovascular diseases (Mukherjee and Samanta, 2001; Oertel et al., 1999). Therefore, the occurrence of this debilitating cycle should be prevented at all times.
Training physical capacity

With the limited muscle mass, autonomic dysfunction (Krassioukov et al., 2007), and other health complications (Haisma et al., 2007), one may wonder whether persons with SCI, and especially those with tetraplegia, are able to maintain or improve their physical capacity. Indeed, the overall levels and duration of physical strain during daily life are considered to be insufficient to achieve an adequate training stimulus (Janssen et al., 1994a). In deconditioned persons with tetraplegia, the short-lasting peak levels of physical strain (e.g. experienced in lifts and by making transfers) during daily life may even lead to overuse injuries (Janssen et al., 1994a; Van Drongelen et al., 2006), especially in persons with a very low physical capacity. One way to reduce the imposed strain in daily life is by increasing the physical work capacity through adequate physical exercise/training (Janssen et al., 1996). Physical strain was inversely related to parameters of physical capacity (Janssen et al., 1994b). A higher aerobic capacity and muscle strength may therefore lead to improved functional ability and may reduce the risk of peak levels of physical strain and thus of overuse injuries (Boninger et al., 2003). The strain depends on a persons training status and choices regarding the execution of activities, together with the external load determined by the activity itself and the physical environment, including assistive technology (Van der Woude et al., 2006). A well-trained person with an optimal physical capacity and health is better adjusted to the imposed strain of daily life, i.e. simply reducing the relative strain (Hjeltnes and Vokac, 1979). Therefore, individuals, with SCI, should be encouraged to be physically active and to engage in sport activities. However, not many sport activities are available or possible, especially not for persons with tetraplegia. Participation in sport activities by those with a high lesion is hampered by many barriers, such as lack of help or special equipment, lack of transportation to the training facility, limited accessibility, lack of knowledge of instructors and health concerns, which may all result in a lack of motivation as well (Scelza et al., 2005). The low physical capacity and vulnerability for overuse injuries create a challenging task to impose an adequate strain to those with SCI. The American College of Sports Medicine (ACSM) training guidelines recommend heart rate as indicator of exercise intensity in able bodied (Pollock, 1998). Heart rate has been used to prescribe exercise intensity in persons with SCI (Figoni, 2003). It
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is questionable however, if these guidelines are appropriate for those with tetraplegia. Therefore, exercise modes and training protocols should be tailored to the abilities of the individual and furthermore, it should allow easy integration into a person’s daily life.

**Hand cycling**

In 1655 a 22 year-old German paraplegic watch-maker named Stephan Farfler (Figure 4) created the first tricycle (with gears and hand cranks) to drive himself to church each Sunday.\(^2\)

![Figure 4: One of the first hand cycles, made in 1655 by Stephan Farfler](http://de.wikipedia.org/wiki/Stephan_Farfler)

**The conventional rigid frame hand cycle**

Farfler’s idea has been copied by others and with the progress of modern technology (and the use of other materials), the hand cycle evolved into a more convenient mobility device, executed with a cycle chain, pedals and tyres. In The Netherlands and France, these conventional rigid frame hand cycles were fairly often used (Engel and Hildebrandt, 1974), although not on a large scale, and only until the late sixties when they gradually disappeared with the availability of motorized transportation (Van der Woude et al., 1986).

\(^2\) (source: http://de.wikipedia.org/wiki/Stephan_Farfler)
Nowadays, the conventional ‘asynchronously’ propelled rigid frame hand cycle type is still a valuable mobility aid in many Third World countries (Mukherjee et al., 2001; 2005; Mukherjee and Samanta, 2001). These locally-built hand cycles (or so-called tricycles (Figure 5) are preferred over hand-rim wheelchairs for outdoor mobility because of the mechanical advantages (Van der Woude et al., 2001a). On muddy dirt roads it is easier to hand cycle than pushing a hand rim wheelchair with two small castor wheels. Moreover, people in these countries are familiar with bicycle technology and they are able to repair tricycles with the existing bicycle materials.

Figure 5: Hand cycling in Mali

The modern rigid frame hand cycle

Only in the last three decades hand cycle systems have been re-developed for other purposes than daily mobility. In the 1980s, hand cycling (as part of adapted cycling) became a recreational sport. In 1998, hand cycling was approved as part of the International Paralympic Comitee Cycling Program and was introduced at the World Cycling Championships for the Disabled. In 2004, a race for hand cycles was introduced at the Paralympic Games in Athens Greece for the first time.

3 source: Suzanne Niesten
Nowadays, many athletes from the USA, Europe, and Australia compete in (inter)national race series.\(^4\)

The design of the rigid frame hand cycles varies from a fully seated position (upright hand cycles) to a much more supine position. In addition, an arm crank trunk power type, where the rider leans forward sitting on the knees,\(^5\) was developed. The designs with a more supine configuration are more aerodynamic although, if trunk muscles can be active, more power may be generated with the arm crank trunk power type.

In contrast to the conventional hand cycle system, the pedals of the modern ones rotate ‘synchronously’. Most of the hand cycles however, are purchased for recreational use and not for competition. For daily use the rigid frame hand cycle is less practical and the add-on hand cycle was developed. In the current study we focussed on the training effects in those using the add-on hand cycle.

*The add-on hand cycle*

The add-on hand cycle was introduced in the same period as the rigid frame hand cycle. Persons with a motor complete C5/6-lesion and lower appeared to be able to attach the add-on hand cycle system to the front of the everyday hand rim wheelchair. This makes it an especially suitable device for persons who have difficulties with making a transfer, which is often a very strenuous and time-consuming activity. The two small castor wheels of the wheelchair are lifted from the floor and the hand cycle wheel, together with the two rear wheels of the wheelchair, forms the hand cycle (Figure 6a). The hand cycle is equipped with gears that can be changed manually or by moving the chin forward or backward against the switches. Studies have been executed to determine the most optimal gear-ratio (Faupin et al., 2006; Van der Woude et al., 2000), crank-mode and crank rate (Verellen et al., 2004). The crank pedals move synchronously with alternating flexion and extension of the arms (Figure 6b). Synchronous hand cycling appears to be more favourable in terms of energy cost, peak power and mechanical efficiency (Abel, 2003; Bafghi et al., 2008; Dallmeijer et al., 2004a; Goosey-Tolfrey and Sindall, 2007; Van der Woude et al., 2000; 2007).

\(^4\) source: http://www.handcycling.co.za/sport.html

\(^5\) www.doubleperformance.nl
The pedals can be modified with special handles, which allow hand cycling with absent/limited grip function: quad grips (Figure 6c). Different crank configurations exist such as straight and wide bull-horn cranks and cranks of different lengths (Goosey-Tolfrey et al., 2008). The wide bull-horn crank configuration is popular in The Netherlands. It allows positioning of the crank axis as low as possible, which is just below the sternum. Consequently, the wide pedals can move alongside the upper legs in the lowest position. An important practical advantage is that persons with a high cervical lesion (resulting in absence or weak elbow extension strength) do not need to push their arms too high against gravity. Depending on the level of lesion, upper body muscles may be active (or not) during hand cycling: e.g. m. deltoideus and pectoralis (as prime power producers) (Bafghi et al., 2008), trapezius, rhomboids, rotator cuff, biceps, brachioradialis and triceps (De Coster et al., 1999). Abdominal muscles, when available, may be active as postural stabilizers (Bafghi et al., 2008). In conclusion, an optimal ergonomic fitting is especially important in those with limited active muscle mass.
\textit{Wheelchair propulsion versus hand cycling}

Hand rim wheelchair propulsion is found to be highly inefficient (Van der Woude et al., 2001b) and straining, often leading to upper extremity overuse problems (Curtis et al., 1999). Moreover, for persons with tetraplegia it is difficult to apply a well-directed force during the short push phase (20-40\% of the cycle) (Dallmeijer et al., 1998; Van der Woude et al., 2001b). Hand cycling may be easier to perform with less coordination problems, thanks to the continuous coupling of the hands to the handles resulting in a closed-chain-motion. Consequently, forces can be applied throughout the full 360\textdegree{} cycle (in both push and pull phase) and the force generation can be adjusted to someone’s physical abilities by using different gears (Van der Woude et al., 2000). A constant force application by different muscle groups during hand cycling is considered to cause less musculoskeletal strain compared with the peak strain during the short push on the hand rim during wheelchair propulsion (Van der Woude et al., 2006). The mechanical efficiency is higher in (hand) cycling than in hand rim wheelchair propulsion (Dallmeijer et al., 2004b; Engel and Hildebrandt, 1974; Janssen et al., 1994a; Mukherjee et al., 2005; Mukherjee and Samanta, 2004; Oertel et al., 1999; Van der Woude et al., 2001a; 1986). Moreover, previous studies comparing arm crank exercise on an arm crank ergometer with hand rim wheelchair propulsion also found a higher mechanical efficiency in arm cranking (Hintzy et al., 2002; Martel et al., 1991; Tropp et al., 1997; Wicks et al., 1983).

In Table 2, assumed similarities and differences between wheelchair exercise, hand cycling and arm crank exercise are summarized.

From clinical practice it is known that persons with lesion level C5 and below, potentially have enough muscle strength to be able to hand cycle functionally outdoors, but this depends on personal factors and health status (Figure 2).

In conclusion, compared to hand rim wheelchair propulsion, it is assumed that the favourable mechanical characteristics of the hand cycle together with an optimal ergonomic tuning of the hand cycle user interface result in potentially less external strain (Van der Woude et al., 2001a; Van Dijk et al., 1990); when moving around outdoors in, a not always well-adjusted environment (Richards et al., 1999).
**Introduction**

<table>
<thead>
<tr>
<th></th>
<th><strong>WCE (current thesis)</strong></th>
<th><strong>HC (current thesis)</strong></th>
<th><strong>ACE (literature)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max ME (%)</strong> (Van der Woude et al., 2006)</td>
<td>&lt;10%</td>
<td>&lt;10%</td>
<td>&gt;13%</td>
</tr>
<tr>
<td><strong>Force application (% PT of CT)</strong></td>
<td>20-40%</td>
<td>20-40%</td>
<td>&gt;100%</td>
</tr>
<tr>
<td><strong>Trainability of CVS</strong></td>
<td>moderate</td>
<td>poor</td>
<td>moderate/good?</td>
</tr>
<tr>
<td><strong>Trainability of MSS</strong></td>
<td>moderate</td>
<td>poor</td>
<td>moderate/good?</td>
</tr>
<tr>
<td><strong>Risk of over-use injuries</strong></td>
<td>moderate</td>
<td>high</td>
<td>low?</td>
</tr>
<tr>
<td><strong>Crank axis</strong></td>
<td>NR</td>
<td>NR</td>
<td>lower sternum</td>
</tr>
<tr>
<td><strong>(A)synchronous</strong></td>
<td>Syn</td>
<td>Syn</td>
<td>Syn</td>
</tr>
<tr>
<td><strong>steering</strong></td>
<td>slightly difficult*</td>
<td>difficult*</td>
<td>easy*</td>
</tr>
<tr>
<td><strong>Coupling hands</strong></td>
<td>slightly difficult*</td>
<td>difficult*</td>
<td>easy*</td>
</tr>
</tbody>
</table>

WCE: wheelchair exercise, HC: hand cycling, ACE: arm crank exercise, PP: paraplegia, TP: tetraplegia, PT: push time, CT: Cyclus time, MSS: musculoskeletal system, CVS: cardiovascular system, QG: Quad Grips, (a)syn: (a)synchronous, NR: not relevant, ?: will be the subject of the current thesis*: no evidence, based only on personal observations

**The use of outdoor mobility modes**

Of those persons with SCI living in the community, it appears that about 80-90% relied on manual or electric wheelchairs after clinical rehabilitation (Biering-Sorensen et al., 2004; Post et al., 1997). Hand cycle use was not mentioned yet in the aforementioned Dutch study (Post et al., 1997). In the Danish study (Biering-Sorensen et al., 2004), which was published eight years later, a small proportion was using the hand cycle for mobility purposes. More recently, from data of the Dutch multi-centre study, the Umbrella project (1999-2005), it was found that approximately 36% of all wheelchair bound patients with SCI in the rehabilitation centres were provided with (and used) an add-on hand cycle after discharge (Valent et al., 2007a).

In the Dutch study of 1997, a large proportion of the wheelchair users were dissatisfied about the use of hand rim wheelchairs in terms of weight and manoeuvrability (Post et al., 1997). From a more recent study by Chaves et al. (2004) the wheelchair was still the most cited limiting factor in participation of persons with SCI, followed by physical impairment and the physical environment. Remarkably, the use of the (add-on) hand cycle is not mentioned in this study as a possible alternative for mobility over longer distances outdoor. Probably, the physical environment (with hills) and climate was more suitable for powered wheelchairs, in contrast to flat countries like The Netherlands and
Introduction

Denmark with a strong tradition of cycling. From Third World countries such as India it is known that the hand cycle is frequently used for outdoor mobility (Mukherjee and Samanta, 2004). In most European countries and the USA however, the prescription of a (add-on) hand cycle as an alternative for outdoor mobility for persons with SCI seems yet uncommon. For persons for whom wheelchair propulsion is too strenuous, powered wheelchairs are recommended, as appears from the clinical guidelines described by Bonniger et al. (2005). According to Van der Woude et al. (2006) however, hand cycling may be a relevant alternative for frail persons or those who are temporarily injured. Janssen et al. (2001) found that with these systems experienced, but non-competitive, hand cyclists with a cervical lesion were able to maintain relatively high average velocities (14 km·hour\(^{-1}\)) for approximately 40 minutes. They claim that well-maintained add-on hand cycle unit systems are well suited for outdoor use, even for individuals with tetraplegia. First time hand cyclists with SCI participating in a study on health promotion were surprised by the ease of use and moreover they expressed how enjoyable it was (Block et al., 2005).

Hand cycling, physical capacity & training
The relatively new (add on) hand cycle seems to offer an easy accessible healthy exercise and mobility mode that can be used regularly in daily life of persons with a paraplegia or tetraplegia. Hand cycling could be used effectively to maintain and train physical capacity during and after the clinical rehabilitation period.

The limited, but growing, number of hand cycling studies focussed on physiology, EMG-activity and peak exercise performance of hand cycling (Abel et al., 2003; 2006; De Coster et al., 1999; Janssen et al., 2001; Knechtle et al., 2004; Rojas Vega et al., 2008). Yet hand cycle training has hardly been studied. Only one study exists on the effects of hand cycle training, showing positive effects on submaximal hand cycle performance with conventional rigid frame ‘asynchronously’ propelled hand cycles in subjects with chronic paraplegia (Mukherjee et al., 2001).

In general, studies on the effects of other structured upper body training programs and physical capacity in (untrained) persons with SCI are scarce; especially in persons with tetraplegia during and after clinical rehabilitation.
Introduction

Training studies on stationary arm ergometers may seem comparable to hand cycle training, but there are some distinct differences (in Table 2) that will be discussed in the current thesis. Nevertheless, structured hand cycle training is hypothesized to have a positive effect on physical capacity, health and quality of life in persons with SCI. In particular, effects are expected in persons with a low capacity e.g. during rehabilitation, as well as (untrained) persons with a longstanding tetraplegia after clinical rehabilitation.

Therefore the main questions of the current thesis are:
- What is the influence of (non-controlled) hand cycle use during and shortly after clinical rehabilitation in persons with SCI on the physical capacity, reflected by peak power output, peak oxygen uptake, muscle strength and pulmonary function?
- What are the effects of structured hand cycle training in persons with SCI during clinical rehabilitation on physical capacity and health?
- What are the effects of structured hand cycle training in persons with chronic tetraplegia on physical capacity, health and quality of life?
- Is training according to heart rate valid in persons with tetraplegia?
- What are the effects of structured upper body training on physical capacity in persons with SCI according to international literature?

Outline of the present thesis

The present thesis investigates the effects of hand cycling on outcome measures of physical capacity and health in persons with SCI during and after the clinical rehabilitation period. Chapter 2 systematically reviews the literature on upper body training and outcomes of physical capacity in persons with SCI. In Chapter 3, an epidemiological study is described in which the influence of hand cycle use on the physical capacity during (and in the year after) clinical rehabilitation is studied. Chapter 4 addresses the question whether training according to heart rate is appropriate in persons with tetraplegia, who generally suffer from a disturbed autonomic nervous system. Chapter 5 outlines the effects of a structured hand cycle interval-training program on physical capacity and health-related quality of life in subjects with tetraplegia and the feasibility of
training in this vulnerable group. Chapter 6 addresses another experimental study on the effects of a structured hand cycle training program during rehabilitation of subjects with SCI. Finally, in Chapter 7, the main findings and conclusions of this thesis are summarized and discussed.

**Context of research: the Dutch program**

The present thesis is part of the SCI-research program ‘Physical strain, work capacity and mechanisms of restoration of mobility in the rehabilitation of persons with SCI; granted by the Netherlands Organisation for Health of Research and Development (ZonMw).\(^6\)

The current thesis includes one epidemiological study (Chapter 3) and two studies with an experimental set-up (Chapter 5 and 6). The latter study uses the data of the Dutch multi-centre project: the Umbrella-project, 2005-2008), which is the epidemiological backbone of the SCI-research program. This observational longitudinal study investigates the restoration of mobility during SCI rehabilitation (De Groot et al., 2006). Eight Dutch rehabilitation centres with a specialized spinal cord unit participated. Between 1999 and 2005 they collected findings over time in 226 subjects with SCI who were wheelchair bound at the start of active rehabilitation. Several outcome measures, which reflect different aspects of functioning, were monitored on 4 separate occasions: at the start of rehabilitation, 3 months into active rehabilitation, at discharge, and 1 year after discharge. Subjects of the Umbrella-project who filled in the questionnaire on hand cycle use were included in Chapter 3 and served as controls in Chapter 6.

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\(^6\) [www.fbw.vu.nl/onderzoek/A4zon/ZONenglish/index.htm](http://www.fbw.vu.nl/onderzoek/A4zon/ZONenglish/index.htm)
Chapter 2

The effects of upper-body exercise on the physical capacity of people with a spinal cord injury: a systematic review

Based on:
The effects of upper body training

Abstract

Objective: The purpose of this systematic literature review was to describe the effects of upper body training on the physical capacity of people with a spinal cord injury (SCI).

Data sources: The databases of PubMed, Cinahl, SPORTDiscus and Cochrane were searched for the years 1970 up to May 2006

Review methods: The following key words: spinal cord injury, paraplegia, tetraplegia and quadriplegia were used in combination with training. The methodological quality of the included articles was assessed with the modified ‘van Tulder et al’ checklist. Studies were described with respect to population, test design, training protocol and mode of training. The training effects on physical capacity, reflected by maximal power output (POpeak) and oxygen uptake (VO2peak), were summarized.

Results: Twenty-five studies were included with a mean score of 8.8 out of 17 items on the quality checklist. The methodological quality was quite low, mostly because of the absence of Randomised Controlled Trials. Therefore no meta-analysis was possible. In the 14 articles of acceptable quality the mean (SD) increase in VO2peak and POpeak, following a period of training, was 17.6 (11.2) % and 26.1 (15.6) %, respectively.

Conclusions: Due to the overall low study quality it is not possible to draw definitive conclusions on training effects for different lesion groups or training modes. The results of the relatively few studies with an acceptable quality seem to support the view that upper body exercise may increase the physical capacity of people with SCI. The magnitude of improvement in POpeak and VO2peak however, varies considerably among studies.
Introduction
As a result of a spinal cord injury (SCI), the somatic and autonomic nervous system are damaged. Most provoking consequence is paralysis of muscle below the level of the lesion, in severity depending on the completeness and level of the lesion. Secondary complications may occur as a consequence of SCI, such as urinary tract infections, spasticity, hypotension, autonomic dysreflexia, pressure sores, arm overuse injuries, fractures, venous thrombosis and respiratory infections (Noreau et al., 2000). Moreover, having lost a considerable part of the functioning of their (lower) body, often leading to a wheelchair dependent life, it is difficult for those with SCI to maintain an active lifestyle. As a consequence of the SCI, the secondary complications and the sedentary lifestyle of people with SCI, deconditioning is likely to occur with increased risks of obesity, diabetes and cardiovascular diseases (Figoni, 1993; Hoffman, 1986). Deconditioning in turn results in a lower physical capacity. Therefore people, especially those with tetraplegia, will have difficulty to cope with the strain of daily activities (Hjeltnes and Vokac, 1979; Janssen et al., 1994). People with SCI who are not able to participate in daily activities appear to be more handicapped - in e.g. the domains of physical independence and mobility - and tend to give lower ratings for quality of life (Manns and Chad, 1999; Noreau and Shephard, 1995; Tate et al., 1994).
To cope adequately with the strain of daily activities and to prevent long-term secondary health problems, it is important to have and maintain an optimum level of physical fitness. Physical fitness is often developed during initial rehabilitation (Haïasma et al., 2006) and must be maintained in a process of a long-term physically active lifestyle and/or rehabilitation aftercare. This requires an understanding - and the availability of - evidence-based training methods and exercise protocols for people with SCI. Although guidelines for upper body training in people with SCI have been published by several authors (Figoni, 2003; Franklin, 1985; Jacobs and Nash, 2004), the experimental evidence-base of these guidelines is unclear. Systematic reviews are lacking or out-dated. In 1986, Hoffman published a review study about upper body training in people with SCI. However, this review does not describe the methodological quality of the included studies and is already quite outdated.
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The purpose of the current review is therefore to systematically summarize the effects of upper body training on physical capacity in people with SCI, while taking into account the methodological quality of the studies. Secondly we will try to compare training effects on physical capacity between people with paraplegia and tetraplegia and between different modes of training.

Active and functional training of the physical capacity in wheelchair dependent people with motor-complete SCI must primarily be acquired through upper body exercise. Therefore, despite the growing use of electrically stimulated lower limb exercise and body weight support treadmill walking, the scope of this study was on training of physical capacity of the upper body. Upper body training is usually performed with exercise in a wheelchair (on a treadmill) or on a wheelchair ergometer (WCE), or with the use of arm-crank exercise (ACE) (Glaser, 1989). During the last years however, other upper body training modes such as circuit resistance training and hand cycling have been used as well.

The two most important components of physical capacity are peak oxygen uptake and power output (Haisma et al., 2006). Muscle strength, cardiovascular and pulmonary function are components that contribute to the level of oxygen uptake and power output (Haisma et al., 2006). In the current study, peak oxygen uptake and peak external power output are studied as the prime outcome parameters of upper body training exercise in SCI.

The main research question of this study is, therefore:
What are the effects of different modes of upper body training on physical capacity, reflected by oxygen uptake and power output, in people with paraplegia or tetraplegia?

Methods
Study identification and selection
The electronic databases of PubMed (Medline), SPORTDiscus, Cinahl and Cochrane were systematically searched with the following (combinations of) keywords: spinal cord injury, paraplegia, tetraplegia and quadriplegia, combined with training. The search was limited to the English language and included publications from 1970 up to May 2006. After this first selection of studies, all hits were investigated more thoroughly. Of all included articles, we scanned the
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references for more hits. To be included in this review, studies had to meet the following inclusion criteria:

1. The research population is described properly, and no more than 25% of the subjects have impairments other than spinal cord injury.
2. The upper extremities are trained.
3. No Functional Electrical Stimulation is part of the training protocol meaning that at least in one of the experimental groups isolated upper body training is performed.
4. The training protocol is described explicitly.
5. One or both of the main components of physical capacity peak oxygen uptake (VO₂peak) or peak power output (PO_peak) are outcome measures of the study.

Qualitative Assessment

The methodological quality was assessed using the 19-item list of Van Tulder et al. (1997). This quality assessment list is designed to score the methodological quality of randomized controlled trials (RCTs). However, non-randomized clinical trials might be included if the available evidence for RCTs is not sufficient (Van Tulder et al., 1997). We discussed the available RCTs separately and scored the methodological quality of all available articles, which met our inclusion criteria.

Blinding of the assessor (item i) was regarded to be a relevant item, but blinding of the trainer (item e) or blinding of the patient (item h) was considered to be not relevant when comparing a training group with a group receiving no training at all. The total number of items that were scored was thus reduced to 17. The quality score was based on the mean score of two independent observers (LV and ET) who used a consensus method to discuss and resolve any disagreements.

We considered the studies with a score of more than 50% (9 or more of the 17 items are scored positive) to be of an “acceptable methodological quality” and studies with less than 9 will be considered to have a “low methodological quality”. Van Tulder et al. (1997) suggested a quality cut-off point of 50% but this was chosen arbitrarily.
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Quantitative analysis
To provide an overview of the actual effects of training of the upper body on physical capacity, the percentage change in $PO_{peak}$ and $VO_{2peak}$ will be described. Only the effects on physical capacity of the studies with an acceptable methodological quality will be discussed further.

Results
After searching the different databases, and following screening of titles and abstracts for consistency with inclusion criteria, 40 papers were identified as potentially relevant (Figure 1). After reading the 40 papers (LV: PhD-student and ET: MSc in Human Movement Sciences; both experienced in physical therapy research methods), 15 training studies were excluded for the following reasons: other outcome measures (Bjerkefors and Thorstensson, 2006; Davis and Shephard, 1990; El-Sayed et al., 2004; Grigorenko et al., 2004; Hicks et al., 2003; Mukherjee et al., 2001; Nemanich et al., 1987; Silva et al., 1998; Yim et al., 1993), mixed population (Keyser et al., 2003; Miles et al., 1982), the population was not described properly (Pollock et al., 1974), training of both arms and legs (Bizzarini et al., 2005) or - as was the case in 2 papers - the results were already published in other included papers (Grange et al., 2002; Hopman et al., 1996). The 25 included studies are summarized in Table 1 (Bougenot et al., 2003; Cooney and Walker, 1986; Dallmeijer et al., 1997; Davis et al., 1991; De Groot et al., 2003; DiCarlo, 1982; DiCarlo, 1988; DiCarlo et al., 1983; Duran et al., 2001; El-Sayed and Younesian, 2005; Gass et al., 1980; Hjeltnes and Wallberg-Henriksson, 1998; Hooker and Wells, 1989; Jacobs et al., 2001; Knutsson et al., 1973; Le Foll-de Moro et al., 2005; McLean and Skinner, 1995; Midha et al., 1999; Nash et al., 2001; Nilsson et al., 1975; Rodgers et al., 2001; Sutbeyaz et al., 2005; Taylor et al., 1986; Tordi et al., 2001; Whiting et al., 1983).
Figure 1: Flowchart for the systematic search and selection of papers

Search terms:
Spinal Cord Injury and Training: 972
Tetraplegia Training + 138 (new found papers)
Quadriplegia Training + 2 (“ “)
Paraplegia Training + 197 (“ “)

Total: 1309 papers

Title/abstract: topic?
1269 excluded:
- No upper body training
- No results on $P_{O_{peak}}$ or $V_{O_{2peak}}$

40 papers selected

Content: topic?
13 excluded:
- No results on $P_{O_{peak}}$ or $V_{O_{2peak}}$
- No training protocol described
- Mixed population (>25% no SCI)
- Training of legs as well

27 papers selected

2 excluded:
- Double data

25 papers selected and summarized

Qualitative assessment

Only two out of 25 studies appeared to be relevant RCTs, investigating the effect of training versus no training in people with SCI (Davis et al., 1991; Taylor et al., 1986). Both studies were of an acceptable, but still rather low, quality score of respectively 9.5 and 10.5.

Only one of two other studies comparing two groups training on different intensities (De Groot et al., 2003; Hooker and Wells, 1989), used randomization (De Groot et al., 2003). One RCT, with a relatively high quality score of 12.5, was designed to study effects of two different training positions (supine versus sitting) (McLean and Skinner, 1995). One of the studies compared training in an untrained group with ‘no training at all’ in sedentary controls, but without
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randomization (Dallmeijer et al., 1997). The remaining studies compared conditioning effects before and after training without a control group. In five out of 25 articles disagreement between the observers existed on more than two items in one paper. Scores were averaged if no consensus was reached and ranged from 6 to 12.5 and the mean score of all papers was 8.8 ± 0.7 (mean ± SD). The methodological quality was acceptable according to our arbitrary standard (i.e. ≥50%) in 14 studies, while 11 studies had a low methodological quality scoring less than 9 points (Tables 1a, b and c.)

Other factors that influenced the quality of research were noted. Blinding of the assessor was not described in the available RCTs (Davis et al., 1991; McLean and Skinner, 1995; Taylor et al., 1986). Compliance was described sufficiently in 10 studies (Bougenot et al., 2003; Cooney and Walker, 1986; Davis et al., 1991; De Groot et al., 2003; Duran et al., 2001; El-Sayed and Younesian, 2005; Gass et al., 1980; Hooker and Wells, 1989; McLean and Skinner, 1995). Drop out rate was not described in 8 studies (DiCarlo et al., 1983; Hjeltnes and Wallberg-Henriksson, 1998; Knutsson et al., 1973; Le Foll-de Moro et al., 2005; Midha et al., 1999; Nilsson et al., 1975; Rodgers et al., 2001; Sutbeyaz et al., 2005). In all other studies the drop out rate was described and found to be acceptable, with the exception of the subjects performing the long term training program in the study of Davis et al. (1991), where the cut-off point of 30% was exceeded. ‘Adverse effects’ were described explicitly in 10 studies, but in general the training was well tolerated (Bougenot et al., 2003; Cooney and Walker, 1986; Dallmeijer et al., 1997; Davis et al., 1991; Duran et al., 2001; El-Sayed and Younesian, 2005; Le Foll-de Moro et al., 2005; McLean and Skinner, 1995; Tordi et al., 2001). Overall the lesion level was described, however not always the completeness of the lesion, described by the American Spinal Injury Association-Impairment Scale (Marino et al., 2003; Maynard et al., 1997) or the previously used Frankel-scale. Finally, training status was not always mentioned in the reviewed studies and its description differed between studies.
**Description of the studies**

**Subject characteristics**

Table 1 summarizes all 25 included studies. Study populations differed considerably in size and composition. The number of subjects per study ranged between 1 and 20 with a mean value of almost 10 subjects per study. With the exception of the study by Gass et al. (1980), hardly any subjects with a Th1-Th5 lesion were enrolled and most studies on subjects with paraplegia included only subjects with lesions below Th6 (Bougenot et al., 2003; Davis et al., 1991; El-Sayed and Younesian, 2005; Jacobs et al., 2001; Le Foll-de Moro et al., 2005; Rodgers et al., 2001; Sutbeyaz et al., 2005; Taylor et al., 1986; Tordi et al., 2001). Six studies included subjects with a time since injury less than one year (De Groot et al., 2003; Duran et al., 2001; Hjeltnes and Wallberg-Henriksson, 1998; Knuttson et al., 1973; Le Foll-de Moro et al., 2005; Sutbeyaz et al., 2005).

**Training mode and protocol**

As can be seen in Table 1, seven studies used arm crank exercise (ACE) as the training mode, and seven studies used wheelchair exercise (WCE). The remaining 11 studies used another training mode (OTHER), often combined with arm crank exercise (Cooney and Walker, 1986; Dallmeijer et al., 1997; Dallmeijer et al., 1994; Hjeltnes and Wallberg-Henriksson, 1998; Jacobs et al., 2001; Sutbeyaz et al., 2005). Most often circuit resistance training or strength training was incorporated in these studies (Cooney and Walker, 1986; Dallmeijer et al., 1997; Duran et al., 2001; Gass et al., 1980; Hjeltnes and Wallberg-Henriksson, 1998; Hooker and Wells, 1989; Midha et al., 1999; Rodgers et al., 2001; Sutbeyaz et al., 2005).
<table>
<thead>
<tr>
<th>Study</th>
<th>Date</th>
<th>Age</th>
<th>Sex</th>
<th>Study</th>
<th>Intervention</th>
<th>Lesion Level</th>
<th>Sample Size</th>
<th>Control Group</th>
<th>Training Program</th>
<th>Training Intensity</th>
<th>Physical Capacity Outcomes</th>
<th>Other Outcomes</th>
<th>Test Device</th>
<th>Test Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Sayed 2005</td>
<td>9.5</td>
<td>31</td>
<td>m,f</td>
<td>Organised Training</td>
<td>&lt;Th10</td>
<td>5</td>
<td>no, 7AB; Also Training</td>
<td>Con</td>
<td>30min/session; 3/wk for 12wks</td>
<td>60 to 65% VO2peak</td>
<td>POpeak</td>
<td>Peak HR, VE and chol</td>
<td>ACE</td>
<td>Con: start: 30W; 2min +30W</td>
</tr>
<tr>
<td>Davis 1991</td>
<td>9.5</td>
<td>31</td>
<td>m</td>
<td>Inactive</td>
<td>L5-Th6</td>
<td>HL:6, HS:4, LL:5, LS:3C:6</td>
<td>yes; 6 RA; Non-training SCI</td>
<td>Con</td>
<td>40min/session; 3/wk for 32wks</td>
<td>50 or 70% VO2peak</td>
<td>VO2peak</td>
<td>MS, SV, PT, submax PO</td>
<td>ACE</td>
<td>Con: start: ?1 min +8,5W</td>
</tr>
<tr>
<td>Taylor 1986</td>
<td>10.5</td>
<td>30</td>
<td>m,f</td>
<td>Trained; Basketball</td>
<td>L5-Th6</td>
<td>5</td>
<td>yes; 5 RA; Non-training SCI</td>
<td>Con</td>
<td>30min/session; 5/wk for 8wks</td>
<td>80% HRpeak</td>
<td>VO2peak</td>
<td>Peak and rest HR, BM, PF MFD</td>
<td>ACE</td>
<td>Con: start: ?4 min +10W</td>
</tr>
<tr>
<td>DiCarlo 1982</td>
<td>8.5</td>
<td>24</td>
<td>m</td>
<td>No Aerobic Training</td>
<td>C6</td>
<td>1</td>
<td>no</td>
<td>Con</td>
<td>30min/session; 3/wk for 8wks</td>
<td>HR=96</td>
<td>POpeak</td>
<td>BM, peak HR and VE, submax PO, HR, VE and VO2</td>
<td>ACE</td>
<td>?:2min +10rpm</td>
</tr>
<tr>
<td>DiCarlo 1988</td>
<td>7</td>
<td>24</td>
<td>?</td>
<td>No Aerobic Training Last 6 months</td>
<td>C7-C5</td>
<td>8</td>
<td>no</td>
<td>?</td>
<td>15/30min/session; 3/wk for 8wks</td>
<td>50 to 60%HRR</td>
<td>POpeak</td>
<td>BM, peak HR and VE, submax PO, HR, VE and VO2</td>
<td>ACE</td>
<td>Start ?:2min +10rpm</td>
</tr>
<tr>
<td>McLean 1995</td>
<td>12.5</td>
<td>34</td>
<td>m</td>
<td>No Aerobic Training Last 6 months</td>
<td>Th1-C5</td>
<td>sit: 7 sup:7</td>
<td>yes; Same intensity Both Groups; RA</td>
<td>Con</td>
<td>20+min/wk; 3/wk for 10wks</td>
<td>60% POpeak</td>
<td>POpeak</td>
<td>Peak and rest HR, BM, SV, PT</td>
<td>ACE</td>
<td>Int: start: ?: 3min40s +10W, Rest: 1min20s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Age</th>
<th>Sex</th>
<th>ASIA-IS</th>
<th>Lesion Level</th>
<th>Sample Size</th>
<th>Control Group</th>
<th>Training Mode</th>
<th>Training Program</th>
<th>Training Intensity</th>
<th>Physical Capacity Outcomes</th>
<th>Other Outcomes</th>
<th>Test Device</th>
<th>Test Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bougenot 2003</td>
<td>2003</td>
<td>35</td>
<td>M</td>
<td>A</td>
<td>L5-Th6</td>
<td>7</td>
<td>no</td>
<td>Int</td>
<td>45 min/session; 3/wk for 6wks</td>
<td>Until 80%HRpeak</td>
<td>VO2peak, POpeak</td>
<td>peak HR and VE, O2P and at VT</td>
<td>WCE</td>
<td>con: start: 15W; 2 min +10W</td>
</tr>
<tr>
<td>Tordi 2001</td>
<td>2001</td>
<td>27</td>
<td>M</td>
<td>A</td>
<td>L4-Th6</td>
<td>5</td>
<td>no</td>
<td>Int</td>
<td>30min/session; 3/wk for 4wks</td>
<td>50 to 80% POpeak</td>
<td>VO2peak, POpeak</td>
<td>submax PO, HR, VE and Vo2, and O2P, PT</td>
<td>WCE</td>
<td>con: start: 15W; 2 min +10W</td>
</tr>
<tr>
<td>Le Foll-de-Moro 2005</td>
<td>2005</td>
<td>29</td>
<td>M</td>
<td>?</td>
<td>Th6-12</td>
<td>6</td>
<td>no</td>
<td>Int</td>
<td>30min/session; 3/wk for 6wks</td>
<td>Until 80%HRpeak</td>
<td>VO2peak, POpeak</td>
<td>peak VE, submax PO, VE, VO2, PF</td>
<td>WCE</td>
<td>con: start: 15W; 2 min +5W</td>
</tr>
<tr>
<td>Whiting 1983</td>
<td>1983</td>
<td>27</td>
<td>M,F</td>
<td>?</td>
<td>C7-C5</td>
<td>2</td>
<td>no</td>
<td>Con</td>
<td>20min/session; 7/wk for 8wks</td>
<td>75-85% HRpeak</td>
<td>VO2peak, POpeak</td>
<td>HRpeak</td>
<td>WCE</td>
<td>con: start: ?; 3 min +5W</td>
</tr>
<tr>
<td>Gass 1980</td>
<td>1980</td>
<td>37</td>
<td>M,F</td>
<td>?</td>
<td>Th4-C6</td>
<td>9</td>
<td>no</td>
<td>Con</td>
<td>Until exhaustion; 5/wk for 7wks</td>
<td>Until exhaustion</td>
<td>VO2peak, peak HR and VE; BM, PF</td>
<td>WCE</td>
<td>con: start: ?; 1min +0,5 km/h</td>
<td></td>
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<tr>
<td>Hooker 1989</td>
<td>1989</td>
<td>31</td>
<td>M,F</td>
<td>?</td>
<td>Th9-C5</td>
<td>6LI 5MI</td>
<td>LI and MI; not RA</td>
<td>Int</td>
<td>20min/session; 3/wk for 8wks</td>
<td>50-80%HRR</td>
<td>VO2peak, peak PO, HR and VO2peak, peak HR, VE, LA, chol</td>
<td>WCE</td>
<td>int: start: 2W; 3 min +2W up to 10W</td>
<td></td>
</tr>
<tr>
<td>Midha 1999</td>
<td>1999</td>
<td>36</td>
<td>M,F</td>
<td>?</td>
<td>L3-C6</td>
<td>12 (10SCI)</td>
<td>No</td>
<td>Con</td>
<td>22 min/session; 2or3/wk for 10wks</td>
<td>55-90%HR (220-age)</td>
<td>VO2peak, peak HR and rest HR; BM, BP, chol</td>
<td>WCE</td>
<td>con: ?</td>
<td></td>
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<table>
<thead>
<tr>
<th>mode</th>
<th>study</th>
<th>meth. score</th>
<th>TSI training</th>
<th>status</th>
<th>age</th>
<th>sex</th>
<th>ASIA-IS</th>
<th>lesion level</th>
<th>sample size</th>
<th>control group</th>
<th>training mode</th>
<th>training program</th>
<th>training intensity</th>
<th>physical capacity outcomes</th>
<th>other outcomes</th>
<th>test device</th>
<th>test protocol</th>
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<tr>
<td>OTHER PARA</td>
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</tr>
<tr>
<td>15</td>
<td>Duran 2000</td>
<td>9</td>
<td>8&lt;1yr</td>
<td>REHAB</td>
<td>26</td>
<td>m,f</td>
<td>A,B,C</td>
<td>Th12-Th3</td>
<td>13</td>
<td>no</td>
<td>WCE, weights, aerobic, HT</td>
<td>120min/session; 3/wk for 16wks</td>
<td>40 to 80% HRR</td>
<td>POpeak</td>
<td>HRpeak / recovery, WC-skills, BM, chol, MS</td>
<td>ACE</td>
<td>con: start: 0W; 2min +12.5W</td>
</tr>
<tr>
<td>16</td>
<td>Jacobs 2001</td>
<td>9.5</td>
<td>0.7yr unclear</td>
<td>39</td>
<td>m</td>
<td>A,B</td>
<td>L1-Th5</td>
<td>10</td>
<td>no</td>
<td>CRT, int</td>
<td>45min/session; 3/wk for 12 wks</td>
<td>50-80% (1RM)</td>
<td>VOpeak</td>
<td>PT, MS</td>
<td>ACE</td>
<td>con: start: 40W; 3 min +10W</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Nash 2001</td>
<td>9.5</td>
<td>1yr unclear</td>
<td>38</td>
<td>m</td>
<td>A</td>
<td>L1-Th5</td>
<td>5</td>
<td>no</td>
<td>CRT, int</td>
<td>45min/session; 3/wk for 12 wks</td>
<td>50-80% (1RM)</td>
<td>VOpeak</td>
<td>Chol</td>
<td>ACE</td>
<td>con: start: 40W; 3 min +10W</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Rodgers 2001</td>
<td>6</td>
<td>7yr unclear</td>
<td>44</td>
<td>16m,</td>
<td>A,B,C</td>
<td>L5-Th3</td>
<td>19</td>
<td>no</td>
<td>strength, rowing cont</td>
<td>2min/session; 3/wk for 12 wks</td>
<td>60% HRR rowing (30 min)</td>
<td>VOpeak</td>
<td>HRpeak , MS</td>
<td>WCE</td>
<td>con: start: ; 1 min +0.3kg load</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Subteyaz 2005</td>
<td>8</td>
<td>&lt;1yr</td>
<td>REHAB</td>
<td>31</td>
<td>12m,</td>
<td>A,B,C</td>
<td>Th12-Th6</td>
<td>20</td>
<td>no</td>
<td>ACE, spirometry</td>
<td>total 60 min:30 min</td>
<td>75-100% VO2peak</td>
<td>VOpeak</td>
<td>peak HR and VE, BP, PF</td>
<td>ACE</td>
<td>n/a</td>
</tr>
<tr>
<td>OTHER TETRA</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Dallmeijer 1997</td>
<td>10.5</td>
<td>1yr trained</td>
<td>and untrained</td>
<td>28</td>
<td>m,f</td>
<td>A,B,C,D</td>
<td>C8-C4</td>
<td>T: 9; U: 6</td>
<td>yes; 9 inactive not RA</td>
<td>quad rugby; con</td>
<td>90to120min/session; 1wk for 9 to 25wks</td>
<td>60+%HRR</td>
<td>VOpeak</td>
<td>HRpeak, ADL, MS</td>
<td>ACE</td>
<td>con: start: 10% POpeak; 1 min +10% POpeak</td>
</tr>
<tr>
<td>OTHER COMBI</td>
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<tr>
<td>21</td>
<td>Cooney 1986</td>
<td>9</td>
<td>2yr unclear</td>
<td>35</td>
<td>m</td>
<td>f</td>
<td>?</td>
<td>5PP: L1-Th9; 5TP: C8-C5</td>
<td>10</td>
<td>no</td>
<td>CRT</td>
<td>30 to 40min/session; 3/wk for 9wks</td>
<td>60 to 90% HRR</td>
<td>HRpeak</td>
<td>POpeak</td>
<td>Speed</td>
<td>ACE</td>
</tr>
<tr>
<td>22</td>
<td>Hjeltnes 1998</td>
<td>9</td>
<td>&lt;1yr</td>
<td>REHAB</td>
<td>25</td>
<td>m</td>
<td>TP:A,B</td>
<td>C8-C6</td>
<td>10 PP 10 TP</td>
<td>no; 7 non training AB, tested once</td>
<td>ACE/WCE, strength</td>
<td>30min/session; 3/wk for 2x8 wks</td>
<td>HI</td>
<td>VOpeak</td>
<td>HRpeak, submax PO, VO2, HR, BP, SV, LA, MS</td>
<td>ACE</td>
<td>int: 2x5 min submax, 3 min max intensity: ?</td>
</tr>
<tr>
<td>23</td>
<td>De Groot 2003</td>
<td>12</td>
<td>&lt;1yr</td>
<td>REHAB</td>
<td>47</td>
<td>m</td>
<td>A,B,C</td>
<td>L1-C5</td>
<td>7</td>
<td>yes; HI and L1; RA</td>
<td>ACE, CRT</td>
<td>60min/session; 3/wk for 8wks</td>
<td>40 to 80% HRR</td>
<td>HRpeak</td>
<td>POpeak</td>
<td>Chol</td>
<td>ACE</td>
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<tr>
<td>24</td>
<td>Nilsson 1975</td>
<td>7.5</td>
<td>1yr trained</td>
<td>36</td>
<td>m</td>
<td>?</td>
<td>PP: 5; TP:2</td>
<td>7</td>
<td>no; 5 not RA SCI tested once</td>
<td>ACE, CRT</td>
<td>? min/session; 3/wk for 7wks</td>
<td>high</td>
<td>VOpeak</td>
<td>Peak HR, LA, MS</td>
<td>ACE</td>
<td>start: 5-33W 6min +11-33W until HR=170</td>
<td></td>
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<tr>
<td>25</td>
<td>Knutsson 1973</td>
<td>6</td>
<td>&lt;1yr</td>
<td>REHAB</td>
<td>30</td>
<td>m</td>
<td>A or B</td>
<td>T5-C5;3 T6-L1;7</td>
<td>10</td>
<td>no</td>
<td>ACE, CRT int</td>
<td>30min/4a 5/wk 6wks</td>
<td>PP:140-180 bpm</td>
<td>POpeak</td>
<td>blood volume, haemoglobin, ACE</td>
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</tr>
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</table>

**Table 1c: Studies on the effects of other training modes**

The effects of upper body training

The training intensities in the studies varied greatly, using different indicators for workload and ranging between 40-90% of the heart rate reserve (HRR), peak heart rate (HRpeak), VO2peak or POpeak. In all studies subjects trained 3 times a week or more, with the exception of Dallmeijer et al. (1997) (only once a week). The duration of the training sessions varied from 20 minutes to 120 minutes; in most studies the sessions lasted 30 minutes. The duration of the training period varied considerably (4-32 weeks).

Training effects

Overall

In Table 2 the pre- and post-training values for VO2peak and POpeak and the relative change (expressed in percentage from the pre-training values) after training are listed. Eighteen of the 21 studies with data on VO2peak (two case-studies and two studies without data on VO2peak (Duran et al., 2001; Knutsson et al., 1973) were excluded) reported a significant increase after training, with Hjeltnes and Wallberg-Henriksson (1998) showing improvements only in the subjects with paraplegia. Three studies reported no increase in VO2peak (Dallmeijer et al., 1997; Hooker and Wells, 1989; Rodgers et al., 2001). For the 13 of 21 studies with an acceptable quality (studies in bold in Table 2), a change in VO2peak between pre-test and post-test ranged from 5.1% to 33.5% with a mean (SD) of 17.6 (11.2) %. Sixteen of 20 studies with data on POpeak (two case-studies and three studies without data on POpeak (Davis et al., 1991; Gass et al., 1980; Taylor et al., 1986) were excluded) reported a significant increase after training. Four studies reported no increase in POpeak (Dallmeijer et al., 1997; DiCarlo et al., 1983; Hooker and Wells, 1989; Midha et al., 1999). For the 12 of 20 studies with an acceptable quality, the change in POpeak between pre- and post-test ranged from 10.1% to 57.2% with a mean (SD) of 26.1 (15.6) %.
### The effects of upper body training

#### Table 2: Change in VO_{2peak} and PO_{peak} between pre- and post-test.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>PO_{peak}</th>
<th>VO_{2peak}</th>
<th>Study</th>
<th>n</th>
<th>PO_{peak}</th>
<th>VO_{2peak}</th>
<th>Study</th>
<th>N</th>
<th>PO_{peak}</th>
<th>VO_{2peak}</th>
</tr>
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<td></td>
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</tr>
<tr>
<td>ACE</td>
<td>Watt</td>
<td>Watt</td>
<td>l/min</td>
<td>l/min</td>
<td>ACE</td>
<td>Watt</td>
<td>Watt</td>
<td>l/min</td>
<td>l/min</td>
<td>ACE</td>
<td>Watt</td>
</tr>
<tr>
<td>El Sayed</td>
<td>5</td>
<td>168</td>
<td>(38)</td>
<td>185</td>
<td>(24)</td>
<td>10.1*</td>
<td>1.80</td>
<td>(0.1)</td>
<td>1.94</td>
<td>(0.05)</td>
<td>7.2*</td>
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<tr>
<td>Davis</td>
<td>18</td>
<td>n/a</td>
<td>(n/a)</td>
<td>146</td>
<td>(38)</td>
<td>15.9*</td>
<td>1.66</td>
<td>(0.15)</td>
<td>1.71</td>
<td>(0.12)</td>
<td>3.1*</td>
</tr>
<tr>
<td>Control</td>
<td>6</td>
<td>n/a</td>
<td>(n/a)</td>
<td>1.90</td>
<td>(38)</td>
<td>10.5*</td>
<td>1.33</td>
<td>(0.15)</td>
<td>1.38</td>
<td>(0.12)</td>
<td>4.3*</td>
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<td>Taylor</td>
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<td>(n/a)</td>
<td>1.37</td>
<td>(38)</td>
<td>14.3*</td>
<td>1.57</td>
<td>(0.15)</td>
<td>1.64</td>
<td>(0.12)</td>
<td>3.9*</td>
</tr>
<tr>
<td>Control</td>
<td>5c</td>
<td>n/a</td>
<td>(n/a)</td>
<td>1.21</td>
<td>(38)</td>
<td>36.4*</td>
<td>1.64</td>
<td>(0.15)</td>
<td>1.64</td>
<td>(0.12)</td>
<td>3.9*</td>
</tr>
<tr>
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<td>33</td>
<td>37</td>
<td>49</td>
<td>33</td>
<td>0.87</td>
<td>1.02</td>
<td>8.6</td>
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<td>Hooker</td>
<td>5MI</td>
<td>33</td>
<td>(33)</td>
<td>38</td>
<td>(33)</td>
<td>13.3**</td>
<td>0.90</td>
<td>(0.15)</td>
<td>1.79</td>
<td>(0.12)</td>
<td>99*</td>
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<td>Midha</td>
<td>10</td>
<td>73</td>
<td>68</td>
<td>6.6**</td>
<td>73</td>
<td>68</td>
<td>6.6**</td>
<td>1.41</td>
<td>1.82</td>
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<td>(n/a)</td>
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<td>(0.14)</td>
<td>34.8**</td>
<td></td>
<td></td>
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<tr>
<td>Dallmeijer</td>
<td>8T</td>
<td>29</td>
<td>17</td>
<td>11ns</td>
<td>29</td>
<td>17</td>
<td>11ns</td>
<td>1.03</td>
<td>1.47</td>
<td>12*</td>
<td>1.03</td>
</tr>
<tr>
<td>deGroot</td>
<td>7HI</td>
<td>68</td>
<td>90</td>
<td>14.7ns</td>
<td>68</td>
<td>90</td>
<td>14.7ns</td>
<td>1.20</td>
<td>1.74</td>
<td>50*</td>
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<td>12</td>
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<td>65</td>
<td>34.4*</td>
<td>49</td>
<td>65</td>
<td>34.4*</td>
<td>1.45</td>
<td>1.88</td>
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<td>1.45</td>
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<tr>
<td>Nash</td>
<td>20</td>
<td>31</td>
<td>52</td>
<td>65***</td>
<td>31</td>
<td>52</td>
<td>65***</td>
<td>1.03</td>
<td>1.10</td>
<td>6.8ns</td>
<td>1.03</td>
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<td>Rodgers</td>
<td>15</td>
<td>46</td>
<td>53</td>
<td>14.6*</td>
<td>46</td>
<td>53</td>
<td>14.6*</td>
<td>9.86</td>
<td>14.6</td>
<td>48***</td>
<td>9.86</td>
</tr>
<tr>
<td>Subteyaz</td>
<td>20</td>
<td>31</td>
<td>52</td>
<td>65***</td>
<td>31</td>
<td>52</td>
<td>65***</td>
<td>1.32</td>
<td>1.68</td>
<td>30.3**</td>
<td>1.32</td>
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<td>CooneyA</td>
<td>5</td>
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<td>107</td>
<td>42.7***</td>
<td>75</td>
<td>107</td>
<td>42.7***</td>
<td>1.37</td>
<td>1.75</td>
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<td>1.37</td>
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<td>22</td>
<td>32</td>
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<td>32</td>
<td>45.5*</td>
<td>0.78</td>
<td>0.81</td>
<td>3.8*</td>
<td>0.78</td>
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</table>

**Level of significance (between pre and post-test) *=p<0.05, **=p<0.01, ***=p<0.001, ns=not significant, ACE=Arm Crank Exercise, WCE=Wheelchair Exercise, OTHER=all other modes of exercise, n/a=not available. T=Trained, U=Untrained, LI = Low Intensity, MI = Moderate Intensity, HI = High Intensity. Papers in bold are studies of acceptable methodological quality. Studies with # involve subjects with Time Since Injury <1yr.**

From Davis et al (1991): only results of all subjects after 8 wk training. For the sake of comparability, we converted the VO_{2peak} values in ml/kg/min into ml/min in several studies; (Bougenot et al., 2003; Cooney and Walker, 1986; De Groot et al., 2003; DiCarlo, 1988; Midha et al., 1999; Subteyaz et al., 2005; Taylor et al., 1986; Tordi et al., 2001)
The effects of upper body training

Paraplegia and tetraplegia

Only two of nine studies with data on subjects with both paraplegia and tetraplegia differentiated between these lesion levels (Cooney and Walker, 1986; Hjeltnes and Wallberg-Henriksson, 1998). As can be seen in Table 2 (studies in bold) and Figure 2a, nine studies of an acceptable quality examined the effect on VO\textsubscript{peak} in people with paraplegia (Bougenot et al., 2003; Cooney and Walker, 1986; Davis et al., 1991; El-Sayed and Younesian, 2005; Hjeltnes and Wallberg-Henriksson, 1998; Jacobs et al., 2001; Nash et al., 2001; Taylor et al., 1986; Tordi et al., 2001), including one study examining subjects with a time since injury of less than one year (Hjeltnes and Wallberg-Henriksson, 1998) and two studies with a randomized control group (Davis et al., 1991; Taylor et al., 1986). Improvements in VO\textsubscript{peak} for subjects with paraplegia ranged between 7% (El-Sayed and Younesian, 2005; Taylor et al., 1986) and 30% (Cooney and Walker, 1986; Hjeltnes and Wallberg-Henriksson, 1998; Jacobs et al., 2001; Nash et al., 2001).

Eight studies of an acceptable quality (Bougenot et al., 2003; Cooney and Walker, 1986; Duran et al., 2001; El-Sayed and Younesian, 2005; Hjeltnes and Wallberg-Henriksson, 1998; Jacobs et al., 2001; Nash et al., 2001; Tordi et al., 2001) used PO\textsubscript{peak} as outcome measures in people with paraplegia (Table 2, Figure 2b). Two studies however, included subjects with a time since injury of less than one year (Duran et al., 2001; Hjeltnes and Wallberg-Henriksson, 1998). The range of improvements in PO\textsubscript{peak} was between 10% and 30% in most studies; except for one study (40%) (Hjeltnes and Wallberg-Henriksson, 1998). None of these eight studies however used a control group.

Only four studies of acceptable quality are available on the effect on VO\textsubscript{peak} and PO\textsubscript{peak} in people with tetraplegia (Cooney and Walker, 1986; Dallmeijer et al., 1997; Hjeltnes and Wallberg-Henriksson, 1998; McLean and Skinner, 1995). Hjeltnes and Wallberg-Henriksson (1998) (time since injury of less than one year) and Dallmeijer et al.(1997) found no effect on VO\textsubscript{peak}. McLean and Skinner (1995) found only a small effect of 8.3%, while Cooney and Walker (1986) found a considerably higher improvement of 29.7% after a resistance training circuit. Only Dallmeijer et al. (1997) included a relevant, but not randomized, (sedentary) control group. Except for Dallmeijer et al. (1997) all studies (Cooney and Walker, 1986; Hjeltnes and Wallberg-Henriksson, 1998;
McLean and Skinner, 1995) found a significant effect on PO\textsubscript{peak}, ranging from 13 to 57\% (Figure 2b).

**Training mode**

Figures 3a and 3b show effects of different training modes on VO\textsubscript{2peak} and PO\textsubscript{peak}. Again the variation among studies is considerable for both outcome measures. Taking into account only the studies with an acceptable quality, and with subjects at least one year post injury (Figure 3a), the gain in physical capacity - especially in VO\textsubscript{2peak} - appears to be higher (30\%) in three (Cooney and Walker, 1986; Jacobs et al., 2001; Nash et al., 2001) out of the four studies using ‘other modes of training’ (Cooney and Walker, 1986; Dallmeijer et al., 1997; Jacobs et al., 2001; Nash et al., 2001) when compared with arm crank exercise or wheelchair exercise (10-20\%). All three studies performed circuit resistance training and in two studies the same training protocol was used (Jacobs et al., 2001; Nash et al., 2001). In the fourth study of ‘other modes of training’ (Dallmeijer et al., 1997), in which data were corrected for change in the control group, no training effect of ‘quad rugby’ was found, but this study used a low training intensity and frequency.

**Figure 2: the effects on VO\textsubscript{2peak}(a) and PO\textsubscript{peak}(b) between different lesion groups**

TP: Tetraplegia, PP: Paraplegia. Square symbols are studies including subjects with TSI<1yr and diamond symbols are studies with TSI>1yr. Filled symbols are studies of an acceptable quality and open symbols are studies of a lower quality. Results in studies of Taylor et al. (1986), Davis et al. (1991) and Dallmeijer et al. (1997) are corrected for changes in a control group. The results in the studies of Cooney & Walker (1986) and Hjeltines (1998) are depicted separately for TP and PP.
The effects of upper body training

Figure 3: the effects on VO_{2peak} (a) and PO_{peak} (b) between training methods

ACE: Arm Crank Exercise, WCE: wheelchair Exercise and OTHER: other modes of training. Square symbols are studies including subjects with TSI<1yr and diamond symbols are studies with TSI>1yr. Filled symbols are studies of an acceptable quality and open symbols are studies of a lower quality. Results in studies of Taylor et al. (1986), Davis et al. (1991) and Dalmeijer et al. (1997) are corrected for changes in a control group. The results in the studies of Cooney & Walker et al. (1986) and Hjeltnes (1998) are merged for TP and PP.

Discussion

The literature on the effects of upper body training in people with spinal cord injury appears to be limited in quantity and quality. One of the problems in research concerning people with SCI is the fact that the intervention groups (and control groups if present) are almost always rather small and heterogeneous, and the statistical power of the studies is thus limited. The heterogeneity is caused by variation in lesion level, completeness of lesion, gender and age. Time since injury (TSI) and training status are also factors that are expected to affect the training effects.

Besides the heterogeneous population, different training protocols and modes account for the variation in outcome of the different studies. Moreover, the different maximal exercise test designs to measure physical capacity (i.e. interval or continuous, the initial power, power increments at each step and the duration of the exercise bouts) might influence the test results. For these reasons the different studies cannot be easily compared and interpreted.
Methodological quality
According to Ginis and Hicks (2005), the value of an RCT is indisputable, but in people with SCI it appears to be a very difficult design because of the heterogeneity of the group and due to the more practical problems of vulnerability for diseases and transportation to the training facility. As a consequence the risk of drop out or poor compliance is high, especially in people with higher lesion levels. Randomization is the most important tool to deal with heterogeneity, however, the problem remains that large subject numbers are needed to secure statistical power in heterogeneous groups. Therefore the value of studies with a quasi-experimental design should certainly - but carefully - be taken into account, because otherwise important and scarce information will be lost. Only two out of 25 studies appeared to be relevant RCTs, but both were of a relatively low methodological quality. Therefore, we decided to include and assess the quality of non-randomised controlled clinical trials as well, using the quality list by Van Tulder (1997). Items common to RCTs are scored, but also other relevant items such as compliance, drop out and adverse effects. Studies without an RCT design still could achieve a low but acceptable score by scoring points on the other items. The overall mean score for all studies was just below the cut-off point of 50%. Due to the overall low methodological quality (absence of control groups) and the heterogeneity of the studies, statistically pooling of the results could not be performed in the current study.

Training effects
Overall
Almost all studies concluded that a training intervention has a positive effect on the physical capacity as reflected by improvements in VO₂peak and PO₂peak. One must be aware, however, that studies that did not find any significant changes may have remained unpublished. Above that, the overall quality of the presented studies is limited. The magnitude of the training effect appears to differ considerably between studies. From our review it appears that studies of a lower methodological quality generally tended to find larger training effects, especially in VO₂peak as is shown in Figures 2a and 3a.
The effects of upper body training

Only the studies of Taylor et al. (1986) and Davis et al. (1991) were executed with small but relevant randomized control groups, and both show modest improvements in VO$_{2\text{peak}}$ of 10.5% (exp) vs. 4% (control) and 15.9% (exp) vs. 3% (control), respectively (Table 2). The post-test of the experimental group in the study by Taylor et al. (1986) showed a significant improvement in VO$_{2\text{peak}}$ compared to the pre-test, and a trend but not significant improvement in comparison to the control group. In this instance the small subject sampling probably compromised the statistical power. In the study of Davis et al. (1991), a significant difference between the control and experimental groups was only attained when the subjects continued training for a longer period than eight weeks, i.e., after 16 and 24 weeks of training. In Table 2 we only reported the results after 8 weeks of training because the reported drop out rate was regarded to be unacceptable after continuation of the training period.

Most studies of acceptable quality were executed without a control group and found gains in both PO$_{\text{peak}}$ and VO$_{2\text{peak}}$ within a range of 10-30%. The effect of training in the studies without a control group may be overestimated, as is shown from the studies with a control group (Dallmeijer et al., 1997; Davis et al., 1991; Taylor et al., 1986). The influence of a learning effect (on the test) or normal daily fluctuations in health and fitness (not uncommon in people with a high SCI) may appear as confounding factors. In most studies in the current review it is unclear to what extent possible methodological confounds might have influenced the training effects.

We decided to highlight training studies in subjects injured within the last year (time since injury less than one year) (De Groot et al., 2003; Duran et al., 2001; Hjeltnes and Wallberg-Henriksson, 1998; Knutsson et al., 1973; Le Foll-de Moro et al., 2005; Sutbeyaz et al., 2005) (Table 2 and Figures 2 and 3) because the effects on the outcome measures may possibly be (also) attributed to neurological recovery, especially in people with tetraplegia. Higher gains in physical capacity are therefore expected in this group. Higher gains however, can also be explained by an extremely inactive (often bed-bound) period in the first period after injury, which seems to be confirmed by data on change in PO$_{\text{peak}}$. Studies with a time since injury of less than one year show higher PO$_{\text{peak}}$ increases compared with studies with a time since injury of more than one year (Figures 2b and 3b). However, there is no clear evidence to assume
The effects of upper body training

higher gains in VO$_{2peak}$. For example, Hjeltnes and Wallberg-Henriksson (1998) found no improvement in VO$_{2peak}$ when training people with tetraplegia shortly after injury, whereas a large improvement was seen in people with paraplegia. Also, De Groot et al. (2003) found an improvement in VO$_{2peak}$ of 33.5% in a mixed group of people with paraplegia and tetraplegia during rehabilitation. Unfortunately no control groups were present in these studies to control for the possible influence of neurological recovery.

Paraplegia and tetraplegia

Due to the low number of studies of acceptable quality (especially in people with tetraplegia) it is difficult to draw conclusions on training effects in relation to lesion level. The few available studies on people with tetraplegia vary considerably in training effect on both PO$_{peak}$ and VO$_{2peak}$. From our review it seems however, that both paraplegia and tetraplegia may benefit from training and no relative differences in training effect seem present. Jacobs and Nash (2004) stated that the magnitude of improvement in VO$_{2peak}$ is inversely proportional to the level of spinal lesion. However, they referred to absolute values of VO$_{2peak}$, whereas in this review we investigated the relative gain (percentage change) in training effect, which is not the same. Moreover it has to be remarked that the training studies on subjects with paraplegia most often examined subjects with lesion level Th6 or below, which may be explained by the fact that lesion levels above Th6 are relatively scarce due to the protection of the thorax. The results on gain in physical capacity may not reflect those with high lesion paraplegia. People with lesion of Th6 or higher may experience autonomic dysfunction that alters cardiac functions during acute exercise. As such, persons with injuries above Th4 may react differently to training than subjects with lesions below Th6 (Glaser, 1989) as well as those with injuries above Th1. However, from the current results on the people with paraplegia and tetraplegia, the relative gain in physical capacity due to upper body training does not necessarily seem to be related to level of lesion.

Training mode

From the limited studies of acceptable quality it is difficult to say whether a training effect is more prominent in arm crank exercise, wheelchair exercise or
other training methods. On the other hand the training effect in the three studies on circuit resistance training (Cooney and Walker, 1986; Jacobs et al., 2001; Nash et al., 2001) seems to be relatively high compared to the studies with arm crank exercise and wheelchair exercise. Unfortunately, no control group was present in these three studies and the training status of the subjects was not described. Moreover, the relatively long training duration (45 minutes) and long training period (12 weeks) may also have contributed to the larger training effect. However, the relatively long and variable training sessions appeared to be well sustainable and tolerated, as “no adverse effects” were reported. Circuit resistance training (including short bouts of arm crank exercise) may therefore be a more effective method of training compared with isolated wheelchair exercise and arm crank exercise, because of the variety in training stimulus. Last but not least, more variety in training may be more attractive to perform and is likely to increase motivation and adherence of the subjects.

Other outcome measures
Muscle strength and pulmonary function are other outcome measures that contribute to the level of physical capacity (Haisma et al., 2006). It appeared to be impossible to compare the effects on muscle strength between the few studies with available data (Dallmeijer et al., 1997; Duran et al., 2001; Hjeltnes and Wallberg-Henriksson, 1998; Jacobs et al., 2001; Nilsson et al., 1975; Rodgers et al., 2001), because of large differences in tested muscle groups and test methods (dynamic, isometric, manual, etc). All studies claim significant improvements in muscle strength, but again, no control groups were present in any of the studies involved. Other upper body training studies in spinal cord injury (Davis and Shephard, 1990; Silva et al., 1998; Yim, 1993), all excluded from this review because they lacked data on VO$_{2peak}$ and PO$_{peak}$, also reported improvement in muscle strength. In the high quality RCT of Hicks et al. (2003) improvements in different muscle groups were reported between 19-34%. From the few studies on pulmonary function (Gass et al., 1980; Le Foll-de Moro et al., 2005; Sutbeyaz et al., 2005; Taylor et al., 1986) only one study was of an acceptable quality and no gain was found (Taylor et al., 1986). Only Sutbeyaz et al. (2005), who incorporated respiratory exercises in the training sessions, found a (low) improvement of 1.1% in Forced Vital Capacity (FVC). Other upper
body training studies in spinal cord injury, again excluded from this review because they lacked data on VO$_{2\text{peak}}$ or PO$_{\text{peak}}$, found an improvement of 9% (Yim, 1993) in FVC or no improvement at all (Silva et al., 1998), although both studies lacked a control group.

**Conclusion**

In general, the methodological quality of the studies on the effects of upper body training in people with spinal cord injury is low (e.g. RCTs are scarce) and acceptable in just over 50% of the studies. The results of this review suggest that evidence is weak to support the view that controlled upper body exercise increases the physical capacity of people with spinal cord injury. The magnitude in improvement in PO$_{\text{peak}}$ and VO$_{2\text{peak}}$, varies considerably among studies. For the studies of an acceptable (but still rather low) quality a range in increase of 10-30% is common. Relatively few studies have been executed in people with tetraplegia or high paraplegia (>Th6). Nevertheless, the relative gain in PO$_{\text{peak}}$ and VO$_{2\text{peak}}$ after training seems to be comparable between both lesion groups. When looking at differences between training modes, circuit resistance training, including a programme of weight lifting and arm cranking or other aerobic exercises, may appear to be more effective in increasing physical capacity than wheelchair exercise or arm crank exercise only. This statement however, is based on a trend in the data rather than empirical testing and further study is required to confirm these findings. Due to the low number of studies and the overall low quality it is not possible however to derive definitive - evidence-based - conclusions and guidelines when comparing training effects between lesion groups or different training modes.

**Recommendations**

Regular exercise in people with spinal cord injury seems beneficial for overall fitness, even when instituted early after injury and for those with high spinal cord lesions. Continued and extended research is clearly needed to find stronger evidence to support this view. It is very important for future research to perform training studies with a high methodological quality in the field of upper body training in people with SCI. An urgent need for RCTs exists, especially in people
The effects of upper body training

with tetraplegia. The RCT design is more complicated in people with spinal cord injury and may require multicenter collaboration to limit effects of heterogeneity, and to solve more practical problems such as transportation to the training facility in order to secure sufficiently large subject numbers and thus statistical power. Furthermore, a more detailed study description of the subject selection and population, training and test protocol, drop out rate, compliance, and adverse effects are necessary to improve the methodological quality and comparability of future studies. Additional research should focus on effects of different training protocols and modes, eventually resulting in training guidelines for (un-) trained people with different levels of SCI.

Clinical Message

- There is weak evidence to support the importance and use of upper body exercise to improve physical capacity in people with SCI.
- Based on the limited data, no definite recommendation can be given regarding the most adequate mode of exercise, training intensity, frequency or duration.
Chapter 3

Influence of hand cycling on physical capacity in the rehabilitation of persons with a spinal cord injury:

A longitudinal cohort study

Based on:
LJM Valent, AJ Dallmeijer, H Houdijk, HJ Slootman, MW Post, LH van der Woude.
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Abstract

Objective: To investigate the influence of hand cycling on outcome measures of physical capacity during and after rehabilitation in persons with paraplegia and tetraplegia in the Netherlands.

Design: A longitudinal cohort study with measurement moments at the start (t1) and end (t2) of clinical rehabilitation and 1 year after discharge (t3). Hand cycle use was assessed by means of questionnaires at t2 and t3.

Setting: Eight rehabilitation centers in the Netherlands.

Participants: Subjects (n=177) with a recent spinal cord injury.

Interventions: All subjects followed the regular rehabilitation program.

Main Outcome Measures: Peak oxygen uptake (VO_{2peak}) and peak power output (PO_{peak}) determined in a hand rim wheelchair peak exercise test, peak muscle strength of the upper extremities, and pulmonary function.

Results: A significantly larger increment in VO_{2peak}, PO_{peak}, and elbow extension strength was found in hand cycling subjects with paraplegia during clinical rehabilitation. No such effect was found in subjects with tetraplegia. In the post-rehabilitation period, no influence of hand cycling on any outcome measure was found in subjects with paraplegia or tetraplegia.

Conclusions: After correction for baseline values and confounders, regular hand cycling (once a week or more) appeared to be beneficial for improving aerobic physical capacity in persons with paraplegia during clinical rehabilitation. The small and heterogeneous study groups may have hampered the finding of positive results of hand cycling in persons with tetraplegia.

Key Words: Physical fitness; rehabilitation; spinal cord injuries.
The influence of hand cycling on physical capacity

Introduction

In the past decade, cycling with a hand cycle has evolved into a major form of adapted sport, practiced at a high level by many athletes worldwide. Not only the rigid-frame hand cycle, but also the add-on hand cycle, a hand cycle unit that can be attached to the hand-rim wheelchair, has become popular for daily outdoor use (Dallmeijer et al., 2004b; Janssen et al., 2001). Many wheelchair users in the Netherlands own an add-on hand cycle, which is commonly provided with a parallel crank setting. Its growing popularity can be attributed to a culture of cycling in a flat country with many cycle tracks and footpaths in every village or city. People in the Netherlands are used to cycling - not only for sport or recreation - but also in daily life, for example to go to work or school or to do their shopping. Another explanation for its popularity is the fact that the hand cycle unit can be attached to the hand rim wheelchair, and therefore no physically demanding transfer to another mobility device is needed. Moreover, the energy cost of hand cycling appears to be considerably lower than hand rim wheelchair propulsion (Dallmeijer et al., 2004b; Mukherjee and Samanta, 2001).

Most people with SCI, and especially those with a high lesion, have a very low physical capacity (Figoni, 1993; Glaser, 1989). Physical capacity can be defined as a multi-dimensional construct of inter-related components, such as peak power output (PO\textsubscript{peak}), peak oxygen uptake (VO\textsubscript{2peak}), muscle strength, and cardiovascular and pulmonary function (Haisma et al., 2006b). Their low physical capacity is a direct consequence of the paralysis of their (lower) body, often leading to a wheelchair-dependent life. Wheelchair dependence implies that it is difficult to maintain an active lifestyle, and that deconditioning is likely to occur. As a consequence, people with SCI have a higher risk of developing obesity, metabolic syndrome, diabetes, and cardiovascular diseases (Myers et al., 2007).

In recent years, hand cycling has been introduced into the Dutch SCI rehabilitation units as a mode of exercise and mobility. Even people with tetraplegia appear to be able to hand cycle, despite (partially) paralyzed arm muscles (Janssen et al., 2001; Valent et al., 2007b) and daily practice shows that this is possible at the start of active clinical rehabilitation. Compared with hand rim wheelchair propulsion, hand
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cycling is less strenuous and this is especially an advantage for people with tetraplegia who — as a consequence of their limited arm function — are at high risk of developing upper-extremity overuse injuries (Kulig et al., 2001; Van Drongelen et al., 2006). Therefore, hand cycling may offer an adequate alternative mode of training or mobility for people with SCI during and after clinical rehabilitation.

The effects of training programs on the physical capacity during and after clinical rehabilitation of people with SCI have been studied, including different modes of training, such as arm-crank exercise, wheelchair exercise, and circuit-resistance training (Valent et al., 2007a). Literature on hand cycling in general, and more specifically concerning people with SCI is limited, but growing (Abel et al., 2006; Dallmeijer et al., 2004a; Dallmeijer et al., 2004b; Janssen et al., 2001; Mukherjee et al., 2001; Mukherjee and Samanta, 2001; Verellen et al., 2004). However, to our knowledge, there is no literature describing the effects of hand cycling on physical capacity during or after the clinical rehabilitation of people with SCI, except for 1 study carried out by Mukherjee et al. (2001) who found a higher mechanical efficiency after hand cycle training in subjects with paraplegia. However, they did not include a control group and the subjects were hand cycling asynchronously, which is not common in the Western world, and is found to be less efficient than synchronous hand cycling (Dallmeijer et al., 2004a).

The main purpose of the present study was to investigate the influence of hand cycling on different outcome measures of physical capacity during and (1 year) after clinical rehabilitation in subjects with SCI. In this observational study, multilevel analysis was applied to compare subjects who hand cycled regularly during and/or 1 year after clinical rehabilitation with subjects who did not hand cycle at all, or only occasionally. The hypothesis was that people who had been hand cycling regularly would show a greater improvement in physical capacity compared with people who had not been hand cycling.
Methods

Participants
The study was part of the Dutch research program “Physical strain, work capacity, and mechanisms of restoration of mobility in the rehabilitation of persons with a spinal cord injury.” Patients who were admitted to 1 of the 8 main Dutch SCI rehabilitation centers during the period 1999 to 2004 were included if they: (1) had acute SCI; (2) had a prognosis of “mainly wheelchair-bound”; (3) had a lesion level of C5 or lower (and consequently were expected to be able to propel a hand cycle); (4) were aged between 18 and 65 years; (5) had sufficient knowledge of the Dutch language; and (6) did not have a progressive disease or psychiatric problem.

Patients were (temporarily) excluded if they had cardiovascular contraindications or serious musculoskeletal complaints.

After being informed about the study, the patients were screened by a physician and signed a written informed consent on a voluntary basis.

Study Design

Trained research assistants performed the standardized measurement protocol, which was approved by the Medical Ethics Committee of the VU University Medical Center. The study included 3 measurements: at the start of active rehabilitation when the subject could sit in a wheelchair for at least 3 hours (t1), on discharge (t2), and 1 year after discharge (t3).

All subjects performed an aerobic exercise test in a hand rim wheelchair to determine PO_{peak} and VO_{2peak}. Subjects, who were not yet able to perform the exercise test at t1, performed the test 3 months after t1. The exercise test was performed in a hand rim wheelchair because this was most closely related to their everyday mobility and because testing in a hand cycle would put those not hand cycling at disadvantage. In addition, muscle strength and pulmonary function, both considered to be possible contributors to the level of PO_{peak} and VO_{2peak} (Janssen et al., 2002), were evaluated. Hand cycle use was monitored retrospectively at both t2 and t3 with a specifically designed questionnaire in which questions were asked about the frequency and duration of hand cycle use in the previous 3
months. From the answers to these questions we defined “regular hand cycling” as hand cycling once a week or more (hand cycling group). “Not hand cycling” was defined as hand cycling less than once a week or not hand cycling at all (non hand cycling group).

All subjects followed the usual care rehabilitation program in their own rehabilitation center. The SCI rehabilitation programs in the Netherlands have been standardized considerably over the past decade (Van Asbeck, 2007) in the 8 specialized rehabilitation centers. In the present study, hand cycling was defined as (non-structured) hand cycle use and/or hand cycle training.

**Measures**

**Subject characteristics**
We studied lesion (level and motor completeness) and personal characteristics (sex, age, body weight, height, time since injury [TSI at t1]), length of active rehabilitation (time t1–t2), and other aerobic sport activities besides hand cycling (e.g. wheelchair basketball, tennis or racing, quad rugby, swimming, or fitness training). Completeness of the lesion was classified according to the American Spinal Injury Association (ASIA) Impairment Scale, in motor complete as AIS A and B and motor incomplete as AIS C and D (Marino, 2003).

**Peak exercise test**
To determine the $P_{peak}$ (in Watt) and $V_{O2peak}$ (in ml/min), an incremental hand rim wheelchair exercise test was performed on a motor-driven treadmill. The test protocol has previously been described by Kilkens et al. (2005). During the test, the velocity of the belt was maintained at 0.56, 0.83, or 1.11 m/s, depending on the level of the lesion and the ability of the subject. The workload was raised every minute by increasing the slope of the belt by 0.36°. The test was terminated when the subject was no longer able to maintain position on the belt. Rolling resistance of the individual wheelchair-user combination on the treadmill was determined in a separate drag-test on the treadmill, as described by Van der Woude et al. (1986).

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1 [treadmill: www.bontetechniek.nl](http://www.bontetechniek.nl)
The influence of hand cycling on physical capacity

The PO_{peak} was calculated from the individual drag force and treadmill belt velocity. The VO_{2} was measured continuously during the test with an Oxycon Delta. The highest value of PO maintained for at least 30 seconds was defined as PO_{peak} and the mean VO_{2} in these 30 seconds as VO_{2peak} (Van der Woude et al., 2002).

Muscle strength
A standardized manual muscle test (MMT) (Kendall, 1993) was performed on seated subjects to determine the strength (0–5 scale) of the shoulder abductors, internal and external shoulder rotators, elbow flexors and extensors, and the wrist extensors in both arms. A sum score of the 6 muscle groups for the left and right arm was computed (MMT total) (Haisma et al., 2006a).

The muscle groups that scored greater than or equal to 3 on the MMT were also tested with hand-held dynamometry (HHD), according to a standardized protocol with subjects in a supine position (Andrews et al., 1996). A break test was executed in which subjects built up a maximal force against a dynamometer, after which the examiner applied a sufficiently higher resistance to break through it (Phillips et al., 2000). Maximal forces were summed for the left and right elbow flexors and also for the left and right elbow extensors. Only subjects with a strength score for both arms were included in the strength analysis.

Pulmonary function
To assess pulmonary function we measured and analyzed the individual flow-volume curves with the Oxycon Delta. The results of the forced vital capacity (FVC) and the peak expiratory flow rate (PEFR) were expressed as a percentage of the predicted values for an able-bodied population matched for age, sex, and height.

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2 Oxycon delta: www.viasyshealthcare.com
3 Microfet: www.biometrics.nl
Data Analyses

Subject characteristics and baseline values for the physical capacity outcome measures at the start of clinical rehabilitation (t1) and at the start of the post-clinical rehabilitation period (t2) were compared between the hand cycling group and the non-hand cycling group with an independent t test ($P \leq 0.05$).

A multilevel regression analysis was applied to investigate the relationship between hand cycling and changes in physical capacity. The main advantage of this statistical method is that it corrects for the dependency of repeated measures within subjects and rehabilitation centers. Separate models were constructed for subjects with paraplegia and tetraplegia, and for the clinical rehabilitation period and post-clinical rehabilitation period. The physical capacity outcome measures at t2 (for the clinical rehabilitation period) and t3 (for the post-clinical rehabilitation period) were used as dependent variables in the respective models. Group (non-hand cycling=0, hand cycling=1) and the baseline value of the physical capacity variable at t1 (for the clinical rehabilitation period) or at t2 (for the post-clinical rehabilitation period) were included as independent variables. For example, the following model reflects the difference in improvement in $PO_{peak}$ between the hand cycling group and the non-hand cycling group during clinical rehabilitation:

\[
PO_{peak\ at\ t2} = \text{Intercept} + \beta_1 \times (PO_{peak\ at\ t1}) + \beta_2 \times \text{hand cycling} + \beta_n \times \text{confounders}
\]

where $\beta_n$ is the regression coefficient.

As possible confounders, the following independent variables were added one by one to the initial model: completeness of the lesion (motor complete=1, motor incomplete=0), sex (man=1, woman=0), age (y), time since injury at t1 (in days), length of active rehabilitation defined as time between t1 and t2 (in days), and participation in other aerobic sport activities (in h/wk). Hand cycle use during clinical rehabilitation (yes=1, no=0) was added as a possible confounder to the second model (post-clinical rehabilitation period). Variables that changed the regression coefficient of hand cycling by at least 10% were identified as confounders and were included in the final model, as was previously described by Maldonano et al. (1993). The level of significance was set at $p \leq 0.05$.

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4 ML-WIN:www.cmm.bristol.ac.uk/MLwiN
Results

Characteristics of the hand cycling group and non-hand cycling group

Data on hand cycle use was available for 137 subjects in the clinical rehabilitation period and for 131 subjects in the post-rehabilitation period (in total 177 individual subjects). Data on 106 subjects were available for both periods. Table 1 shows the characteristics of the hand cycling group and the non-hand cycling group during and after clinical rehabilitation. Except for age in the paraplegic group, no significant differences in characteristics were found between the hand cycling group and the non-hand cycling group at the start of clinical rehabilitation (baseline t1). At the start of the post-clinical rehabilitation period (baseline t2), no significant differences in personal characteristics were found between the hand cycling group and the non-hand cycling group.

Tables 2 and 3 describe the physical capacity outcomes of the hand cycling group and the non-hand cycling group during and after clinical rehabilitation, respectively. For each outcome measure, only subjects who completed both the baseline and the follow-up test were included. Because not all subjects were able to perform all the tests on all occasions, a variable number of subjects are presented for each outcome measure. At the start of the active rehabilitation (t1), no differences in baseline values were found between the hand cycling group and the non-hand cycling group. At the start of the post-clinical rehabilitation period (t2), subjects with paraplegia in the hand cycling group had significantly higher values for muscle strength (MMT total, p=0.04; HHD elbow extension, p=.02), compared with the non-hand cycling group. No differences in baseline values were found in subjects with tetraplegia for the post-clinical rehabilitation period.
The influence of hand cycling on physical capacity

Table 1: Characteristics of the 2 groups, hand cycling (HC) or not hand cycling (non-HC), during and after rehabilitation

<table>
<thead>
<tr>
<th>Subject</th>
<th>AIS A or B (%yes)</th>
<th>Age (year)</th>
<th>Body Weight (kg)</th>
<th>Height (cm)</th>
<th>gend (% men)</th>
<th>TSI at t1 (days)</th>
<th>Time t1 - t2 (days)</th>
<th>Aerobic Sports (h/wk)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>During rehabilitation (at baseline t1)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP Non-HC</td>
<td>56</td>
<td>71</td>
<td>42±14</td>
<td>72.3±15.2</td>
<td>177±10</td>
<td>73</td>
<td>92±57</td>
<td>153±68</td>
</tr>
<tr>
<td>HC</td>
<td>35</td>
<td>80</td>
<td>40±15</td>
<td>76.1±13.4</td>
<td>179±10</td>
<td>67</td>
<td>97±67</td>
<td>177±113</td>
</tr>
<tr>
<td>p-value</td>
<td>0.64</td>
<td>0.50</td>
<td>0.29</td>
<td>0.38</td>
<td>0.36</td>
<td>0.71</td>
<td>0.23</td>
<td>0.78</td>
</tr>
<tr>
<td>TP Non-HC</td>
<td>26</td>
<td>58</td>
<td>44±14</td>
<td>69.0±11.6</td>
<td>176±8</td>
<td>69</td>
<td>120±98</td>
<td>226±145</td>
</tr>
<tr>
<td>HC</td>
<td>20</td>
<td>80</td>
<td>33±10</td>
<td>68.8±14.2</td>
<td>177±10</td>
<td>80</td>
<td>110±58</td>
<td>254±198</td>
</tr>
<tr>
<td>p-value</td>
<td>0.11</td>
<td>0.01</td>
<td>0.93</td>
<td>0.91</td>
<td>0.41</td>
<td>0.67</td>
<td>0.61</td>
<td>0.94</td>
</tr>
<tr>
<td><strong>After rehabilitation (at baseline t2)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP Non-HC</td>
<td>60</td>
<td>70</td>
<td>48±15</td>
<td>75.8±16.0</td>
<td>178±10</td>
<td>70</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>HC</td>
<td>34</td>
<td>71</td>
<td>39±15</td>
<td>75.2±11.8</td>
<td>177±8</td>
<td>77</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>p-value</td>
<td>0.72</td>
<td>0.12</td>
<td>0.83</td>
<td>0.83</td>
<td>0.50</td>
<td>0.90</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>TP Non-HC</td>
<td>28</td>
<td>50</td>
<td>38±14</td>
<td>70.0±13.2</td>
<td>179±11</td>
<td>68</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>HC</td>
<td>9</td>
<td>56</td>
<td>33±7</td>
<td>75.0±17.9</td>
<td>181±11</td>
<td>89</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>p-value</td>
<td>0.67</td>
<td>0.26</td>
<td>0.38</td>
<td>0.11</td>
<td>0.22</td>
<td>0.27</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE. Values are mean ± SD, except for AIS and gender: gender, PP: paraplegia, TP: tetraplegia, Aerobic sports: other aerobic sports apart from hand cycling, during and after rehabilitation obtained from a questionnaire at t2 and t3, respectively. Abbreviations: AIS Grade A or B, motor complete lesion; HC, hand cycling group; NA, not applicable; Non-HC, non-hand cycling group; SD, standard deviation.

Hand cycling during clinical rehabilitation

Table 2 shows that during clinical rehabilitation subjects in the hand cycling group and the non-hand cycling group on average improved on all outcome measures.

**POpeak and VO2peak**

Test results for both POpeak and VO2peak at t1 and at t2 were available for 94 and 90 subjects, respectively. Table 4 shows the results of the multilevel regression analysis during and after clinical rehabilitation. During clinical rehabilitation there was a significant relationship between hand cycling and change in both POpeak and VO2peak in the paraplegic group. After correction for length of active rehabilitation (time t1 – t2), age, sex, and TSI at t1, POpeak increased on average 6.2W more in the hand cycling group than in the non-hand cycling group. Compared with baseline at t1, POpeak improved about 42% (16W) and 26% (10W) in the hand cycling group and the non-hand cycling group, respectively.

In subjects with paraplegia, VO2peak increased 0.21 L/min more in the hand cycling
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group than in the non-hand cycling group during clinical rehabilitation, with age, sex, and completeness of lesion added to the model as confounders. Compared with baseline at t1, \( VO_{2\text{peak}} \) improved approximately 29% (0.32 L/min) in the hand cycling group and 8% (0.10 L/min) in the non-hand cycling group, respectively. No influence of hand cycling was found on \( VO_{2\text{peak}} \) expressed in \( \text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \). In subjects with tetraplegia no relationship between hand cycling and the outcome measures \( PO_{\text{peak}} \) and \( VO_{2\text{peak}} \) was found during rehabilitation.

**Muscle strength**

In subjects with paraplegia, elbow extension strength (measured with HHD) increased significantly more in the hand cycling group than in the non-hand cycling group. Table 4 shows that after correcting for the confounders age, sex, and length of active rehabilitation, elbow extension strength increased 43N more in the hand cycling group than in the non-hand cycling group. Table 2 shows that, compared to baseline at t1, there was an improvement in strength of approximately 30% in the hand cycling group and 15% in the non-hand cycling group. However, this finding did not apply to subjects with tetraplegia: no relationship was found between hand cycling and upper-arm strength (measured with MMT) and elbow flexion strength (measured with HHD) during the clinical rehabilitation period.

**Pulmonary function**

No relationship was found between hand cycling and pulmonary function (PEFR, FVC) during clinical rehabilitation in subjects with paraplegia or subjects with tetraplegia.
The influence of hand cycling on physical capacity

Table 2: cross-sectional values of the outcome measures at baseline (t1) and at follow-up (t2) during rehabilitation

<table>
<thead>
<tr>
<th>Outcome Measures</th>
<th>Paraplegia</th>
<th></th>
<th>Tetraplegia</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n t1</td>
<td>t2</td>
<td>n t1</td>
<td>t2</td>
</tr>
<tr>
<td>POpeak (W)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>28</td>
<td>37.3 ± 19.6</td>
<td>52.8 ± 23.6</td>
<td>12</td>
</tr>
<tr>
<td>Non-HC</td>
<td>40</td>
<td>38.0 ± 20.3</td>
<td>48.1 ± 20.7</td>
<td>14</td>
</tr>
<tr>
<td>VO2peak (L/min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>29</td>
<td>1.10 ± 0.23</td>
<td>1.42 ± 0.45</td>
<td>11</td>
</tr>
<tr>
<td>Non-HC</td>
<td>38</td>
<td>1.22 ± 0.48</td>
<td>1.32 ± 0.47</td>
<td>12</td>
</tr>
<tr>
<td>VO2peak (mL·kg⁻¹·min⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>29</td>
<td>14.6 ± 6.0</td>
<td>18.5 ± 6.3</td>
<td>9</td>
</tr>
<tr>
<td>Non-HC</td>
<td>36</td>
<td>16.3 ± 6.0</td>
<td>18.1 ± 6.2</td>
<td>11</td>
</tr>
<tr>
<td>MMT Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>36</td>
<td>58.2 ± 3.3</td>
<td>59.5 ± 2.1</td>
<td>20</td>
</tr>
<tr>
<td>Non-HC</td>
<td>55</td>
<td>56.0 ± 12.3</td>
<td>57.0 ± 12.1</td>
<td>24</td>
</tr>
<tr>
<td>HHD elbow flexion (l+r) (N)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>26</td>
<td>487 ± 133</td>
<td>546 ± 153</td>
<td>17</td>
</tr>
<tr>
<td>Non-HC</td>
<td>40</td>
<td>487 ± 153</td>
<td>533 ± 146</td>
<td>19</td>
</tr>
<tr>
<td>HHD elbow extension (l+r) (N)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>28</td>
<td>320 ± 118</td>
<td>417 ± 129</td>
<td>7</td>
</tr>
<tr>
<td>Non-HC</td>
<td>47</td>
<td>342 ± 107</td>
<td>393 ± 109</td>
<td>15</td>
</tr>
<tr>
<td>FVC (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>33</td>
<td>77.5 ± 22.5</td>
<td>87.1 ± 19.5</td>
<td>19</td>
</tr>
<tr>
<td>Non-HC</td>
<td>49</td>
<td>80.2 ± 27.6</td>
<td>86.5 ± 24.0</td>
<td>23</td>
</tr>
<tr>
<td>PEFR (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>33</td>
<td>62.2 ± 17.1</td>
<td>71.1 ± 15.5</td>
<td>19</td>
</tr>
<tr>
<td>Non-HC</td>
<td>49</td>
<td>58.7 ± 24.2</td>
<td>66.8 ± 20.3</td>
<td>23</td>
</tr>
</tbody>
</table>

NOTE. Values are mean ± SD. For each outcome measure, only subjects with baseline and follow-up measurements are included. There were no significant differences at baseline during rehabilitation (t1) between the hand cycling group and the non-hand cycling group (p ≤ 0.05). Abbreviations: l, left; r, right. HHD: Hand-held dynamometry, FVC: Forced vital capacity, PEFR: Peak expiratory flow rate.

Hand cycling in the post-clinical rehabilitation period

Table 3 shows that during the year after clinical rehabilitation subjects in both the hand cycling group and the non-hand cycling group improved only marginally on all outcome measures. In contrast to the results during clinical rehabilitation, no significant effect of hand cycling was found on POpeak and VO2peak, muscle strength (MMT total, elbow flexion strength), or pulmonary function (PEFR, FVC). Hand cycling during rehabilitation appeared to be a confounder for the effect of hand cycling in the post-rehabilitation period in most outcome measures. A large number of subjects (≈25% in all outcome measures) had missing values for this confounder. Therefore, we performed a multilevel regression analysis without this confounder (see Table 4). In addition, we also performed an analysis with this...
confounder on the subgroup of subjects with data on hand cycling during rehabilitation. Results were the same, except for elbow extension strength. After adding the confounder hand cycling during clinical rehabilitation, no significant effect of hand cycling on elbow extension strength was found anymore in a subgroup of 53 subjects (p=0.83). Due to the low number of subjects and the unequal distribution over the hand cycling group and the non-hand cycling group, a multilevel regression analysis could not be performed after clinical rehabilitation for subjects with tetraplegia.

Table 3: Cross-sectional values of the outcome measures at baseline (t2) and at follow-up (t3) after rehabilitation

<table>
<thead>
<tr>
<th>Outcome Measures</th>
<th>Paraplegia</th>
<th>Tetraplegia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>t2</td>
</tr>
<tr>
<td>POpeak (W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>26</td>
<td>54.6 ± 22.6</td>
</tr>
<tr>
<td>Non-HC</td>
<td>36</td>
<td>46.9 ± 22.1</td>
</tr>
<tr>
<td>VO2peak (L/min)</td>
<td>26</td>
<td>1.38 ± 0.46</td>
</tr>
<tr>
<td>HC</td>
<td>33</td>
<td>1.26 ± 0.46</td>
</tr>
<tr>
<td>Non-HC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VO2peak (mL·kg⁻¹·min⁻¹)</td>
<td>26</td>
<td>18.8 ± 6.6</td>
</tr>
<tr>
<td>HC</td>
<td>33</td>
<td>17.5 ± 5.9</td>
</tr>
<tr>
<td>Non-HC</td>
<td>53</td>
<td>60.0 ± 0.2*</td>
</tr>
<tr>
<td>MMT Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>33</td>
<td>59.0 ± 2.6</td>
</tr>
<tr>
<td>Non-HC</td>
<td>53</td>
<td>60.0 ± 0.2*</td>
</tr>
<tr>
<td>HHD elbow flexion (l+r) (N)</td>
<td>21</td>
<td>568 ± 128</td>
</tr>
<tr>
<td>HC</td>
<td>34</td>
<td>499 ± 140</td>
</tr>
<tr>
<td>Non-HC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HHD elbow extension (l+r) (N)</td>
<td>26</td>
<td>427 ± 99*</td>
</tr>
<tr>
<td>HC</td>
<td>41</td>
<td>367 ± 95</td>
</tr>
<tr>
<td>Non-HC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FVC (%)</td>
<td>30</td>
<td>89.9 ± 20.6</td>
</tr>
<tr>
<td>HC</td>
<td>46</td>
<td>90.9 ± 18.9</td>
</tr>
<tr>
<td>Non-HC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEFR (%)</td>
<td>30</td>
<td>69.9 ± 14.5</td>
</tr>
<tr>
<td>HC</td>
<td>46</td>
<td>69.9 ± 20.6</td>
</tr>
</tbody>
</table>

NOTE. Values are mean ± SD. For each outcome measure, only subjects with baseline and follow-up measurements are included. *Significant differences at baseline (after rehabilitation; at t2) between the hand cycling group and the non-hand cycling group (ps.05).
The influence of hand cycling on physical capacity

Table 4: The regression equation of hand cycling (β2 regression coefficient) after adding a confounders (that change β2 >10%) to the model

<table>
<thead>
<tr>
<th>Outcome Measures</th>
<th>During Rehabilitation</th>
<th>Tetraplegia</th>
<th>Paraplegia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n β2 ± SE p-value</td>
<td>n β2 ± SE p-value</td>
<td>n β2 ± SE p-value</td>
</tr>
<tr>
<td>PO (W)</td>
<td>68 6.2 ±2.4 0.00</td>
<td>26 2.6±2.8 0.35</td>
<td>62 0.3±2.9 0.92</td>
</tr>
<tr>
<td>VO2peak (L/min)</td>
<td>67 0.21 ± 0.07 0.00</td>
<td>23 0.11 ± 0.11 0.32</td>
<td>59 0.01 ± 0.07 0.89</td>
</tr>
<tr>
<td>(mL·kg(^{-1})·min(^{-1}))</td>
<td>65 1.55 ± 0.96 0.11</td>
<td>20 0.81 ± 1.50 0.59</td>
<td>59 -0.9 ± 0.9 0.32</td>
</tr>
<tr>
<td>MMT total</td>
<td>88 0.4 ± 0.6 0.51</td>
<td>44 -1.5 ± 1.6 0.35</td>
<td>86 -0.1 ± 0.2 0.44</td>
</tr>
<tr>
<td>HHD elbow flexion (N)</td>
<td>66 5 ± 18 0.78</td>
<td>36 -9.7 ± 25.7 0.71</td>
<td>56 23 ± 24 0.34</td>
</tr>
<tr>
<td>HHD elbow extension (N)</td>
<td>75 43 ± 17 0.01</td>
<td>22 -41.8 ± 28.1 0.14</td>
<td>67 28 ± 13 0.03</td>
</tr>
<tr>
<td>FVC (%)</td>
<td>82 0.4 ± 3.2 0.90</td>
<td>42 0.7 ± 4.7 0.88</td>
<td>76 3.1 ± 2.6 0.23</td>
</tr>
<tr>
<td>PEFR (%)</td>
<td>82 2.1 ± 3.1 0.51</td>
<td>42 3.5 ± 4.1 0.39</td>
<td>76 2.5 ± 2.8 0.37</td>
</tr>
</tbody>
</table>

Abbreviation: SE, standard error.

Discussion

The aim of this longitudinal cohort study was to investigate the influence of active hand cycling on changes in physical capacity during and after clinical rehabilitation in subjects with SCI. In subjects with paraplegia, after correction for confounders and baseline values, we found a significantly larger improvement in POpeak, VO2peak, and elbow extension strength in the hand cycling group, compared to the non-hand cycling group in the clinical rehabilitation period. However in subjects with tetraplegia, no significant relationship between hand cycling and any of the physical capacity outcome measures was found during rehabilitation. In the post-clinical rehabilitation period there was no influence of hand cycling on any of the outcome measures.

POpeak and VO2peak

Clinical rehabilitation period

Compared with the overall improvements that were achieved during clinical rehabilitation, the effects of hand cycling on POpeak and VO2peak in subjects with paraplegia are considered to be substantial, and therefore clinically relevant. In subjects with tetraplegia, the small number of subjects and the heterogeneity of the
The influence of hand cycling on physical capacity

groups may have reduced the statistical power. Moreover, much lower absolute gains can be expected compared to subjects with paraplegia (Jacobs and Nash, 2004).

The results of the current study seem to be in agreement with the results of studies on the effects of upper-body exercise training in people with a recent SCI (De Groot et al., 2003; Duran et al., 2001; Hjeltnes and Wallberg-Henriksson, 1998; Knuttson E, 1973; Le Foll-de Moro et al., 2005; Sutbeyaz et al., 2005). Improvements in $P_{\text{O}_{\text{peak}}}$ and $V_{\text{O}_{\text{peak}}}$ within a range of 20% to 45% have been reported. However, these studies did not include a control group receiving usual care, whereas we are interested in the improvement that can be attributed to hand cycling in addition to usual care. Comparison of our results with the results of other studies of training during rehabilitation is limited due to differences in study design and differences in the rehabilitation process in different countries, such as length of stay in the hospital and in the rehabilitation centers. The latter appears to be relatively long in the Netherlands. Although the generalizability of results to other countries is limited, results indicate that hand cycling in the first year post-injury (regardless of other therapies) offers an appropriate exercise mode to improve the physical capacity.

Post-clinical rehabilitation period
Tables 3 and 4 show that, regardless of hand cycling, after rehabilitation little or no improvements were found in any of the outcome measures, while considerable improvements were found during the clinical rehabilitation period. Possibly, the greatest gain may be expected during rehabilitation, because in the first place, subjects who are deconditioned after a long period of immobilization are starting an intensive rehabilitation training program, and, second, natural recovery is more likely to occur during rehabilitation. Another factor for the lack of influence of hand cycling in the post-rehabilitation period was probably that 50% of the subjects in the hand cycling group were already hand cycling regularly during clinical rehabilitation, and consequently reached a higher physical capacity on discharge. Consequently, the hand cycling group started with higher baseline values for
muscle strength, compared to the non-hand cycling group in the post-clinical rehabilitation period. Apparently, they were able to maintain this higher level of fitness, but in order to further augment their fitness level, higher exercise intensities may have been required. Our data showed that few subjects trained more often than twice a week, which is explained by the fact that most of them hand cycled purely for recreational and transportation purposes. In the post-clinical rehabilitation period the high level of activity attained during rehabilitation should at least be maintained or extended in order to achieve further improvement. This, however, depends on the intrinsic motivation of individuals and their personal and practical situation.

**Other Outcome Measures**

*Muscle strength*

Sensitivity to change in muscle strength, measured with the MMT method, is poor (Noreau and Vachon, 1998). A ceiling effect occurred in 64 of 91 subjects with paraplegia at the start of the active rehabilitation, which limits the expression of a possible training effect on this measure. However, there was also no effect of hand cycling found in persons with tetraplegia. As we assumed that elbow flexion and extension are important for hand cycling in the pull-and-push phase, respectively, we measured both muscle groups with the HHD. The HHD scores of both muscle groups are considered to be more sensitive than the scores of MMT (Noreau and Vachon, 1998) and have a high intra-rater reliability in subjects with tetraplegia (Burns et al., 2005). The positive effect of hand cycling on elbow extension in those with paraplegia supports this view. The lack of effect in subjects with tetraplegia was probably due to the overall low number of subjects in this group.

*Pulmonary function*

We expected that during rehabilitation subjects with tetraplegia would benefit most from hand cycling. However, we did not see any difference in improvement for percentage of FVC or percentage of PEFR between the hand cycling group and the non-hand cycling groups during or after rehabilitation in subjects with
The influence of hand cycling on physical capacity

paraplegia or tetraplegia. Both groups improved in pulmonary function during clinical rehabilitation but this may be attributed to natural recovery (Anke et al., 1993; Ledsome and Sharp, 1981) and the fact that all subjects followed the regular active rehabilitation program. Also in other studies no positive effects of upper-body training on pulmonary function were found in subjects with SCI (Gass et al., 1980; Le Foll-de Moro et al., 2005; Sutbeyaz et al., 2005; Taylor et al., 1986), where only one (Gass et al., 1980) of these studies focused on subjects with tetraplegia.

Study Limitations
One limitation of the present study is that missing values are considerable, because data on the outcome measure had to be available for 2 sequential measurement moments. Not all subjects were able to perform the tests on all occasions and this applies in particular to the peak wheelchair exercise test. It appeared that, despite a test protocol that was especially designed for subjects with the lowest physical capacity, 50% of those with a lesion level of C5 or C6 were not able to perform the test in the first 3 months of active rehabilitation, although some of them were hand cycling during rehabilitation. On the other hand there were also subjects with incomplete lesions and a relatively high physical capacity that dropped out of the project because they regained walking ability during rehabilitation. Therefore, the results of PO_{peak} and VO_{2peak} do only apply to subjects with SCI who depend on a wheelchair and are able to propel a wheelchair independently.

In the present study, the relationship between hand cycling and the outcome measures of physical capacity is not necessarily a causal relationship. Because this study was designed as an observational cohort study, no controlled training protocol was imposed and no randomized control group was included. The frequency (and intensity) of training was reported by the subjects themselves, and is therefore subjective. A hand cycle frequency of at least once a week is rather low to induce training effects but nevertheless, we found positive effects in subjects with paraplegia during the rehabilitation period.
Another limitation of this observational design is that subjects who are doing well are more likely to hand cycle regularly. However, this is not supported by our results, which show equal baseline values on all outcome measures in the hand cycling group and the non-hand cycling group at the start of rehabilitation. On the other hand, the higher baseline values in the hand cycling group at the start of the post-clinical rehabilitation period may support the assumption of a selection bias, although this can also be explained by the fact that half of the subjects in the hand cycling group had already started hand cycling during rehabilitation. A more suitable design to investigate the effects of hand cycle training would be a randomized controlled trial. We are currently investigating the effects of structured hand cycle training (interval training twice a week) on physical capacity in subjects with SCI.

**Conclusions**

The results suggest that regular hand cycle training is beneficial for improving or maintaining physical capacity after SCI during clinical rehabilitation. Therefore, the prescription of a structured hand cycling training program is recommended during and after the clinical rehabilitation of subjects with SCI. Moreover, training in functional hand cycle use is needed (especially in subjects with tetraplegia) to enable and support independent hand cycling after discharge.
Acknowledgments

We thank our research assistants for their extensive work and also the following rehabilitation centers for their collaboration: de Hoogstraat Rehabilitation Center (Utrecht), Amsterdam Rehabilitation Center, Hoensbroeck Rehabilitation Center, Sint Maartenskliniek (Nijmegen), Heliomare Rehabilitation Center (Wijk aan Zee), Beatrixoord (Haren), Het Roessingh (Enschede) and Rijndam Rehabilitation Center (Rotterdam).

The Health Research and Development Council of The Netherlands (grant nos. 014-32-012, 14350003) supported this study.
Chapter 4

The individual relationship between heart rate and oxygen uptake in people with tetraplegia during exercise

Based on:
Abstract

Study design: Descriptive study

Objective: To examine the individual heart rate-oxygen uptake (HR-VO₂) relationship during exercise in persons with tetraplegia.

Setting: Rehabilitation Centre Heliomare, Wijk aan Zee, the Netherlands

Methods: The HR-VO₂ relationship was determined in untrained subjects with motor complete tetraplegia (C5 or C6, n=10 and C7 or C8, n=10) during a discontinuous graded exercise hand cycle test. The mean HR and VO₂ of the final 60 sec of 2-min exercise blocks were used for calculation of the individual correlation coefficient and the Standard Error of the Estimate (SEE).

Results: Two subjects of the C5-C6 group were not able to complete the test. Individual Pearson’s correlation coefficients (r) ranged from 0.68 to 0.97 and SEE from 2.6 to 22.4% VO₂-Reserve (VO₂R). The mean Pearson’s r and SEE were 0.81 ± 0.12 and 10.6 ± 5.6%VO₂R in the C5-C6 group and 0.91 ± 0.07 and 7.0 ± 3.2%VO₂R in the C7-C8 group, respectively. Two subjects of the C5-C6 group and six subjects of the C7-C8 group attained a linear HR-VO₂ relationship with an acceptable SEE (≤6.0%) and r (>0.90).

Conclusions: The HR-VO₂ relationship appeared linear in only 8 out of 18 subjects. An individual analysis of the HR-VO₂ relationship is necessary to determine whether HR can be used to quantify exercise intensity. The use of heart rate to prescribe training intensity should be reconsidered in persons with tetraplegia.

Keywords: tetraplegia; heart rate; oxygen uptake; hand cycling; training intensity
Introduction
In able-bodied persons, heart rate (HR) and oxygen uptake (VO₂) are linearly related and therefore exercise training intensity can be prescribed, based on HR. This is an advantage because the measurement of VO₂ during training is complicated, whereas HR can be easily recorded. In persons with Spinal Cord Injury (SCI) heart rate has also been used to prescribe training intensity (Figoni, 2003), as well as to indicate physical strain in daily activities (Dallmeijer et al., 1999; Janssen et al., 1994; Kilkens et al., 2004). The guidelines of the American College of Sports Medicine (ACSM) for training of able-bodied persons - 50-85% Heart Rate Reserve (HRR) (Pollock, 1998) - have also been applied in training studies with persons with paraplegia (Hooker and Wells, 1989) as well as tetraplegia (DiCarlo, 1988; Hopman et al., 1996). These guidelines may be valid for persons with paraplegia, as several studies (Bar-On and Nene, 1990; Goosey-Tolfrey and Tolfrey, 2004; Hjeltnes, 1977; Hooker et al., 1993; Schmid et al., 1998; Tolfrey et al., 2001) showed a strong individual linear HR-VO₂ relationship in persons with paraplegia. In individuals with tetraplegia however, this may be different as a result of the disturbed sympathetic innervation, which may affect the HR-VO₂ relationship.

The sympathetic innervation of the heart derives from Th1 to Th4 and therefore spinal cord lesions at or above Th4 may lead to inappropriate cardio-acceleration (Glaser, 1989). The increase in HR during exercise in these persons is mostly due to withdrawal of vagal parasympathetic stimulation (Freyschuss and Knutsson, 1969). As a consequence, maximal HR in individuals with tetraplegia is often restricted to about 130 beats per minute (bpm) (Figoni, 2003). Moreover, normal cardiovascular responses to exercise (e.g. vasoconstriction in relatively inactive tissues and increased blood flow to active muscle) are diminished as a consequence of the disturbed sympathetic nervous system (Glaser, 1989). In a study of Hjeltnes et al. (1998) in persons with tetraplegia it was indeed shown that, compared to able-bodied, mean blood pressure and oxygen tension (PO₂) in arterial blood were reduced during graded exercise. Furthermore, as a consequence of the disturbed sympathetic innervation, Autonomic Dysreflexia (AD) may occur in subjects with a lesion level at or above Th6 (Eltorai et al., 1992). AD may result in an uncontrolled
The HR-VO2-relationship in tetraplegia

elevation of blood pressure and during exercise this may lead to sudden changes in heart rate and eventually a higher HR\textsubscript{peak} and VO2\textsubscript{peak} (Schmid et al., 1998). Apart from the disturbed sympathetic innervation, persons with tetraplegia have a low physical capacity as a consequence of the low active muscle mass and inactivity of the venous muscle pump. Because of the disturbed sympathetic innervation and the low physical capacity it is questionable whether HR can be used for monitoring exercise intensity in persons with high level paraplegia or tetraplegia.

When looking more closely at studies investigating the HR-VO2 relationship in persons with paraplegia, hardly any subjects with a complete Th1-Th4 lesion - with possibly disturbed sympathetic innervation of the heart - were included (Bar-On and Nene, 1990; Goosey-Tolfrey and Tolfrey, 2004; Hooker et al., 1993; Tolfrey et al., 2001). Moreover, only a few studies have focused on the HR-VO2 relationship in persons with tetraplegia (Coutts et al., 1985; McLean et al., 1995; Schmid et al., 1998) and only one focused on the individual relationship (McLean et al., 1995). The available studies all use hand rim wheelchair or arm crank exercise to investigate the HR-VO2 relationship.

In the last decade hand cycling (Figure 1) has become a very popular alternative for daily outdoor wheelchair use in the Netherlands, also among persons with tetraplegia. These systems were found to be more efficient and less straining than hand rim wheelchair propulsion (Dallmeijer et al., 2004; Van der Woude et al., 2001) and can be used also in early rehabilitation and in fragile individuals. Moreover, it seems possible to attain significantly higher peak VO2, Power Output and HR-values in hand cycling compared to wheelchair propulsion (Dallmeijer et al., 2004). Therefore hand cycling seems to be very appropriate for training and testing of persons with tetraplegia.

The aim of this study is to examine the individual HR-VO2 relationship in individuals with tetraplegia to answer the question: Can HR be used to quantify exercise intensity in persons with tetraplegia during hand cycling?
Methods

Subjects

Twenty subjects, aged between 21 and 64, participated in this study. Ten subjects were classified as having a high-level cervical lesion (C5 or C6) and ten were classified as having a low-level cervical lesion (C7 or C8) (Table 1).

Table 1: Individual and mean (SD) values for personal characteristics

<table>
<thead>
<tr>
<th>C7-C8</th>
<th>lesion (l/r)</th>
<th>AIS</th>
<th>age (yrs)</th>
<th>gender (m/f)</th>
<th>TSI (yrs)</th>
<th>weight (kg)</th>
<th>height (cm)</th>
<th>experience in hand cycling</th>
<th>training status (min/wk)</th>
<th>wheelchair daily use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C7C8</td>
<td>A</td>
<td>32</td>
<td>m</td>
<td>13</td>
<td>78</td>
<td>203</td>
<td>yes</td>
<td>0</td>
<td>hand rim</td>
</tr>
<tr>
<td>2</td>
<td>C6C7</td>
<td>B</td>
<td>22</td>
<td>m</td>
<td>2</td>
<td>86</td>
<td>195</td>
<td>yes</td>
<td>30</td>
<td>hand rim</td>
</tr>
<tr>
<td>3</td>
<td>C7C7</td>
<td>B</td>
<td>32</td>
<td>m</td>
<td>6</td>
<td>77</td>
<td>176</td>
<td>yes</td>
<td>90</td>
<td>hand rim</td>
</tr>
<tr>
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<td>B</td>
<td>54</td>
<td>m</td>
<td>28</td>
<td>81</td>
<td>174</td>
<td>yes</td>
<td>120</td>
<td>hand rim</td>
</tr>
<tr>
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<td>C8C8</td>
<td>B</td>
<td>31</td>
<td>m</td>
<td>6</td>
<td>83</td>
<td>187</td>
<td>yes</td>
<td>60</td>
<td>hand rim</td>
</tr>
<tr>
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<td>m</td>
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<td>electric</td>
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<td>B</td>
<td>47</td>
<td>m</td>
<td>1.5</td>
<td>63</td>
<td>180</td>
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<td>120</td>
<td>hand rim</td>
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<td>8</td>
<td>C6C7</td>
<td>B</td>
<td>29</td>
<td>m</td>
<td>7</td>
<td>69</td>
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<td>yes</td>
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C5-C6

|      |             |      |          |            |          |            |            |                          |                        |                     |
| 11   | C5C5        | A    | 44        | m          | 7.5       | 113        | 178        | yes                      | 120                    | electric            |
| 12   | C6C6        | B    | 37        | m          | 15        | 85         | 186        | yes                      | 120                    | hand rim            |
| 13   | C6C6        | A    | 41        | m          | 3         | 117        | 179        | yes                      | 0                      | electric            |
| 14   | C6C6        | B    | 58        | f          | 42        | 81         | 173        | no                       | 0                      | electric            |
| 15   | C5C5        | A    | 33        | m          | 1.5       | 51         | 170        | yes                      | 120                    | both                |
| 16   | C5C6        | B    | 33        | m          | 2.5       | 65         | 165        | yes                      | 120                    | both                |
| 17   | C6C6        | B    | 41        | m          | 15        | 83         | 198        | no                       | 0                      | electric            |
| 18   | C5C6        | B    | 46        | f          | 7         | 80         | 172        | no                       | 90                     | both                |
| 19   | C5C6        | A    | 32        | m          | 3.5       | 77         | 188        | yes                      | 0                      | hand rim            |
| 20   | C5C6        | A    | 21        | m          | 6         | 60         | 180        | yes                      | 0                      | both                |
| Mean | 41.6         | 10.8 | 83.6      | 179        | 57        |             |             |                          |                        |                     |
| SD   | 8.1          | 12.8 | 20.8      | 10         | 60        |             |             |                          |                        |                     |

Mean (total) 38.9 9.6 82.0 181 51

SD 10.8 10.4 17.7 10 54

I: left, r: right, AIS: Asia impairment Scale grade A and B, TSI: time since injury

All subjects had motor complete lesions, classified on the ASIA Impairment Scale (AIS) (Marino et al., 2003) as A or B. Seven subjects of the high lesion group and one subject of the low lesion group used an electric powered wheelchair. The other subjects all used manual wheelchairs. All participants were considered untrained to moderately trained (no more than 2 hours of sport participation weekly during the last three months). Four subjects were not experienced in hand cycling at all (Table 1). Prior to testing, all participants were
medically screened by a physician. Exclusion criteria were: Serious overuse injuries of the upper extremities or other impairments which do not allow performing physical activity (pressure sores), bladder infection and other medical conditions, use of beta-blockers and cardiovascular diseases. The subjects were closely monitored on symptoms of Autonomic Dysreflexia (AD) before and during the execution of the test. Symptoms of AD (Eltorai et al., 1992; Mathias and Frankel, 1992) are extreme hypertension and abnormal high or low heart rate. Above lesion level: pounding headache, initially pallor, flushed skin, excessive sweating, nasal stuffiness and anxiety. Below lesion level: pallor, goose bumps and cold skin. If any of the symptoms would occur, the test was terminated and not included in the analysis. Approval was obtained from the Medical Ethics Committee of the VU University Medical Center in Amsterdam and all subjects signed an informed consent form. Subject 7, 15 and 16 were in the final stage of the clinical rehabilitation and the other subjects were measured after rehabilitation.

**Design & Protocol**

To determine the individual relationship between HR and VO₂, subjects with tetraplegia performed a standardized discontinuous graded exercise hand cycle test on a motor driven treadmill. The medical examination prior to the test included AIS-scoring, Blood Pressure (BP) measurement and medication use. Before subjects started the test, they were asked to empty their bladder to prevent the occurrence of symptoms of AD. Oxygen uptake (VO₂, l/min), carbon dioxide output (VCO₂, l/min) and ventilation (Ve, l/min) were continuously measured using a computerized breath-by-breath gas analysing system.¹ Heart rate (HR in bpm) was recorded with a heart rate monitor.² Prior to the graded exercise hand cycle test, resting values for metabolic and heart rate parameters were measured during 5 minutes of sitting rest. Subsequently, the subjects familiarised with hand cycling on the treadmill during two minutes. In these minutes, the velocity of the treadmill and cadence of the hand cycle were adjusted to the ability of the subject within the range of 4 to 7 km/h and a cadence of approximately 60 rpm. After a 3 min rest following the familiarisation

¹ Oxycon delta: www.viasyshealthcare.com
² HR-monitor Polar: www.polar-nederland.nl
The HR-VO₂-relationship in tetraplegia

period, the subjects performed the discontinuous graded exercise test. Exercise bouts of 2 minutes were followed by 30 seconds of rest. In each exercise step, power output (PO) was increased with increments of 2.00 to 5.25 Watt, depending on the estimated individual capacity. This process continued until exhaustion or until the subject indicated that he/she wanted to stop. Average HR and VO₂-values over the last 60 seconds of each exercise bout were used for analysis. If the last uncompleted block exceeded more than 60 seconds, the HR and VO₂-value were included as well. The highest VO₂-value attained over 60 seconds during the test was defined as the VO₂peak. Respiratory Exchange Ratio (RER) was calculated as the ratio between VCO₂ and VO₂. Rating of Perceived Exertion (RPE) (Borg, 1982) on the 10-point Borg scale was assessed immediately after the end of the graded exercise hand cycle test. PO was increased - through a pulley system which was positioned behind the treadmill and connected to the rear wheel axle of the hand cycle by a rope (Dallmeijer et al., 2004) - by adding extra weight (F_add in N). External PO was calculated from rolling resistance (F_roll), added load (F_add) and treadmill belt velocity (v) according to:

\[
PO (W) = (F_{roll} + F_{add}) \times v \tag{1}
\]

F_roll was determined in a separate drag test with the subject sitting passively in the hand cycle (Van der Woude et al., 1986).

**Hand cycle**

Subjects were tested using their own rigid frame wheelchair and attach-unit hand cycle. If the subject did not own one, the Rehabilitation Centre provided a hand cycle. All hand cycles were equipped with a synchronous crank system and a bullhorn steer.³ The crank axis of the steering was positioned as low as possible.

**Statistics**

For each participant a linear regression analysis was performed and Pearson's correlation coefficient (r) was calculated, using the paired data of VO₂ and HR

³ [www.doubleperformance.nl](http://www.doubleperformance.nl)
values of each exercise block. The actual error of the predicted VO₂ from the regression equation is commonly (Goosey-Tolfrey and Tolfrey, 2004; Tolfrey et al., 2001) reflected by the standard error of the estimate (SEE), expressed in the units of measurement. To determine the accuracy of the VO₂-prediction in the individual regression equations, the SEE was calculated according to:

$$\text{SEE} = s_{(VO₂)} \times (1-r^2)^{\frac{1}{2}} \quad (2)$$

Where $s_{(VO₂)}$ is the standard deviation of the individual data points and $r$ is the individual HR-VO₂ Pearson’s correlation coefficient.

Because absolute values of $\text{SEE(VO₂)}$ depend on the individual range of VO₂ (i.e. range between VO₂ rest and VO₂ peak: $\text{VO₂R} = \text{VO₂peak} - \text{VO₂rest}$), SEE is also expressed as a percentage of the individual VO₂R. The SEE of VO₂R, given a certain HR, can be interpreted the same way as the standard deviation and the 95% confidence interval of the predicted value can be calculated. For example, a recommended range of training intensity of 60-85% HRR (is comparable to 60-85% VO₂R (Swain and Leutholtz, 1997) would allow a HR corresponding with 72%HRR (or VO₂R) and $\text{SEE} \leq 6\%$HRR (or VO₂R) to actually train within this range. Statistical analyses were performed.\(^4\)

\(^4\) SPSS 12.01 for Windows: www.spss.com
Results

In Table 2, the physiological characteristics are presented for all subjects divided over the C5-C6 and the C7-C8 lesion group. All subjects attained the VO\textsubscript{2peak} during the last exercise bout. It was found that 17 out of 20 subjects reached a RER above 1.00. Subject 1 and 14 reached a RER of 0.97 and subject 6 a RER of 0.93. Eleven subjects scored a RPE of 6 or lower on the 10-point Borg scale. Two subjects (15 and 16) had a very low physical capacity and were able to complete only 3 exercise intervals of the peak capacity test. Because of the low number of data points these subjects were excluded from the analysis.

Table 2: Individual and mean (SD) values of the physiological characteristics of the graded maximal exercise hand cycle test

<table>
<thead>
<tr>
<th>C7-C8</th>
<th>HR rest bpm</th>
<th>HR peak bpm</th>
<th>VO\textsubscript{2} rest ml/min</th>
<th>VO\textsubscript{2} peak ml/min</th>
<th>PO peak Watt</th>
<th>RER</th>
<th>Initial PO Watt</th>
<th>Δ PO block Watt</th>
<th>Duration test Min</th>
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<td>1.4</td>
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</table>

HR: heart rate, VO\textsubscript{2}: oxygen uptake, PO: power output, RER: respiratory exchange ratio, Δ PO block: increment in PO
The HR-VO₂-relationship in tetraplegia

Table 3 shows Pearson’s r and SEE of the paired HR and VO₂ for the remaining participants (n=18). Individual data points and regression lines of representative subjects of the C5-C6 group and the C7-C8 group are shown in Figure 1. Pearson’s r ranged from 0.68 and 0.97 (mean 0.81 ± 0.12) for the C5-C6 group and from 0.79 to 0.97 (mean 0.91 ± 0.07) for the C7-C8 group. The results of the SEE(VO₂) showed mean values of 57± 25 ml/min in the C5-C6 group and 67±39 ml/min in the C7-C8-group. The SEE(%VO₂R) showed mean values of 10.6 ± 5.6% in the C5-C6 group and 7.0 ± 3.2% in the C7-C8 group, respectively. The mean r for the whole group was 0.87± 0.10 and the SEE(%VO₂R) was 8.6 ± 4.6%. In table 3 it is shown that 2 subjects of the C5-C6 group and 6 subjects of the C7-C8 group attained a SEE ≤ 6.0%VO₂R. All these subjects showed Pearson’s r of 0.90 or higher.

Table 3: Individual and mean Pearson correlation coefficient and SEE of HR-VO2 data of the graded exercise test

<table>
<thead>
<tr>
<th>C7-C8</th>
<th>Lesion</th>
<th>VO₂ HR Pearson’s r</th>
<th>p-value</th>
<th>data points (n)</th>
<th>SEE (VO₂) (ml/min)</th>
<th>SEE (%VO₂R) %</th>
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</tr>
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<td>0.000</td>
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<th>C5-C6</th>
<th>Lesion</th>
<th>VO₂ HR Pearson’s r</th>
<th>p-value</th>
<th>data points (n)</th>
<th>SEE (VO₂) (ml/min)</th>
<th>SEE (%VO₂R) %</th>
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<td>0.066</td>
<td>7</td>
<td>82</td>
<td>13.0</td>
</tr>
<tr>
<td>19</td>
<td>C6C6</td>
<td>0.83*</td>
<td>0.022</td>
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<tr>
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<td>C5C6</td>
<td>0.72 NS</td>
<td>0.172</td>
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<td>29</td>
<td>9.0</td>
</tr>
<tr>
<td>mean</td>
<td>0.81</td>
<td>0.117</td>
<td>6.6</td>
<td>57</td>
<td>10.6</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>0.12</td>
<td>0.117</td>
<td>2.0</td>
<td>25</td>
<td>5.6</td>
<td></td>
</tr>
</tbody>
</table>

| C5-C8 | mean   | 0.87               | 8.0     | 62              | 8.6               |
| SD    | 0.10   | 8.0                | 2.5     | 33              | 4.6               |

With p<0.01** and p<0.05*, NS: Not significant, l: left, r: right, SEE: standard error of the estimate. In bold are values with SEE (%VO₂R) >6.0.
The HR-VO₂-relationship in tetraplegia

Figure 1: Typical examples of individual HR-VO₂ regression lines of persons with C7 or C8-lesion (a and b) and persons with C5 or C6 lesion (c and d)

In Table 4 mean values of PO peak, HR peak, HRR, VO₂peak and VO₂R of subjects with SEE ≤ 6.0% (n=8) and SEE > 6%VO₂R (n=10) are shown. These two groups showed no significant differences.

Table 4: Mean values of PO peak, HR peak, HRR, VO₂peak, and VO₂R for subjects with SEE ≤ 6% and SEE > 6%

<table>
<thead>
<tr>
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<th>SEE ≤ 6.0% (n=8)</th>
<th>SEE &gt;6.0% (n=10)</th>
<th>p-value</th>
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<tr>
<td>PO peak (W)</td>
<td>47±21</td>
<td>29±12</td>
<td>0.230</td>
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<tr>
<td>HR peak (bpm)</td>
<td>112±28</td>
<td>112±17</td>
<td>0.934</td>
</tr>
<tr>
<td>HRR (bpm)</td>
<td>55±24</td>
<td>51±19</td>
<td>0.729</td>
</tr>
<tr>
<td>VO₂peak (ml/min)</td>
<td>1223±399</td>
<td>1018±341</td>
<td>0.255</td>
</tr>
<tr>
<td>VO₂R (ml/min)</td>
<td>918±373</td>
<td>714±346</td>
<td>0.248</td>
</tr>
</tbody>
</table>

SEE: Standard error of the estimate, PO peak: peak power output, HR peak: peak heart rate, HRR: heart rate reserve, VO₂peak: peak oxygen uptake, VO₂R: oxygen uptake reserve.
The aim of this study was to examine the individual HR-VO₂ relationships in subjects with tetraplegia to answer the question whether HR can be used to quantify exercise intensity in persons with tetraplegia. We found a satisfactory linear relationship in eight out of 18 subjects, indicating that HR is useful in some, but not all persons with tetraplegia.

**Strength of the HR-VO₂ relationship**

According to the ACSM-guidelines a training intensity is prescribed as a range, e.g. training hard within 60-85% HRR or VO₂R. With an estimated training intensity of 72%HRR or VO₂R and a SEE of 6%VO₂R, it can be assumed with 95% confidence that the actual training intensity is between 60-84%. Therefore, in our opinion a SEE of ± 6%VO₂R is acceptable since it keeps training intensity within the required range. Eight out of 18 subjects had a SEE lower than the cut-off-value of 6% and are assumed to have a satisfactory linear HR-VO₂ relationship. All these eight subjects also had a correlation coefficient of 0.90 or higher.

Well trained athletes with paraplegia in studies of Goosey-Tolfrey and Tolfrey (2004) and Tolfrey et al. (2001) showed much higher mean Pearson’s r-values of 0.97± 0.02 and 0.99 ± 0.01 respectively, as well as a lower SEE of 3.4±1.4 and 2.6±1.0 %HRpeak, respectively than subjects in the current study (see Table 3). Two other studies showed lower Pearson’s r-values in subjects with paraplegia, ranging from 0.85-0.99 (Bar-On and Nene, 1990) and 0.74-0.99 (Hooker et al., 1993). Both studies concluded that a linear relationship exists whereas the correlation coefficients, at least in some subjects, were rather low. The mean Pearson’s r-values of our study are comparable with Mc Lean et al. (1995) during arm cranking (mean r = 0.85) and higher than values presented by Coutts et al. (1985) and Schmidt et al. (1998) (r=0.65 and r=0.69 respectively) during wheelchair propulsion. Mc Lean et al. (1995) concluded that HR should not be used for prescribing exercise for individuals with tetraplegia because HR and VO₂ are too variable to accurately reflect the work being done. Unfortunately none of these authors presented their data with a standard deviation or SEE.
The above-mentioned studies indicate that a linear relationship exists in persons with paraplegia below Th4 (Bar-On and Nene, 1990; Goosey-Tolfrey and Tolfrey, 2004; Hooker et al., 1993; Tolfrey et al., 2001), but not in (all) persons with tetraplegia (Coutts et al., 1985; McLean et al., 1995; Schmid et al., 1998). In the current study, the HR-VO$_2$ relationship was found to be linear in only eight out of 18 subjects. The unstable relationship in the other 10 subjects may be explained by the disturbed sympathetic innervation or other factors related to the low physical capacity and muscle mass involved.

The disturbed sympathetic system

Persons with tetraplegia have a low HR$_{\text{peak}}$ and consequently often also a small HRR (HR$_{\text{peak}}$ - HR$_{\text{rest}}$). Our results show that a small HRR or low HR$_{\text{peak}}$, e.g. in subjects 4, 6 and 10 (Figure 1a), does not necessary result in a lower correlation coefficient or a higher SEE, as is shown in table 4. This is not in agreement with McLean et al.(1995) who explained the higher HR-VO$_2$ correlation in the supine position compared to the sitting position, by the significant higher range over which the heart rate can accelerate. The severity of cardiovascular dysfunction after SCI correlates well with the severity of injury to the spinal motor and sensory pathways scored with the AIS (Furlan et al., 2003). Nevertheless in subjects with AIS B and possibly even in AIS A, there is still a chance of survival of some autonomic fibers that extend below injury level. It is unclear from our results, what the influence of the disturbed sympathetic system on heart rate or blood flow and O$_2$ transport to the muscles might have been in our subjects. From the study of Hjeltnes et al.(1998) however, it appeared that the observed arterial PO$_2$ was low, but not the limiting factor during increased work loads in individuals with motor complete tetraplegia.

AD could also be responsible for a disturbed HR-VO$_2$-relationship due to a sudden rise or fall in HR-values. However, subjects were screened before and throughout the test for symptoms of AD and no symptoms occurred. AD should be prevented because in some cases extremely high BP-values can even lead to death from cardiac dysfunction or a stroke (Eltorai et al., 1992).
**Physical capacity**

Two subjects (15 and 16) had to be excluded from further analysis because they were not able to complete more than three blocks, despite very small increments per bout (2 W). A very low physical capacity is often seen in these subjects, especially in (untrained) persons with a C5-C6 lesion. Consequently, the influence of a measurement error (an outlier) or normal fluctuations in VO\textsubscript{2} will be relatively large when only few data points are spread out over a small VO\textsubscript{2}R. This may be a possible explanation for the lower correlation in some subjects (13 and 20, see also Figure 1d). Subject 12 and 17 (Figure 1c), both with a relatively large VO\textsubscript{2}R, are the only subjects from the C5-C6 group with an acceptable Pearson’s r.

However, our results show that a large VO\textsubscript{2}R (e.g. subject 1 in Figure 1b) does not always result in a satisfactory linear relationship as is shown in our results: No significant differences in PO\textsubscript{peak}, VO\textsubscript{2peak} and VO\textsubscript{2}R were found between the 8 subjects with satisfying Pearson’s r and SEE and the other 10 subjects, as is shown in Table 4. On the other hand, it seems that an extremely low physical capacity and VO\textsubscript{2}R always coincidence with an unstable HR-VO\textsubscript{2} relationship (Figure 1).

**Limitations of the study**

It was beyond the scope of the current study to clarify the influence of the disturbed sympathetic system on the individual HR-VO\textsubscript{2} relationship in persons with tetraplegia. However it would be interesting in future to investigate the influence of the sympathetic system on the HR-VO\textsubscript{2} relationship during exercise as well; by measuring blood pressure, catecholamine concentration (Schmid et al., 1998) and blood gas, as was done by Hjeltnes et al. (1998) or by analysing the beat-to-beat heart rate variability (Grimm et al., 1997) or blood pressure variability (Wecht et al., 2000).

Moreover, it should be remarked that in this study we have not looked into the reproducibility of the found regression equations. It may be possible that the day-to-day variability has an influence on the individual regression equations. Even in able-bodied people intra-individual variability can be substantial between days (McCrorry et al., 1997).
Practical implications
Results of this study showed that heart rate is useful in some, but not all, individuals with tetraplegia to monitor training intensity. The Borg-scale may be a possible alternative, indicating the overall perceived exertion. However, the rather low RPE values at the end of the test and the reported local (arm) muscle soreness as reason for stopping, indicate that using the Borg-scale to monitor training intensity has severe limitations for persons with tetraplegia. Another option to monitor training intensity is continuously monitoring of power output and subsequently training at %PO_{peak}. For hand cycling commercially available power measuring crank systems used in cycling, may be suitable. However, to our knowledge the validity and reliability has not been tested in hand cycling at low power output-levels seen in persons with tetraplegia.

Conclusion
From our data it appears that the HR-VO₂ relationship was found to be linear in 8 out of 20 individuals with an acceptable SEE(% VO₂R) ≤6.0% and a r>0.90. Therefore HR can be used in some, but not all, individuals with tetraplegia to monitor training intensity. No single reason such as a low HRR as a consequence of the disturbed autonomic nervous system, AD or the limited physical capacity could be indicated to explain the HR-VO₂ relationship. It is therefore likely that a combination of these factors is responsible for the lack of a linear HR-VO₂ relationship. Our results however, did not allow elucidating the underlying mechanisms why some subjects have, and others do not, have a useful HR-VO₂ relationship. It is concluded that the use of heart rate as an indicator of training intensity should be reconsidered in persons with tetraplegia: An individual analysis of the HR-VO₂ relationship is necessary to determine whether HR can be used to prescribe exercise intensity. Further research should focus on the test-retest-reliability and alternative indicators of training intensity such as % peak power output should be explored.
Chapter 5

The effects of hand cycle training on physical capacity and health-related quality of life in individuals with tetraplegia
ABSTRACT

Objective: To evaluate the effects of a structured hand cycle training program in individuals with chronic tetraplegia.

Design: Pre- (t1) and post (t2) outcome measures on physical capacity and health-related quality of life were compared. In addition, double baseline data (t0, t1) were available for a subgroup.

Setting: Structured hand cycle interval training at home or in a rehabilitation centre in the Netherlands.

Participants: Untrained to moderately trained subjects with tetraplegia; time since injury > 2 yrs (n=22)

Intervention: An 8-12 week hand cycle interval training program

Main outcome measures: Primary outcomes were: peak power output (POpeak) and peak oxygen uptake (VO2peak) as determined in hand cycle peak exercise tests on a motor driven treadmill. Secondary outcome measures were: peak muscle strength of the upper extremities (with hand-held dynamometry), pulmonary function (forced vital capacity and peak expiratory flow) and health-related quality of life (SF36).

Results: We found a statistically significant effect of the structured hand cycle training on physical capacity as reflected by POpeak and VO2peak. Except for abduction, no significant effects were found on muscle strength, spirometric values or quality of life.

Conclusion: Despite dropouts and non-compliance (due to health and practical problems), untrained subjects with tetraplegia were able to improve their physical capacity through regular hand cycle interval training.

Key Words: Spinal cord injury, peak oxygen uptake, peak power output, sub maximal oxygen uptake, muscle strength, pulmonary function.
INTRODUCTION

The physical capacity of most people with a cervical spinal cord injury (SCI) is low (Glaser, 1989). Additional to the complete or incomplete paralysis many other factors may contribute to the low physical capacity of this group. Persons with tetraplegia have a disturbed sympathetic nervous system that might lead to bradycardia, orthostatic hypotension, autonomic dysreflexia, temperature dysregulation and sweating disturbances (Krassioukov et al., 2007). Depending on the location and severity of the lesion, cardiovascular responses to exercise (e.g. increased blood flow to active muscles and vasoconstriction in relatively inactive tissues) may be disturbed (Glaser, 1989; Krassioukov et al., 2007). Secondary complications like urinary tract infections, spasms, pressure sores or overuse injuries in the upper extremity may also lead to inactivity and deconditioning. Other barriers for physical activity are both intrinsic, such as lack of energy or motivation, as well as extrinsic, such as costs, not knowing where to exercise, accessibility of facilities and knowledgeable instructors (Scelza et al., 2005). Interestingly, also concerns that exercise may be too difficult and even health concerns kept those with tetraplegia from exercising (Scelza et al., 2005). Deconditioning may eventually lead to additional health problems such as obesity, diabetes and cardiovascular problems (Myers et al., 2007). Therefore, it is suggested that a certain level of physical activity and fitness is important for persons with tetraplegia to maintain (or even improve) functioning, participation, health and quality of life (Noreau and Shephard, 1995).

Hand-rim wheelchair propulsion and hand cycling (in contrast to arm cranking) are functional modes of regular daily mobility that are assumed to help persons with tetraplegia to maintain a physically active lifestyle. Hand rim wheelchair propulsion is however highly inefficient (Van der Woude et al., 2001) and straining, often leading to upper extremity overuse problems (Curtis et al., 1999). For persons with tetraplegia it may even be difficult to apply a well-directed force during every push (Dallmeijer et al., 1998). For them, hand cycling may be easier to perform than hand rim wheelchair propulsion. The hands are fixed in pedals with special grips and forces can be continuously applied over the full 360° cycle in both push and pull phase. In contrast, during
hand cycle training in persons with tetraplegia

Hand cycle training in persons with tetraplegia

hand rim wheelchair propulsion, force can only be applied in 20-40% of the cycle (Van der Woude et al., 2001). In addition, Dallmeijer et al. (2004) found, in subjects with paraplegia, a higher mechanical efficiency and peak power output in hand cycling compared to hand-rim wheelchair propulsion. According to clinical experience, persons for whom hand rim wheelchair propulsion is too strenuous, appear to be able to hand cycle a few hundred meters after only a few practising sessions.

Only few intervention studies are available on the effects of upper body training in persons with tetraplegia (Valent et al., 2007a). These studies were executed using different modes of arm exercise: arm cranking (DiCarlo, 1988; McLean and Skinner, 1995), wheelchair propulsion (Whiting RB, 1983), circuit resistance training (Cooney and Walker, 1986) or quad rugby (Dallmeijer et al., 1997). Furthermore, the ergonomics of arm cranking in the above-mentioned studies (DiCarlo, 1988; McLean and Skinner, 1995) differs substantially from hand cycling in the current study: i.e. asynchronous arm cranking versus synchronous hand cycling and a high versus low position of the crank axis, respectively.

Except for one training study (Dallmeijer et al., 1997), none of the studies included a (randomised) control group and the effects of training on physical capacity were not consistent (Valent et al., 2007a). Training studies on the effects of hand cycling in persons with SCI are even more scarce with only one study in subjects with paraplegia (Mukherjee et al., 2001) and no studies in subjects with tetraplegia. In a recent observational study on the influence of hand cycling during and one year after clinical rehabilitation, we found clinically relevant improvements in physical capacity (in $P_{O_{peak}}$ and $V_{O_{2peak}}$) in patients with paraplegia during rehabilitation, but not in patients with tetraplegia probably due to small and heterogeneous groups (Valent et al., 2008).

The aim of the present study was to evaluate the effects of a structured hand cycle interval training intervention on physical capacity and health-related quality of life in persons with tetraplegia at least 2 yrs post-injury. It was hypothesized that a structured hand cycle training intervention significantly improves physical work capacity (reflected by the primary outcomes $P_{O_{peak}}$, $V_{O_{2peak}}$ and secondary outcomes pulmonary function and arm muscle strength) and health-related quality of life.
METHODS
Subjects
Former patients with chronic cervical SCI of three Dutch rehabilitation centers were approached to participate in the current training study. Subjects were included if they 1) had been discharged from clinical rehabilitation more than one year ago and had a time since injury (TSI) of at least 2 yrs, 2) had a motor (in)complete C5-C8 lesion, 3) were wheelchair bound 4) received physical training for less than 2 hours a week over the past 3 months, 5) were between 18 and 65 yrs of age, 6) had sufficient knowledge of the Dutch language. A physician medically screened all subjects. Exclusion criteria were: severe (overuse) injuries of the upper extremities, secondary health problems (i.e. pressure sores, bladder infections, cardiovascular diseases or contraindications according to American College of Sports Medicine (ACSM) guidelines) or other medical conditions that did not allow performing physical activity. Approval was obtained from the local Medical Ethics Committee and all subjects signed an informed consent form.

Design
The pre-post training design involved a pre-training test, one week before the start of the 8-12 week training period (t1), and a post-training test, one week after the end of the training period (t2). In a subgroup we had the opportunity to do a control test approximately ten weeks before the start of the training period (t0). The double baseline design in this subgroup thus involved three measurement sessions: t0, t1 and t2. Peak power output and peak oxygen uptake during the hand cycle peak exercise test were the primary outcome measures of physical capacity. In addition, muscle strength, pulmonary function and health-related quality of life were evaluated at all measurement occasions as secondary outcome measures.

Intervention: hand cycling
The add-on hand cycle
Subjects used an add-on hand cycle system (equipped with bull horn shaped cranks and a front wheel) which is coupled to the front of the regular everyday
Hand cycle training in persons with tetraplegia

Hand rim wheelchair. The two small front wheels of the wheelchair are lifted and the hand cycle wheel in front together with the two rear wheels of the wheelchair form the hand cycle. The crank pedals move synchronously with alternating flexion and extension of the arms. In contrast to conventional straight cranks, the wide bullhorn cranks allows the crank axis to be positioned as low as possible, slightly above the upper legs and consequently the pedals can move alongside the knees (in its lowest position). The hand cycle is equipped with gears that can be changed manually or by moving the chin forward/backward to the switches.

Training protocol
Since not all persons in the current study were acquainted with hand cycling, three practice sessions were executed once a week in the three weeks before the control test. The hand cycle interval training protocol was structured in intensity, frequency and duration. For all subjects we aimed at a total of 24 training sessions within a continuous period of 8 to 12 weeks. Those subjects who were using a hand-rim wheelchair as primary mode of mobility were assumed to be able to keep a training frequency of 3 training sessions a week for eight weeks. Those who used an electrical wheelchair were advised to train twice a week for 12 weeks. All subjects were asked to continue there regular other physical activities and to make up for a missed training session if possible. Depending on their personal situation, subjects had the opportunity to train in the rehabilitation centre or at home and both indoors and outdoors. To ensure training in case of bad weather conditions, those who were training at home also received bicycle indoor equipment that was adjusted for hand cycling. The duration of one training session was between 35 and 45 minutes (including a short warming-up and cooling-down session). In the first week of training, the sessions consisted of six repetitions of 3 minutes of hand cycling followed by a 2 minutes rest interval. During the training period the number of repetitions increased to eight and the hand cycle time of each block increased to 4 minutes, while resting time decreased to one minute (Appendix 1). To avoid

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1 Hand cycle attach unit with bullhorn steer: www.doubleperformance.nl

2 Bicycle indoor trainer; Minoura Magturbo: www.minoura.jp
Hand cycle training in persons with tetraplegia

muscle fatigue or injury, at least one day of rest was scheduled in between training days. During training, subjects were monitored on heart rate which allowed them to train according to the prescribed personal heart rate intensity, as well as to evaluate whether the training was well sustainable (Valent et al., 2007b). Training intensity was intended to range between 60-80% heart rate reserve (HRR = HR_{peak} - HR_{rest} as determined during the exercise test). Perceived exertion was monitored using the Borg’s 10 point scale and was intended to range between 4-7 for training (Noble et al., 1983). In order to report pain and/or complaints to the upper extremities immediately after the training sessions as well as to report their rating of perceived exertion on the Borg scale, subjects were asked to keep a training diary. If serious complaints to the upper extremities or illness occurred the subjects were asked to contact the trainer/researcher before continuation of the training.

Outcomes

Physical capacity

Prior to testing, subjects were asked to empty their bladder to help prevent possible bouts of autonomic dysreflexia. Heart rate and oxygen uptake during rest (HR_{rest} and VO_{2rest}) were monitored during five minutes of quiet sitting. Subsequently, subjects were familiarized with the hand cycle on the treadmill and the experimental velocity was adjusted to the ability of the subject, but within the range of 1.11-1.94 m·s^{-1} and a gear setting resulting in a cadence of approximately 60 rpm. Mean sub maximal oxygen uptake (VO_{2submax}) and heart rate (HR_{submax}) were measured at a constant load in the last 30 seconds of a 3-minute sub maximal hand cycle bout. Since velocity and gear were kept the same during all measurement occasions, PO_{submax} was comparable between measurements and a lower VO_{2submax} would indicate an increased mechanical efficiency.

After three minutes of rest, peak power output (PO_{peak}, W), peak oxygen uptake (VO_{2peak}, ml·min^{-1}) and peak heart rate (HR_{peak}, beats·min^{-1}) were determined in a discontinuous graded peak exercise test performed in the hand cycle on a motor-driven treadmill (Appendix 1; Figure 1). Exercise bouts of two minutes

3 treadmill: www.bontetechniek.nl
were interspaced with a rest-period of 30 s. After each exercise step, the workload was increased by adding additional resistance ($F_{add}$) to the back of the hand cycle by means of a pulley system (Dallmeijer et al., 2004). Increments of 2.00-5.25 W (depending on the level of the lesion and the ability of the subject) were imposed until exhaustion was reached or until the subject indicated that he/she wanted to stop. The test protocol was previously described by Valent et al. (2007b). Rolling resistance ($F_{rol}$) of the individual hand cycle-user combination on the treadmill was determined in a drag-test on the treadmill (Van der Woude et al., 1986). The PO was calculated from the separately measured individual drag-force ($F_{rol}$; N), the additional resistance ($F_{add}$; N) and treadmill belt velocity ($v$; m·s$^{-1}$):

$$PO = (F_{rol} + F_{add}) \times v \quad [W]$$

During the test, VO$_2$ was measured continuously with an Oxycon Delta.$^4$ The highest average 30 sec values of PO and VO$_2$ during the test were defined as PO$_{peak}$ and VO$_{2peak}$. Heart rate was continuously monitored with a heart rate monitor$^5$ and HR$_{peak}$ was defined as the highest heart rate recorded in a 5 sec interval. The cardiovascular efficiency, reflected by the oxygen pulse (O$_2$P, ml·beat$^{-1}$) was calculated from VO$_{2peak}$ and HR$_{peak}$ ($O_2P \ [ml \cdot beat^{-1}] = \frac{VO_{2peak} \ [ml \cdot min^{-1}]}{HR_{peak} \ [beats \cdot min^{-1}]}$) (Wasserman K, 1999).

**Muscle strength**

Arm muscle groups (elbow flexion and extension, shoulder exo- and endorotation and abduction) that scored $\geq$ 3 on manual muscle testing (MMT) were tested with hand-held dynamometry (HHD),$^6$ according to a standardized protocol (Andrews et al., 1996). A break test was executed in which the subjects built up a peak force against a dynamometer after which the examiner applied a sufficiently higher resistance to break through it (Phillips et al., 2000). The peak force of the left and right side muscle groups were summed. Only subjects with

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$^4$ Oxycon delta: www.viasyshealthcare.com
$^5$ HR-monitor Polar: www.polar-nederland.nl
$^6$ Microfet: www.biometrics.nl
a strength-score for both left and right side for a certain muscle group were included in the strength analysis.

Pulmonary function
To assess training effects on pulmonary function we measured and analysed simple spirometric values with the Oxycon Delta.\textsuperscript{4} Forced vital capacity (FVC) and the peak expiratory flow (PEF) were recorded both in ml·min\textsuperscript{-1} and relative to the age, gender and body weight corrected norm population (%).

Health-related quality of life
Health-related quality of life (QOL) (Wood-Dauphinee et al., 2002) was scored on three out of eight domains of the SF-36: Mental Health, Vitality and perceived General Health.

Adverse effects
Pain to the upper extremities (the musculoskeletal system) was scored before and after the training period with a self-designed questionnaire on a 5 point scale (with 1= not serious and 5 =very serious) (Van Drongelen et al., 2006). We scored shoulders, elbows and wrists separately, but the scores for left and right were summed. A questionnaire was also used to score possible other training and/or exercise-related complaints (not to the musculoskeletal system) on items such as abundant sweating, not being able to sweat, numb feeling, itchiness, too cold, too hot.

Statistical analyses
The change between the pre- and post-training outcome measures was examined using a two-tailed Students’ paired t-tests (p< 0.05). In addition, for those subjects of the subgroup who completed the double baseline design, a paired t-test was performed to compare the differences between the changes in outcome measures over the training period (t2-t1) with the change over the preceding non-training control period (t1-t0) (p< 0.05).
RESULTS

Subjects

22 subjects were included in this training study (Table 1).

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<th>Subject</th>
<th>Gend</th>
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<th>Weight</th>
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<td>60</td>
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<td>El</td>
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<td>(10)</td>
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<td>m</td>
<td>51</td>
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<td>110</td>
<td>C6</td>
<td>Th1</td>
<td>A</td>
<td>Hr</td>
<td>Yes</td>
<td>-</td>
</tr>
</tbody>
</table>

| Mean    | 39  | 10  | 81   |       | 8    | 19    | 42.5 | 50.9 | 1.32 | 1.43  |
| Sd      | 12  | 7   | 17   |       | 1    | 3     | 21.9 | 25.4 | 0.40 | 0.43  |


Five out of 22 subjects were moderately active (1.5 hours a week) and all other subjects were not or minimally physically active. 15 out of 22 subjects completed the training period (t1-t2): 8 subjects performed the pre- (t1) and post-training (t2) tests and 7 subjects (#1-7) also performed an additional control test (t0). Seven out of 22 subjects dropped out during the training period due to various reasons: problems with transportation to the training facility (#18), a chronic urinary tract infection (#19), persistent bowel problems combined with spasms (#20), pressure ulcers as a consequence of a fall out of the wheelchair at home (#21), work-related overuse injury to the elbow (#22), serious pain as a consequence of bowel problems (#17) and because of illness.
Hand cycle training in persons with tetraplegia

No significant differences were found in personal and lesion characteristics between the seven subjects who dropped-out (Table 1) and those who completed the training (n=15); age: 43±13 vs. 38 ± 11 yrs, TSI: 9 ± 7 vs. 10 ± 8 yrs, body mass: 87.4 ± 22.2 vs.78.2. ± 13.3 kg, number of subjects with lesion level: C5:2, C6:3, C7:1 and C8:1 (n=7) vs. C5:3, C6:6, C7:4 and C8:2 (n=15), number of subjects with AIS (Marino et al., 2003): A:3, B:4, C:0 and D:0 (n=7) vs. A:3, B:9, C:1 and D:1 (n=15), respectively. The differences between the dropouts and the subjects who completed the training in baseline-values for the main outcome measures POpeak and VO2peak were: 26.5± 7.2 W versus 42.5 ± 21.9 W (p=0.099) and 0.93 ± 0.25 versus 1.32±0.40 L/min (p=0.04). This suggests a somewhat better physical work capacity at baseline for the subjects that completed the training.

Training

Protocol

It turned out to be difficult for the subjects to complete 24 training sessions within the given period (Table 1). The mean number of completed sessions for the training group (n=15) was 20 (± 3) and 5 subjects missed 5-7 sessions which is more than 20% of all training sessions. Main reasons reported for missing or postponing training sessions were: not feeling well because of an illness (urinary tract infection, flu), transportation problems, too busy (with work) or too tired, no persons available to help starting up training (especially for those with high tetraplegia who were training at home). Overuse injuries were not mentioned as reason for missing a training session although three subjects were advised once to postpone the training with one day and/or to train at a lower intensity (or gear) during the next session, to prevent the possible development of such overuse complaints.

The distances covered during the hand cycling training sessions improved over time and varied from 2-7 km. All subjects managed to train (n=15) between 60-80% HRR on average (with the 1-2 minute rest intervals included). During the 3-4 minute hand cycle intervals the HR was between 70-80% HRR. A mean intensity of 6 (±1) on the 10-point Borg-scale was reported after training compared to 7(±2) after completing the peak exercise test. Especially, subjects with a very limited active muscle mass and a high body mass, who were already
exerting at a near maximal level when moving the hand cycle forward, had to use the hand cycle indoor trainer. The adjustable and low initial power level - possible with the use of an indoor trainer- allowed them to train within the anticipated intensity range during the initial phase of the training. After 4-6 weeks of training all subjects who completed the training were able to train outside at the suggested intensity (without the indoor trainer).

**Adverse effects**

The training (n=15) was never stopped because of pain complaints to the arms and/or shoulders. Comparing pre- and post-training (and within the double baseline group), no increase in subjective pain scores around wrists or elbows was found. Three subjects (# 3, 6 and 11) out of 15 reported a slightly higher shoulder pain score post-training compared to pre-training. All three mentioned that this was muscle soreness as a consequence of training too hard (with a (too) high gear setting) and the pain disappeared gradually within one day after training. From the questionnaire ‘other experienced physical pain complaints’ it appeared that three subjects (# 5, 6 and 14) felt substantially less cold below lesion level after the training period compared to baseline, which was regarded positive. Other than that, no differences were seen in severity of other complaints.
Outcomes

Hand cycle capacity

Table 2 presents the results of the pre-post-test outcomes (n=15).

<table>
<thead>
<tr>
<th>Physical Capacity</th>
<th>Pre-training t1</th>
<th>Post-training t2</th>
<th>Difference (t2-t1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hand cycle capacity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PO peak (W)</td>
<td>15</td>
<td>42.5 (21.9)</td>
<td>50.8 (25.4)</td>
</tr>
<tr>
<td>VO2peak (ml·min⁻¹)</td>
<td>15</td>
<td>1317 (399)</td>
<td>1431 (427)</td>
</tr>
<tr>
<td>VO2peak (ml·kg⁻¹·min⁻¹)</td>
<td>14</td>
<td>17.3 (5.2)</td>
<td>19.1 (5.7)</td>
</tr>
<tr>
<td>O2P peak (ml·beat⁻¹)</td>
<td>14</td>
<td>10.7 (2.8)</td>
<td>12.0 (4.0)</td>
</tr>
<tr>
<td>VE peak (L·min⁻¹)</td>
<td>15</td>
<td>52.0 (17.3)</td>
<td>54.9 (19.2)</td>
</tr>
<tr>
<td>RER peak</td>
<td>15</td>
<td>1.10 (0.16)</td>
<td>1.10 (0.14)</td>
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<tr>
<td>VO2submax (ml·min⁻¹)</td>
<td>14</td>
<td>834 (116)</td>
<td>761 (58)</td>
</tr>
<tr>
<td>HRsubmax (bpm)</td>
<td>14</td>
<td>92 (17)</td>
<td>88 (18)</td>
</tr>
<tr>
<td>HRrest (bpm)</td>
<td>14</td>
<td>61 (13)</td>
<td>66 (13)</td>
</tr>
<tr>
<td>VO2rest (ml·min⁻¹)</td>
<td>14</td>
<td>347 (59)</td>
<td>345 (35)</td>
</tr>
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Muscle strength (HHD)

<table>
<thead>
<tr>
<th>Muscle function</th>
<th>Pre-training t1</th>
<th>Post-training t2</th>
<th>Difference (t2-t1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>extension (L+R) (N)</td>
<td>8</td>
<td>331 (99)</td>
<td>321 (96)</td>
</tr>
<tr>
<td>flexion (L+R) (N)</td>
<td>15</td>
<td>571 (176)</td>
<td>578 (177)</td>
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<tr>
<td>Endorotation (L+R) (N)</td>
<td>12</td>
<td>358 (130)</td>
<td>360 (118)</td>
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<tr>
<td>exorotation (L+R) (N)</td>
<td>14</td>
<td>294 (101)</td>
<td>304 (177)</td>
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<tr>
<td>abduction (L+R) (N)</td>
<td>15</td>
<td>336 (86)</td>
<td>355 (80)</td>
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Pulmonary function

<table>
<thead>
<tr>
<th>Pulmonary function</th>
<th>Pre-training t1</th>
<th>Post-training t2</th>
<th>Difference (t2-t1)</th>
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</thead>
<tbody>
<tr>
<td>FVC (L·min⁻¹)</td>
<td>15</td>
<td>3.80 (1.24)</td>
<td>3.82 (1.21)</td>
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<tr>
<td>(%)</td>
<td>15</td>
<td>75.5 (15.4)</td>
<td>76.8 (17)</td>
</tr>
<tr>
<td>PEF (L·min⁻¹)</td>
<td>15</td>
<td>6.52 (2.23)</td>
<td>6.14 (2.00)</td>
</tr>
<tr>
<td>(%)</td>
<td>15</td>
<td>70.0 (21.3)</td>
<td>66.3 (18.9)</td>
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QOL SF-36

<table>
<thead>
<tr>
<th>QOL SF-36</th>
<th>Pre-training t1</th>
<th>Post-training t2</th>
<th>Difference (t2-t1)</th>
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</thead>
<tbody>
<tr>
<td>General health (%)</td>
<td>14</td>
<td>74 (20)</td>
<td>77 (21)</td>
</tr>
<tr>
<td>Mental health (%)</td>
<td>14</td>
<td>74 (13)</td>
<td>79 (9)</td>
</tr>
<tr>
<td>Vitality (%)</td>
<td>14</td>
<td>65 (15)</td>
<td>69 (9)</td>
</tr>
</tbody>
</table>

CI: confidence interval, PO peak: peak power output, VO2peak: Peak oxygen uptake, O2P peak: peak oxygen pulse =, VO2submax: sub maximal oxygen uptake, HRsubmax: submaximal heart rate, HRrest: rest Heart rate, VO2rest: rest oxygen uptake, RER: respiratory exchange ratio, VE: ventilation, HHD: Hand held dynamometry, QOL: Quality of life: % of maximal score. For some outcome measures of hand cycle capacity data was missing in one (but not the same) subject due to measurement errors. Muscle strength was not available in subjects for all muscle groups (as they scored less than 3 on MMT or not feasible due to pain).

Mean RER was 1.10 in both pre and post-test suggesting that, in general, peak capacity VO2 was reached. VO2peak significantly improved on average 114 (±204) ml·min⁻¹ after training which was an increase of 8.7 (±13.9) % (n=15; Table 2). Also, a significant improvement in PO peak of 8.3 (±5.8) W was found after training, which was an increase of 20.2 (±15.0) %.

No significant improvement in O2P:1.3 (±0.2) (p=0.06) was seen in the pre-post-training comparison (n=14; Table 2). As expected, HRpeak (n=14) did not change
between pre- (128 (±24) b·min⁻¹) and post-training (127 (±27) b·min⁻¹). A significant decrease in sub maximal oxygen uptake during hand cycling of 73 ± 122 ml·min⁻¹ (8.8 ± (14.6) %) (p=0.04) was found (n=14; Table 2) at a constant power output, indicating an improved gross mechanical efficiency during hand cycling. No differences in VO₂rest were found due to training. In contrast, HRrest appeared to be significantly higher after training in the pre-post group (n=14; Table 2).

Secondary outcomes
Of all arm muscle groups, only shoulder abduction strength improved significantly at the post-training measurement (5.6 (±11) %; table 2). No effects of hand cycle training were found on pulmonary function outcome measures and on any of the health-related quality of life variables: general health, mental health and vitality.

Double baseline data
When comparing the change in outcomes between the training period and the control period in the small double baseline group (n=7), a significant improvement in VO₂peak (p=0.045) was found with +188 (± 200) ml·min⁻¹ (15.5 (±15.7) %) vs. 0 (± 164) ml·min⁻¹ (0 (± 13.8) %). No significant improvement in POpeak (p=0.06) was found after training: +8.0 (± 4.5) W (20.3 (± 11.4) %) as compared to +2.7 (± 5.7) W (7.0 (± 14.9) %) for the control period. No training effects in O₂P, HRpeak or VO₂submax were found when controlling for difference over the baseline period. A significant difference in HRrest was found: +8 (± 9) beats·min⁻¹ over the training period compared to -6 (± 6) beats·min⁻¹ (p=0.004) over the double baseline period. Small but significant improvements were found in shoulder exorotation: 4.3 (± 2.7) % vs. -3.3 (± 4.3) % and elbow flexion: 4.2 (± 4.7) % vs. -1.8 (± 3.3) % in the respective training and double baseline periods.
DISCUSSION
Structured hand cycle interval training showed significant positive effects on the primary outcomes of physical capacity ($P_{O_{peak}}$, $V_{O_{2peak}}$). On the majority of the other outcome measures, no significant effects were found. As is demonstrated in the current study, people with tetraplegia can improve their physical work capacity in a structured way, but the relatively high number of drop-outs and missed training sessions show that maintaining the training schedule is difficult in this group.

Training
We aimed at including untrained subjects with tetraplegia and encountered a relatively high dropout of approximately 30%. It appeared that the dropouts had a lower physical capacity at baseline compared to the subjects who completed the training period. The low physical capacity in the dropouts may have been a result of a (long) history of health problems that prevented them from maintaining their fitness level. Furthermore, persons with a relatively low physical capacity, regardless of lesion level, may be more vulnerable and thus more prone to develop health problems. On the other hand, health problems, although less severe, were also responsible for the high non-compliance rate found in the subjects who were training. It should be noted that health problems in both dropouts and training subjects were not related to the training. Therefore, (untrained) people with tetraplegia are vulnerable (Ginis and Hicks, 2005) and health-problems are likely to interfere with their life and thus also during a training period.

Protocol
From a preceding pilot project in untrained subjects with tetraplegia, interval training appeared to be more suitable than continuous aerobic training; Most of our pilot-subjects were not able to hand cycle continuously for more than approximately 5-7 minutes whereas several hand cycle blocks of 3 minutes, with rest in between, were well sustainable. Based on observation, subjects really needed the rest periods between the bouts of hand cycling in order to prevent extreme muscle fatigue and to delay muscle soreness. Therefore an interval-training (and discontinuous test) protocol was designed, which evidently
allowed more people with tetraplegia to start and maintain the training scheme, even those with a very limited fitness at the start. Of all subjects entering the study (n=22), those who successfully completed the training (n=15) were able to train within 60-80%HRR, although some only with an indoor trainer during the first weeks of training. This intensity is within the range of 50-90% HRR, HR_{peak} and PO_{peak} imposed in previous upper body training studies in persons with tetraplegia (Valent et al., 2007a). The broad range (60-80%HRR) accounts for the variety in intensity common during interval-training, but also for the extremely low HRR as a consequence of the disturbed innervation of the heart resulting in a low HR_{peak} in persons with tetraplegia (Valent et al., 2007b).

**Adverse effects**

In about 40% of the subjects, light to moderate pain to the upper extremities was already present before they were included, although this never involved serious pain. Pain to the upper extremities, especially to the shoulder, is common in persons with tetraplegia with a prevalence between 40-70% (Curtis et al., 1999; Van Drongelen et al., 2006). Moreover, they are at higher risk of developing musculoskeletal pain as a consequence of partial paralysis of thoraco-humeral muscles and imbalance in shoulder muscles (Curtis et al., 1999). In this study, shoulder pain involved soreness to muscles around the shoulders and it appeared to be a temporarily consequence of training. In addition, we noticed that two out of three subjects with shoulder complaints (#2 and 3) were the only subjects out of 22 who were using conventional straight cranks (with a high positioned crank axis). They were forced to move their arms (further) against gravity above shoulder level, which may be disadvantageous for the shoulders. In training studies executed with arm cranking in subjects with tetraplegia the pedal axis was aligned with the midpoint of the subject’s sternum (McLean and Skinner, 1995) or with shoulder level (DiCarlo, 1988), while (except for these two subjects) in the current study the highest position was at or below shoulder level.

We believe that hand cycling with a well-adjusted hand cycle offers a suitable mode of exercise, although the risk of over-use injuries is always present in persons with tetraplegia when being active. Especially untrained subjects with complete tetraplegia (with a low active muscle mass) may be extra prone to
injuries to muscles and tendons. For example, we saw that, despite instructions, our subjects tended to cycle with high(er) gears instead of high(er) pedal frequencies. Cycling at a high gear may be a potential overload for the musculoskeletal system but is not reflected by exercise intensity (HRR). Therefore, especially in the first weeks of training, supervision is recommended.

Outcomes

Hand cycle capacity

The primary outcome measures in the study, PO\textsubscript{peak} and VO\textsubscript{2peak}, showed significant improvements over the training period. In the current study we also controlled for possible natural variations over time and test-learning effects for a subgroup. The training effects found on our primary outcome measures were upheld in the double baseline subgroup. Although some effects on secondary outcome measures were not confirmed. For example, our submaximal oxygen uptake improved according to the pre-post test design, which was in agreement with Mukherjee et al. (2001). However, when analyzing the double-baseline subgroup no effect was found.

Table 1 shows the large inter-individual differences in our main outcomes and clearly an improvement of 8 W after training is more substantial for someone with a baseline-value of 16 W than for someone with a baseline of 60 W. Moreover, it is difficult to compare absolute gains in PO\textsubscript{peak} and VO\textsubscript{2peak} with literature when different test devices and protocols have been used and with subject with different training status (Valent et al., 2007a). The relative gains of 20.2% in PO\textsubscript{peak} and 8.7% in VO\textsubscript{2peak} in the present study were in agreement with McLean and Skinner (1995), who found gains of 13.7% and 8.3% respectively. Their untrained subjects with tetraplegia were arm crank exercising at an intensity of 60% of PO\textsubscript{peak}, 3 times weekly for 10 weeks. In another study on arm crank exercise in young persons with tetraplegia, gains were found of 23.8% in PO\textsubscript{peak} and 99% in VO\textsubscript{2peak} (DiCarlo, 1988) Cooney and Walker (1986) trained 5 subjects with tetraplegia (and 5 with paraplegia) and found gains in PO\textsubscript{peak} and VO\textsubscript{2peak} of 57 and 30% respectively. Their subjects, with unknown training status, performed circuit resistance training, 30 a 40 minutes 3 times weekly for 9 weeks. Dallmeijer et al. (1997) did not find any significant improvements in PO\textsubscript{peak} and VO\textsubscript{2peak} after quad rugby training.
However, this study involved only one training session a week. During clinical rehabilitation, Hjeltnes and Walberg-Henriksson (1998) found significant gains in \( \text{PO}_{\text{peak}} \) but no improvements in \( \text{VO}_{2\text{peak}} \).

The question remains how much improvement is clinically relevant. According to Brehm et al. (2004), 10% is considered to be a meaningful change and therefore the improvement in \( \text{PO}_{\text{peak}} \) in the current study is designated clinically relevant and the change in \( \text{VO}_{2\text{peak}} \) as near to clinically relevant.

The gains in work capacity express the ability to improve fitness in those with tetraplegia. The effects of hand cycle training will probably be primarily local and not necessarily central, given the extremely low muscle mass that is actively involved in the exercise in this population (Glaser, 1989). The greater relative increase (20.2%) in \( \text{PO}_{\text{peak}} \) (as compared to \( \text{VO}_{2\text{peak}} \) (8.7%)), indicates an improvement in gross mechanical efficiency (De Groot et al., 2002), i.e. effects in (reduced co-contraction as part of) muscle coordination of the arms and shoulders, as well as in the external force production.

**Muscle strength**

We only found some minor (borderline) significant improvements in muscle strength (shoulder abduction, elbow flexion and shoulder exorotation) after hand cycling, which were not considered clinically relevant. In general however, subjects reported to feel stronger. A possible explanation may be that muscle endurance has improved but not isometric peak strength (which we had measured).

**Pulmonary function**

We did not find any improvements in FVC or PEF. From literature however, it appears that the effects of upper body training on pulmonary function in persons with high paraplegia and tetraplegia are not uniform (Crane et al., 1994; Gass et al., 1980; Valent et al., 2007a).

**Quality of life**

Probably, the small sample size as well as the short period of training in the current study hampered a functional change in health-related quality of life as a possible consequence of increased fitness. Hicks et al (2003) found a
significant improvement on quality of life after nine months of exercise training compared to a randomised control group, which however is a considerably longer training period compared to the current study. A significant association is assumed between physical fitness and outcomes on quality of life, well-being and participation (Noreau and Shephard, 1995).

\( HR_{\text{rest}} \)

Although \( HR_{\text{rest}} \) was not an intended outcome of the current study, it is interesting to note that a consistent increase in \( HR_{\text{rest}} \) was found after training, which is in agreement with previous training studies in subjects with tetraplegia (McLean and Skinner, 1995; Phillips et al., 1989). In untrained individuals without SCI, a decrease in \( HR_{\text{rest}} \) can be expected as a consequence of aerobic training (Wilmore et al., 2001). The higher \( HR_{\text{rest}} \) may have been the result of a central adaptation to the hormonal system induced by training, resulting in an increase in sympathetic drive or a decrease in parasympathetic tone (Phillips et al., 1989). This adaptation may have been triggered by an increase in the resting metabolic rate, resulting in an increased blood circulation, reflected by a higher \( HR_{\text{rest}} \). The fact that some subjects reported to feel less cold during the day, since they were hand cycle training is in line with this. On the other hand, we did not find an increase in \( VO_2_{\text{rest}} \) to support this hypothesis. Finally, a higher \( HR_{\text{rest}} \) due to overtraining did not seem likely when taking into account the unchanged scores on vitality (e.g. fatigue and exhaustion).

**Study limitations**

The most optimal study design (a RCT) was not feasible due to the small number of available subjects. Another limitation is the variability in (baseline) physical capacity between subjects. However, coalescing subgroups to reduce variability is hampered by the small sample size.

The number of drop-outs and non-compliance due to circumstances is considerable, but not uncommon in training studies in persons with tetraplegia (Valent et al., 2007a). Due to dropouts, the subject group serving as their own controls (n=7) was small to perform statistical analysis of a double baseline group.
Our subjects trained less than the planned number of training sessions (which may have had a negative effect on the results) but nevertheless, an effect was found on the primary outcomes of physical capacity.

**Recommendations**

When prescribing a hand cycle training program for vulnerable persons with tetraplegia, an interval-training protocol at 60-80%HRR (8-12 weeks, 2-3 sessions a week) appears appropriate to prevent the occurrence of serious muscle fatigue and over-use injuries. Depending on the activity level in the preceding period and the abilities of the individual with tetraplegia, the training frequency and intensity should be adjusted and build up gradually, preferably over a longer period. It may be worth considering starting hand cycle training already during (early) rehabilitation as part of a healthy active lifestyle program to learn and accommodate individuals to the importance of exercise and to learn to cope with the personal and practical barriers in an early stage. Training after conclusion of rehabilitation and under the supervision of the rehabilitation center or other local specialized personal can help maintain motivation and prevent and/or reduce personal barriers.

The literature on upper body training effects in subjects with SCI really lacks sufficient attention to those with tetraplegia (Valent et al., 2007a). Therefore, future research should focus on the optimization of training protocols specifically designed for persons with tetraplegia and on the ergonomic design of the hand cycle in those individuals.

**In conclusion**

Taking into account the dropouts in the current study, hand cycle training in subjects with tetraplegia is most likely to be successful in those with a relatively higher baseline physical capacity. However, also subjects who were training appeared to be vulnerable due to health reasons. In spite of non-compliance, the training subjects were able to improve their physical capacity, reflected by peak power output and oxygen uptake, even after a relatively short training period of 8-12 weeks. Marginal effects were found on muscle strength of the upper extremities and hand cycle efficiency. No effects of hand cycle training were found on pulmonary function and health-related quality of life. Larger study
groups are required here. Finally, due to training all subjects were able to hand cycle distances outside, indicating the potential of the hand cycle for daily ambulation as well as for a physically active lifestyle.

Acknowledgements
We thank the Netherlands Organisation for Health, Research and Development ZON-MW who supported this study (grant number: 014-32-012), in The Hague. Furthermore, we thank all subjects for their enthusiastic participation and the trainers in the rehabilitation centers Heliomare, RCA and the Hoogstraat for their help with the training sessions.
Appendix 1

Training protocol:

<table>
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<tr>
<th>Week 1</th>
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<th>Week 5</th>
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Figure 1: Hand cycle test
Chapter 6

Effects of hand cycle training on wheelchair capacity during clinical rehabilitation in persons with spinal cord injury
ABSTRACT

Objective: To evaluate the effects of a structured hand cycle training program on physical capacity in subjects with spinal cord injury (SCI) during clinical rehabilitation.

Design: Twenty subjects who followed hand cycle training were compared with matched control subjects from a Dutch longitudinal cohort study, who received usual care.

Setting: Two rehabilitation centres in the Netherlands.

Participants: \( n = 20 \) patients with SCI

Intervention: A hand cycle training program (twice a week) in addition to usual care

Main outcome measures: Primary outcomes of hand rim wheelchair capacity were: peak power output (PO_{peak}), peak oxygen uptake (VO_{2peak}) and oxygen pulse. Secondary outcome measures were: isometric peak muscle strength of the upper extremities and pulmonary function. Hand cycle capacity was evaluated in the training group only.

Results: Strong tendencies for improvement were found in wheelchair capacity, reflected by PO_{peak} and oxygen pulse after additional hand cycle training. Significant effects on shoulder exo- and endo-rotation and unilateral elbow flexion strength were found but no improvements on pulmonary function.

Conclusion: Additional hand cycle training during clinical rehabilitation seems to show similar or slightly favourable results on fitness and muscle strength compared with regular care. The heterogeneous subject group and large variation in training period may explain the lack of significant effects of additional hand cycle training on wheelchair capacity.

Keywords
Clinical rehabilitation, spinal cord injury, peak oxygen uptake, peak power output, muscle strength, pulmonary function, hand cycling.
INTRODUCTION
Clinical rehabilitation of persons with spinal cord injury (SCI) primarily focuses on achieving functional goals that contribute to a satisfactory degree of independence, participation and quality of life after discharge (Noreau and Shephard, 1995). Daily activity, however, may impose a peak strain on the upper body in persons with SCI, especially in those with tetraplegia. They generally have an extremely low physical capacity (Glaser, 1989) due to the low active muscle mass, the imbalance in thoracohumeral muscle strength (Curtis et al., 1999) and the disturbed autonomic nervous system. To deal with the strain of daily activities, it is important for persons with SCI to optimize physical capacity through regular exercise (Janssen et al., 1994). Moreover, wheelchair-bound persons are at a higher risk for secondary health problems such as pressure sores, urinary tract infections, obesity, metabolic syndrome, diabetes and cardiovascular diseases (Myers et al., 2007). Physical activity and training can help prevent some of these long-term problems. Therefore, clinical rehabilitation should not only focus on achieving functional goals but also strive for the highest possible fitness level, preferably leading to adoption of an active lifestyle (Fernhall et al., 2008). During clinical rehabilitation, various aerobic exercise modes are available to improve the physical capacity of patients with SCI: swimming, wheelchair training, fitness, and different sports such as wheelchair basketball and tennis. Not all these activities are appropriate for patients with low ability levels and at the start of active clinical rehabilitation. For example, hand rim wheelchair propulsion is a very strenuous activity because of the peak forces that occur in the shoulder and wrist joints during the short push phase (Van der Woude et al., 2001; Van Drongelen et al., 2006). Furthermore, several exercise activities (e.g. swimming) cannot always easily be performed in the own environment after discharge.

In the past decade, the add-on hand cycle has become popular for mobility and recreation in the Netherlands. Consequently hand cycling more and more is becoming an integrated part of the Dutch rehabilitation program (Valent et al., 2008; Van der Woude et al., 1986). Compared to hand rim wheelchair propulsion, hand cycling is less straining and more efficient (Dallmeijer et al., 2004b). Moreover, with the hands fixed in pedals during the full 360° cycle, forces are continuously applied in contrast to the short and technically difficult
repeated push in hand rim wheelchair propulsion (Dallmeijer et al., 1998). Therefore, hand cycling is assumed to be suitable for people with SCI during (and after) clinical rehabilitation. Two previous studies showed positive effects of hand cycle training after clinical rehabilitation in subjects with paraplegia (Mukherjee et al., 2001) and tetraplegia (Valent et al., submitted). A previous observational study evaluated the influence of hand cycling on physical capacity during clinical rehabilitation (Valent et al., 2008). After correction for baseline values and confounders (personal and lesion characteristics), a clinically relevant improvement in wheelchair capacity was found in the hand cycle group, compared to the controls. Until today, no controlled hand cycle training studies during clinical rehabilitation are available.

Based on previous studies (Valent et al., submitted; 2008), we assume that hand cycle training during clinical rehabilitation leads to both a higher hand cycling capacity and hand rim wheelchair exercise capacity. Training effects on both are expected as we assume that most upper body muscles that are active in hand cycling are also used for hand rim wheelchair propulsion.

In the current study the following hypothesis was tested: When compared to regular care, a controlled structured hand cycling program has a positive effect on wheelchair exercise capacity in subjects with SCI during clinical rehabilitation.

**METHODS**

**Subjects**

**Experimental subjects**

Patients of two Dutch rehabilitation centers were approached to participate in the current study. They were included if they: 1) had an acute SCI; 2) had a prognosis of ‘remaining mainly wheelchair-bound;’ 3) had a lesion level of C5 or lower (and consequently were expected to be able to propel a hand cycle); 4) were aged between 18 and 65 years; 5) had sufficient knowledge of the Dutch language; and 6) did not have a progressive disease or psychiatric problem; 7) were free of halo-frames or corset; 8) were made familiar with hand cycling and agreed to participate according the training protocol. Patients were excluded if they had cardiovascular contra-indications, serious musculoskeletal complaints,
or other medical complications that contra indicate exercise. After being informed about the study, the patients signed a written consent voluntarily.

**Control subjects**

The matched control group was selected from a large Dutch cohort study on restoration of mobility in SCI rehabilitation who received regular care (Haisma et al., 2006). Matching was based on personal and lesion characteristics (Haisma et al., 2006): age (preferably within +/-5 years and otherwise +/- 10 years), gender (male or female), lesion level (paraplegia, tetraplegia at C5 or C6, tetraplegia at C7 or C8) and motor completeness of lesion (yes or no). Subjects who were hand cycling more than once a week were excluded and data had to be available for the wheelchair maximal exercise test at the same measurement occasions (at baseline and follow-up) as for the experimental case. Finally, if more than one subject complied with these characteristics, the control subject with a baseline peak power output \( (P_{O_{peak}}) \) most close to the baseline value of the experimental matching counterpart was chosen. This procedure was followed for all individual experimental subjects. To ensure comparable groups of subjects at pre and post-test, missing data of any of the outcomes for one of the two matched subjects led to exclusion of that pair on that outcome.

**Design**

Experimental subjects received hand cycle training in addition to regular care and the control subjects only received regular care (preferably without hand cycling or only occasionally). The research design included two measurement occasions: the first measurement occasion was in the week before the start of the hand cycle training program. For patients with paraplegia this was at the start of the active rehabilitation, which is defined as the moment when subjects were able to sit for 3 hours (Dallmeijer et al., 2005). Subjects with paraplegia had to start 6 weeks or 3 months later in case of halo-frames. Subjects with tetraplegia started three months after the start of active rehabilitation, because they were generally not able to perform the wheelchair test earlier in the rehabilitation period (Haisma et al., 2006). For all subjects the second measurement occasion was in the week before discharge. Outcome measures of physical capacity (wheelchair exercise capacity, muscle strength and
pulmonary function) were compared between hand cycling subjects and matched control subjects. The training group also performed a graded hand cycle capacity test, which allowed us to compare pre- and post-training.

**Testing Procedure**

**Physical capacity**

*Wheelchair exercise capacity*

To determine the peak power output (PO\text{peak}, W) and peak oxygen uptake (VO\text{2peak}, ml·min\(^{-1}\)), a graded hand-rim wheelchair exercise test was performed on a motor-driven treadmill pre and post training in both experimental subjects and controls.\(^1\) The test protocol was previously described by Kilkens et al. (2005). During the test, the velocity of the belt was maintained constant at 0.56, 0.83 or 1.11 m·s\(^{-1}\) depending on the level of the lesion and the ability of the subject. The workload was raised every minute by increasing the slope of the belt by 0.36 degrees. The test was ended when the subject was no longer able to maintain the position and speed on the belt. The PO\text{peak} was calculated from the individual drag force and treadmill belt velocity, as described by Van der Woude et al. (1986). The VO\text{2} was continuously measured during the test with an Oxycon Delta.\(^2\) The highest values of PO and VO\text{2} maintained during the same 30 second period during the test were defined as PO\text{peak} and VO\text{2peak} respectively. Heart rate was continuously monitored with a heart rate monitor.\(^3\) The cardiovascular efficiency, reflected by oxygen pulse (O\text{2P}, ml·beat\(^{-1}\)) was calculated from VO\text{2peak} and HR\text{peak}. O\text{2P} [ml·beat\(^{-1}\)] = VO\text{2peak} [ml · min\(^{-1}\)] / HR\text{peak}[beats · min\(^{-1}\)] (Wasserman K, 1999). Respiratory exchange ratio (RER) was calculated as the ratio between CO\text{2} and VO\text{2}.

**Muscle strength**

Left and right arm muscle groups (shoulder abduction, exo- and endo-rotation and elbow flexion and extension) that scored \(\geq 3\) on manual muscle testing (MMT) were tested with a hand-held dynamometer (HHD),\(^4\) according to a standardized protocol (Andrews et al., 1996). A break test was executed:

\(^1\) treadmill: www.bontetechniek.nl

\(^2\) Oxycon delta: www.viasyshealthcare.com

\(^3\) HR-monitor Polar: www.polar-nederland.nl
Hand cycle training during rehabilitation

Subjects had to build up a maximal force against a dynamometer after which the examiner applied a higher resistance to break through it (Phillips et al., 2000).

Pulmonary function
To assess pulmonary function, we measured and analysed the flow-volume curves with the Oxycon Delta. Forced vital capacity (FVC) and the peak expiratory flow rate (PEFR) were recorded both absolute in ml·min⁻¹ and relative to the age, gender and body weight corrected norm population (%).

Hand cycle capacity
To determine hand cycling capacity, reflected by PO peak and VO₂peak, an additional discontinuous graded hand cycle exercise test was executed 2-3 days after the wheelchair peak exercise test on a motor driven treadmill. The test protocol was previously described by Valent et al. (2007). The experimental velocity was adjusted to the ability of the subject, but within the range of 1.11-1.94 m·s⁻¹ and a gear setting resulting in a cadence of approximately 60 rpm. Exercise bouts of two minutes were interspaced with a rest period of 30 s. Each exercise step the workload was increased with 2.00-5.25 W using a pulley system (Valent et al., 2007) until exhaustion was reached. VO₂ and HR were measured continuously during the test.

Training
The add-on hand cycle
The wheelchair-hand cycle unit was provided by the rehabilitation centre and adapted to the anthropometry of the individual. The add-on hand cycle unit (executed with cranks and a wheel) can be attached to the front of the hand rim wheelchair. The crank pedals move synchronously with alternating elbow/shoulder flexion and extension of both arms. Most of our hand cycles were equipped with wide bull-horn cranks which allow positioning of the crank axis as low as possible, slightly above the upper legs and consequently the pedals can move alongside the knees (in the lowest position). The hand cycle is equipped with gears that can be changed manually or with the chin.

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4 Microfet:www.biometrics.nl
5 www.doubleperformance.nl
Training protocol

Subjects with paraplegia started the hand cycle training program at the start of active rehabilitation and those with tetraplegia started three months later. Both continued training twice a week until discharge. The duration of training sessions was between 35 and 45 minutes (including a short warm-up and cool-down session). Most of the time, we trained outside with the group on cycle tracks and in case of bad weather we trained inside. For practical reasons the sessions were always scheduled at the end of the day. The rating of perceived exertion had to be between 4-7 on the Borg’s 10-point scale (Noble et al., 1983). From a previous study in untrained subjects with tetraplegia (in the post-clinical period) interval training appeared to be more suitable than continuous aerobic training (Tordi et al., 2001; Valent et al., submitted) In the first practice sessions of our subjects with tetraplegia we used bicycle indoor equipment\textsuperscript{6} adjusted for hand cycling to ensure a low initial power level. At the start of the training program, subjects with tetraplegia had to be able to hand cycle continuously for approximately 2 minutes. Pre-training sessions were performed until the subjects were able to achieve this. The first training sessions involved interval training with several 1 to 2-minute blocks of hand cycling, followed by 3 to 4 minutes of rest. During the course of the training period, the hand cycling blocks could be gradually increased to 3 to 4 minutes while rest blocks reduced to 1 to 2 minutes. Persons with paraplegia were able to start with an interval-training schedule of 3 to 4 minutes exercise with 1 to 2 minutes rest in between. In these subjects, the rest period gradually changed into “active rest” (cycling at a lower intensity, i.e. velocity) as fitness level improved. No other demanding aerobic exercise training was performed on training days and at least two days were scheduled in between training days. Subjects were asked to make up for a missed training session if possible. Subjects were asked to maintain a training diary and to report pain and/or complaints to the upper extremities, as well as their rating of perceived exertion on the Borg scale immediately after the training sessions. If serious complaints to the upper extremities or illness occurred, the subjects were asked to contact the trainer/researcher before continuation of the training.

\textsuperscript{6}Bicycle indoor trainer; Minoura Magturbo: www.minoura.jp
Statistical analyses
The pre- and post-test outcomes of the experimental subjects were compared with the pre and post-test outcomes of the matched control subjects using ANOVA for repeated measures, analyzing the interaction of measurement (pre and post test) and group (training and control). P-value was set at 0.05.

RESULTS
Subjects
Twenty subjects were included in the study (Table 1). Three subjects dropped out after the pre-test for various reasons, not related to hand cycle training (depressive disorder, severe neurological pain, tendonitis elbow). The baseline characteristics of our experimental group (and control group) only differed on age (46 ± 15 yrs and 40 ±14 yrs respectively) from those of the longitudinal Dutch cohort group (Haisma et al., 2006).

We were able to find matched control subjects among the longitudinal cohort group that complied with our matching criteria for subject characteristics for all 17 remaining experimental subjects. For one subject with a C8-lesion (#14) no control subject with a C7 or C8-lesion was available and we selected a control with a Th3-lesion. Table 1 describes the personal and lesion characteristics of the experimental and control group and gives information on training compliance. The length of the active rehabilitation period, other sports activities (fitness, swimming and wheelchair sports) and $PO_{peak}$ baseline –values were comparable between both groups.

**Table 1: Personal and lesion characteristics of the experimental and control group**

<table>
<thead>
<tr>
<th>Lesion</th>
<th>AIS</th>
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<th>body</th>
<th>active</th>
<th>other</th>
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<td>6</td>
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<td>mean</td>
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<td>50-107</td>
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<td>Contr</td>
<td>11</td>
<td>6</td>
<td>11</td>
<td>6</td>
<td>13</td>
<td>4</td>
<td>range</td>
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<td>7-17</td>
<td>17±3</td>
</tr>
</tbody>
</table>

Training
No chronic overuse injuries were reported associated to the hand cycle training. Subjects occasionally reported muscle soreness but generally recovered well from the training sessions. The training period varied from 9 to 39 weeks. Consequently, the total number of training sessions also varied substantially between subjects: from 16 to 31 sessions in persons with paraplegia, and 15 to 72 sessions in subjects with tetraplegia. Subjects missed on average 13 ± 3% of the training sessions during the training period (Table 1). Reasons mentioned were medical conditions such as flu, urinary tract infections, autonomic dysregulation and pressure sores. In the training diaries the subjects reported a perceived exertion of 4-7 on the 10-point Borg-scale.

Outcome measures
Results for all outcome measures are shown in Table 2. Subject numbers differed among outcome measures because of various reasons: two subjects (#1 and #10) were not able to perform the wheelchair exercise tests at either occasions due to spasticity and lack of arm strength (or left-right strength differences). In two subjects (# 5 and #9) we missed data on the post hand cycle test because of an unexpected early discharge. We missed data on the wheelchair and hand cycle tests in one subject (#11) due to the inability to keep a constant velocity on the treadmill. Furthermore, it was not possible to measure strength of all muscle groups due to paralysis or due to pain provoked by muscle testing. In addition, if an experimental or his matching control subject missed data on an outcome value, than both subjects were excluded from analysis, e.g. the low number of subjects on HRpeak can be explained by missing data in the control subjects.
Wheelchair exercise capacity

Although no significant effect of hand cycle training was found for the training versus control group on the outcome measures of wheelchair capacity, positive trends were found for PO\textsubscript{peak} and oxygen pulse with p-values of 0.079 and 0.052, respectively (Table 2). No significant effect of hand cycle training was found for VO\textsubscript{2peak}. After correction for body mass, again a trend (p=0.070) was found for PO\textsubscript{peak} (W·kg\textsuperscript{-1}), but no effect on VO\textsubscript{2peak} (ml·min\textsuperscript{-1}·kg\textsuperscript{-1}).

Muscle strength

As is shown in Table 2, significantly larger improvements were found in the experimental group compared to the control group for muscle strength of elbow flexion (only left), shoulder exo-rotation and shoulder endo-rotation (both left and right). No training effect was found for the other muscle groups.
Pulmonary function
No significant training effects of hand cycling were found for pulmonary function.

Hand cycle capacity
Comparing pre- with post-test results in the training group only, we found substantial improvements in $PO_{\text{peak}}$ ($p=0.000$) (Figure 1a), but only a trend for improvement in $VO_{2\text{peak}}$ ($p=0.065$) (Figure 1b).

Figure 1a and 1b: pre and post test results of $PO_{\text{peak}}$ and $VO_{2\text{peak}}$ in the hand cycle test (experimental group) and in the wheelchair (experimental and control group)

DISCUSSION
The aim of this study was to determine the effect of structured hand cycle training twice a week in comparison with usual care during active rehabilitation of persons with SCI. Although a strong tendency for an improvement in wheelchair exercise capacity, reflected by borderline effects in $PO_{\text{peak}}$ and oxygen pulse, was found in the training group in comparison to the regular care group, there was no significant improvement in $VO_{2\text{peak}}$. However, we did find significantly larger improvements of arm muscle strength in the training subjects compared to the controls, whereas no training effect was seen in pulmonary function.
Training effects

Although a strong tendency was found for an improved $PO_{peak}$ ($p=0.079$) after HC-training in the current study, the positive effects on $PO_{peak}$ and $VO_{2peak}$ of a previous non-controlled hand cycle training study during clinical rehabilitation could not be confirmed (Valent et al., 2008). Oxygen pulse, available in a subgroup of only 9 (pairs of) subjects, improved nearly significant ($p=0.051$) suggesting some improvement in cardiovascular efficiency.

It is difficult to compare our results on $PO_{peak}$ and $VO_{2peak}$ with the few studies that focused on the effects of structured upper body training programs during clinical rehabilitation of subjects with recent SCI (De Groot et al., 2003; Hjeltnes and Wallberg-Henriksson, 1998; Knuttson E, 1973; Le Foll-de Moro et al., 2005; Sutbeyaz et al., 2005). Like the current study, previous studies involved small and heterogeneous subject groups but in contrast, they were without a control group receiving regular care/treatment (De Groot et al., 2003; Hjeltnes and Wallberg-Henriksson, 1998; Knuttson E, 1973; Le Foll-de Moro et al., 2005; Sutbeyaz et al., 2005). Moreover, it seems more valid to conclude that the improvements of these studies were the result of the total rehabilitation program whereas our focus was on the additional effect of hand cycle training to regular care.

Peak arm muscle strength, especially of shoulder exo-rotation and endo-rotation, improved significantly more in the hand cycling group compared to the control subjects. These improvements of more than 10% are considered clinically relevant according Brehm et al. (2004) but were not in agreement with the muscle groups in a previous study in which only a significant improvement in elbow extension strength in patients with paraplegia was found after hand cycling (Valent et al., 2008). However, the latter observational cohort study was not a controlled training study like the current study. Another experimental training study in subjects with tetraplegia found small significant gains in some muscle groups (e.g. shoulder abduction) after a structured hand cycle training (Valent et al., submitted). This study however, involved subjects with chronic tetraplegia more than 2 years after discharge. Although our training protocol was not primarily designed to train muscle strength, the interval protocol appeared to allow a significant contribution to shoulder muscle strength.
Pulmonary function improved in the HC group over time but no improvements were found that could be attributed to hand cycling alone. These findings were in agreement with previous aerobic upper body training studies from which it seems that clinically relevant improvements (>10%) (Brehm et al., 2004) in pulmonary function are not commonly found (Taylor et al., 1986; Valent et al., submitted; Valent et al., 2008; Yim, 1993).

Hand cycle and wheelchair capacity
In terms of test-specificity, it makes more sense to evaluate hand cycle training in a hand cycle test than in a wheelchair since hand cycling is more efficient than hand rim propulsion. Relatively larger gains in POpeak are more likely to be found in the hand cycle test. Unfortunately, data on hand cycle capacity was not available in the control subjects. Nevertheless, the mean relative changes in POpeak and VO2peak of the hand cycle test of subjects in the training group were of the same magnitude as in the wheelchair test, suggesting that training effects were comparable. Some transfer of the hand cycle training effect may be expected since all our subjects also participated in other therapies focusing on daily hand rim wheelchair use and training. At least part of the upper body musculature that is trained in hand cycling will be used in hand rim wheelchair propulsion.

Both in the wheelchair and hand cycle test, our experimental subjects had gains (%) in POpeak that were approximately 3 times higher than gains (%) in VO2peak. The relatively greater improvement in POpeak over the increase in VO2peak is in agreement with other studies on the effects of clinical rehabilitation in persons with SCI (Haisma et al., 2006; Hjeltnes and Wallberg-Henriksson, 1998; Valent et al., 2008). The relatively high gains in POpeak compared with VO2peak suggest an improved mechanical efficiency (i.e. skill, coordination) in both wheelchair propulsion and hand cycling during clinical rehabilitation; probably as a consequence of an improved exercise technique (muscle coordination of the arms and shoulders) and/or a local adaptation in muscle metabolism (Hjeltnes and Wallberg-Henriksson, 1998). The higher VO2peak and POpeak -values in the hand cycle test compared to the wheelchair test are expected to be a result of the differences in test-protocols (discontinuous vs. continuous) and -mode (hand cycle vs. hand rim).
Although continuous and discontinuous arm crank protocols yielded comparable results in able bodied (Washburn and Seals, 1983), especially our hand cycling subjects with tetraplegia may have performed better thanks to the discontinuous protocol. This is based on a previous study in which muscle fatigue (often mentioned as reason for stopping) was delayed by including short rest intervals (Valent et al., submitted). Hand cycling (as test mode) is more efficient (Dallmeijer et al., 2004b) and easier than wheelchair propulsion (Dallmeijer et al., 1998). In addition, we noticed that when propelling their wheelchair, several subjects had difficulty to keep a straight line due to muscle strength differences (right and left-side) or spasticity. These problems did not occur during hand cycling on a treadmill. Based on these results, hand cycling seems a more favourable mode of exercise testing than hand rim wheelchair propulsion.

Training
Most subjects were very motivated to follow the sessions and an important motivation for participation was the opportunity to be outside (out of the centre). The training protocol appeared to be well sustainable for all subjects. As there were only two training sessions weekly there seemed to be enough time to recover from the specific hand cycle training. However, it occurred that the hand cycle session (scheduled as the last therapy of the day) was missed because subjects were ill, too tired or had mild over-use complaints due to other therapies and/or due to strenuous activities like making transfers etc. The reported non-compliance (on average 13%) is a phenomenon typically seen in training studies in (untrained) persons with recent SCI (Chapter 2). This can be explained by the vulnerable condition of the SCI-patients during the clinical period as a consequence of the preceding inactive bed-bound period and unstable medical conditions resulting in e.g. urinary tract infections, bowel problems, orthostatic hypotension or autonomic dysregulation (Haisma et al., 2007b).

Three subjects with tetraplegia stayed in the rehabilitation centre for a long period and thus also had a longer period of hand cycle training. Although all three improved substantially, it is not justified to conclude that more hand cycle training sessions lead to more improvement; the larger gain may also be attributed to the longer period in the rehabilitation centre (and participation in
other therapies). The latter however, is in contrast with Haisma et al. (2007a) who found that, within the Dutch cohort group, a longer rehabilitation period was negatively associated with fitness improvements or recovery over time. It appeared that long staying patients (who had achieved functional goals) were mainly waiting in the last phase of rehabilitation until post discharge facilities - e.g. home adaptations and assistive equipment - were arranged whereas training goals were subordinate.

Limitation of the study
The design of the current study is not optimal, which is a randomized clinical trial. We did match our experimental subjects with controls but it is unclear whether they did not hand cycle regularly because it was not offered to them, due to lack of interest, or due to physical or medical problems creating selection bias. However, it was found that the experimental and control group had comparable mean baseline-values of $P_{O_{peak}}$, therefore we regarded the controls as valid counterparts.

From the current study, it appeared that the subjects trained less than the planned frequency. Together with a short training period, some subjects probably did not complete enough training sessions to benefit from the hand cycle training. For example, we noticed that one subject (# 14 with a C8-lesion) had a short rehabilitation period and completed only 15 training sessions. As in all subjects with tetraplegia, we included this subject after three months of active rehabilitation. He had managed to improve in fitness considerably in the first three months and started with a relatively high baseline level, which may explain his early discharge and the fact that he was the only subject showing no improvements on $P_{O_{peak}}$ during both wheelchair (and hand cycle) tests. It appeared that excluding this subject from the analysis, a significant improvement in $P_{O_{peak}}$ ($p=0.034$) was found on wheelchair capacity. We were only able to evaluate wheelchair or hand cycle capacity in 5 out of 7 subjects with tetraplegia, although from training we saw that all 7 subjects managed to build up their hand cycling capacity; from a few meters to a few km outside. To conclude, the (positive) effects of hand cycle training in the current study might be underestimated due to the small and heterogeneous subject group and due to missing values.
Recommendations
Based on the results in the current study, it is safe for persons with SCI to start hand cycle training in the beginning of active rehabilitation. Although (for reasons of exercise testing) we started later in subjects with tetraplegia, we think it is wise to start with preparing and practising hand cycling as soon as active rehabilitation begins. To prevent over-use injuries, it is advised to prevent any activity above shoulder level by placing the crank axis as low as possible. (Bonninger et al., 2005; Valent et al., submitted) It is also advised to hand cycle synchronously, as the mechanical efficiency appears to be significantly higher compared to asynchronous hand cycling (Bafghi et al., 2008; Dallmeijer et al., 2004a). Patients with tetraplegia, are advised to start training with an indoor trainer or a well-adapted arm crank device, to allow the use of low initial power levels. Furthermore, we recommend the use of interval training protocols to build up fitness in wheelchair-bound persons with a low initial physical capacity (Tordi et al., 2001; Valent et al., submitted). Moreover, the recovery time in between hand cycling blocks reduces the repetitive strain on the musculoskeletal system and thus prevent the occurrence of overuse injuries (Bonninger et al., 2005).

In conclusion, to overcome barriers holding persons with SCI back from future hand cycling, rehabilitation programs should also focus on functional and independent hand cycle use in the own environment. More research in persons with SCI is needed to optimize and integrate aerobic training protocols and modes (e.g. hand cycling) in the rehabilitation program.

CONCLUSIONS
Compared to matched controls receiving regular care, we found a tendency for improvement in $PO_{peak}$ and oxygen pulse after structured hand cycle training. In addition, we found positive effects of hand cycling on muscle strength of shoulder endo-rotation and exo-rotation but no effect on pulmonary function. No adverse effects of hand cycling were found. Therefore, compared with usual care during clinical rehabilitation, hand cycling seems to be a safe exercise mode for persons with SCI to build up fitness and muscle strength, showing similar or favourable results. The heterogeneous group of subjects and missing
values, together with a large variation in length of the training period may have affected statistical power of this study.

Acknowledgements
We thank the Netherlands Organisation for Health, Research and Development ZON-MW who supported this study (grant numbers: 014-32-012 and 14350003), in The Hague.
Furthermore, we thank all subjects for their enthusiastic participation and the trainers in the rehabilitation centers Heliomare and Rehabilitation Center Amsterdam for their help with the training.
Chapter 7

General discussion
Discussion

Upper body training in persons with SCI

The aim of the current thesis was to investigate the effects of hand cycling on physical capacity and health in persons with SCI during and after rehabilitation. Before the main findings will be discussed, a state of the art of literature on the effects of upper body training on physical capacity is presented. Regular exercise in persons with SCI is considered to be beneficial for overall fitness (Devillard et al., 2007; Figoni, 1990; Glaser, 1989; Noreau and Shephard, 1995; Rimaud et al., 2005). Based on the review in Chapter 2 and the recent review by Fernhall et al. (2008) it is concluded however that, due to the limited number of studies, the small and heterogeneous subject groups and the low methodological quality of the studies (with hardly any randomized controlled trials: RCTs), the evidence in literature is not strong. It was not possible in the review of Chapter 2 to compare the effects on physical capacity between specific training modes, especially not during clinical rehabilitation. The lack of control groups (receiving usual care or no training) but also differences in training protocols and training periods hinder comparison between available studies.

Persons with paraplegia and tetraplegia are expected to benefit from training and although the absolute gains in physical capacity may be larger in persons with paraplegia (Jacobs and Nash, 2004), the relative gains compared with baseline, are considered to be comparable. In persons with a chronic paraplegia the improvements were between 10 and 30% for $P_{O_{peak}}$ and $V_{O_{2peak}}$. The number of studies on persons with tetraplegia however was too small to draw conclusions on relative gain (Chapter 2). The most commonly used training modes were arm crank exercise, wheelchair exercise and circuit resistance training. Studies on the effects of hand cycle training on $P_{O_{peak}}$ and $V_{O_{2peak}}$ were previously not available and thus not included in the review of Chapter 2.

Compared to the conventional training options, hand cycling is considered to be an appropriate mode of training for persons with SCI: i.e. more efficient and mechanically less straining compared to hand rim propulsion. Therefore, in current study the objective was to investigate the effects of hand cycle training
compared with no hand cycle training, in persons with SCI during and after the clinical rehabilitation period. Special attention was given to those with cervical lesions as less is known about the effects of exercise in this group with physiological and cardiovascular mechanisms that deviate from generally patterns (Figoni, 1993; Hjeltines et al., 1998). In addition, the need for regular well-adjusted exercise is suggested to be even more important in this fragile population.

**Effects of hand cycling**

Three studies were performed on the effects of hand cycling in persons with SCI: an epidemiological study during and (shortly) after clinical rehabilitation (Chapter 3), an experimental study in the post-clinical rehabilitation period in subjects with tetraplegia (Chapter 5) and an experimental study in the clinical period (Chapter 6).

**Main outcomes: \( PO_{\text{peak}} \) and \( VO_{2\text{peak}} \)**

The results of the epidemiological study (Chapter 3: (Valent et al., 2008)) showed significant gains in hand rim wheelchair capacity (reflected by \( PO_{\text{peak}} \) and \( VO_{2\text{peak}} \)) in persons who hand cycle regularly during rehabilitation compared to non-hand cycle users. These results were however only found in those with paraplegia and not in persons with tetraplegia. The latter group was however smaller and more heterogeneous. In the (quasi) experimental hand cycle training study that was performed during clinical rehabilitation (Chapter 6), trends in improvements of wheelchair capacity for \( PO_{\text{peak}} \) and oxygen pulse, but not for \( VO_{2\text{peak}} \), were found for persons who received additional hand cycle training compared to matched controls receiving usual treatment. Improvements for \( PO_{\text{peak}} \) and \( VO_{2\text{peak}} \) were however found in the experimental and control group.

The trend of improvement may be explained, among others, by the heterogeneity of the SCI-group (with all lesion levels) and the variation in duration of training. Comparison with previous upper body training studies during clinical rehabilitation is hampered because, in contrast to the current study, only pre-post-training designs were used. After clinical rehabilitation (Chapter 5), the subjects with chronic tetraplegia improved significantly on \( PO_{\text{peak}} \) and \( VO_{2\text{peak}} \), as determined in a hand cycle


Discussion

exercise test. The subgroup in which effects of a preceding non-training period were compared with the hand cycle training period, showed similar positive results. Comparison of the effects of hand cycling with the few other upper body training studies in persons with chronic tetraplegia (Cooney and Walker, 1986; Dallmeijer et al., 1997; DiCarlo, 1988; McLean and Skinner, 1995) is again difficult in the post-clinical rehabilitation period, mainly due to different training protocols and training status. The findings however seem in agreement with the arm crank training study of Mc Lean and Skinner (1995).

All three studies combined, mostly positive effects were found for \( P_{O_{peak}} \) and \( V_{O_{2peak}} \) following hand cycling, as can be seen in Table 1. Nonetheless, in the experimental study during the clinical rehabilitation period (Chapter 6) only trends of improvement were reported whereas more clear improvements were reported in the post-clinical experimental subjects (Chapter 5).

It is interesting to discuss these results in relation to the phase of rehabilitation: the clinical or post-clinical rehabilitation period. During early rehabilitation, subjects are generally unstable and prone to over-use injuries and other complications, which may limit trainability, especially after a bed-bound period, while at the same time natural recovery may occur. During the post-clinical rehabilitation period, persons with SCI are generally more stable, although especially those with tetraplegia may remain more prone to health complications as is explained in the introductory chapter and appeared from Chapter 5. In all three studies, subjects were vulnerable because they were in the clinical rehabilitation phase or because they were persons with tetraplegia. As a consequence of the vulnerability (resulting in non-compliance), gains were expected to be low. On the other hand, in all three studies subjects were untrained and were expected to profit from training. Especially training with a hand cycle, offers a suitable exercise mode to gradually improve physical capacity.

In addition, a possible explanation why persons of the epidemiological study (Chapter 3) who were hand cycling regularly in the first year after discharge, did not improve (Table 1), was that most of them were already well trained on hand cycling during rehabilitation. Not much gain could be expected unless the frequency and intensity of hand cycling would have been markedly increased, which did not occur. Structured hand cycle training in persons with a
Discussion

longstanding (cervical) lesion did however result in significant improvements in PO_{peak} and VO_{2peak}, as is shown in Table 1 (Chapter 5). It was assumed that (especially untrained) subjects with longstanding paraplegia (not investigated in the current thesis) would show positive and probably more homogeneous results than the subjects with chronic tetraplegia following structured hand cycle training. In addition, we did see clear improvements in the homogenous group of subjects with paraplegia during clinical rehabilitation in the epidemiological study of Chapter 3, Table 1.

Furthermore, in comparison with the training study during rehabilitation (Chapter 6), the training set-up in the post-clinical rehabilitation study (Chapter 5) was more standardized (with a fixed number of training sessions). Finally, during the clinical rehabilitation period the contrast between the training and control group (both receiving a considerable amount of physical training) is assumed to be considerably smaller than the contrast between the training and control group in the post-rehabilitation period. Therefore, it is less likely to find positive training effects in the clinical rehabilitation period.

Table 1: The effects of hand cycling on the main outcome measures

<table>
<thead>
<tr>
<th></th>
<th>Physical capacity</th>
<th>Muscle strength</th>
<th>Pulmonary function</th>
<th>Health-QOL</th>
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<td>VO_{2peak}</td>
<td>EE,EF,</td>
<td>- FVC (%)</td>
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<td>EX,EN, AB</td>
<td>- PEF</td>
<td>- General h. - Mental h. - Vitality</td>
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<td>PP</td>
<td>TP PP</td>
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</table>

Epidem: Epidemiological, Exp: Experimental, rehab: rehabilitation, Health-QOL: health-related quality of life, p: p-value is bold when significant. Muscle groups are bold with significant positive effects of hand cycling. EE: elbow extension, EF: elbow flexion, EXO: shoulder exo-rotation, ENDO: shoulder endo-rotation, AB: shoulder abduction, TP: tetraplegia, PP: paraplegia, NA: not available or no statistical analysis possible due to small sample size, wc: wheelchair exercise test, bc: hand cycle exercise test, nC: no comparison with control group (usual care)
Discussion

Other outcomes
Besides wheelchair and hand cycle capacity, secondary outcomes such as muscle strength and pulmonary function were evaluated. One might expect both elbow extension (m. triceps) and flexion (m. biceps) to improve, as they are important muscles involved in the respective push and pull movement during hand cycling (De Coster et al., 1999). In the epidemiological study (Chapter 3) a relationship was found between regular hand cycle use and elbow extension strength in persons with paraplegia during and after clinical rehabilitation, but no relationship was found with any of the other studied muscle groups (elbow flexion strength, shoulder abduction and -endorotation or – exorotation). In persons with tetraplegia none such relationships were found. This may be explained by the fact that the measurement of muscle strength was not possible of all muscle groups of the subjects with tetraplegia; e.g. strength during extension of the m. triceps since this function is absent in persons with motor complete cervical lesions C5 or C6. This implies that the already small and heterogeneous group of persons with tetraplegia became even smaller. The same applied to the experimental subjects in the post-clinical rehabilitation period in Chapter 5 in which we found marginal effects on shoulder abduction, shoulder exorotation and elbow flexion strength, but no effects on elbow extension strength. In Chapter 6 we found positive effects on shoulder endorotation and exorotation strength and unilateral elbow flexion strength after structured hand cycle training, in comparison to matched controls.

In conclusion, in all three studies some statistically significant improvements in arm strength as a result of hand cycling were found. The improvements were not very consistent as they were reported in different muscle groups (Table 1). It is important to state however, that subjects were trained primarily to build up aerobic capacity/ fitness and functionally to be able to cover distances outdoors and not specifically to increase muscle strength. Strength training studies in persons with paraplegia (Jacobs et al., 2002b; 2001; Nash et al., 2001; 2002; 2007) support the view that specific protocols may lead to more outspoken peak strength improvements after hand cycle training. Furthermore, based on personal observation, possibly not peak muscle strength, which was measured in the present studies, but muscle endurance may be improved after hand cycle training. A better wheelchair or hand cycle exercise test performance may also
be the result of local muscle adaptations, resulting in an improved muscle endurance (Harvey, 2008).

Another secondary outcome of physical capacity, which we have evaluated, is pulmonary function, which is affected in persons with high paraplegia or tetraplegia. The pulmonary function of these persons is expected to benefit most from exercise training (Crane et al., 1994). Pulmonary function improved during clinical rehabilitation (Chapters 3 and 6) which is in agreement with the study of Mueller et al. (2008) but these improvements of pulmonary function could not be attributed to hand cycling alone (Table 1). In contrast, we did not find significant pre-post hand cycle training effects on pulmonary function in persons with chronic tetraplegia after clinical rehabilitation (Chapter 5). These findings were in agreement with previous aerobic upper body training studies (Taylor et al., 1986; Valent et al., 2007a; Yim, 1993). Significant and clinically relevant improvements, defined as >10% (Brehm et al., 2004) in pulmonary function as a result of aerobic training are not commonly found in persons with a longstanding SCI.

Health-related quality of life did not change significantly, most likely due to the short training period of 8-12 weeks but also due to the small subject group in combination with lack of responsiveness of the outcome measures (questionnaires) in Chapter 5. Indeed, Hicks et al. (2003) found a significant improvement on quality of life after a considerably longer period of nine months of upper body training. After a few weeks of training, experimental subjects of both studies described in Chapters 5 and 6 appeared to be able to hand cycle distances outside. Most of them enjoyed the training sessions, in particular those who were training in a group. The long distances covered outdoors, even by subjects with tetraplegia (Janssen et al., 2001), indicate the potential of the hand cycle for daily ambulation and thus a more physically active lifestyle. It has been concluded by several authors (Giacobbi, 2008; Manns and Chad, 1999; Tasiemski et al., 2005) that fitter and more active persons with SCI perceived themselves as less ‘handicapped’ than their inactive peers, while lower levels of participation are a significant predictor of depression (Tate et al., 1994) but this was not investigated in the present thesis. However, a larger subject group performing hand cycle training for a longer period is expected to show a positive effect on quality of life.
Discussion

As stated already in the introductory chapter, quality of life is closely associated with a higher degree of independent living and participation (Noreau and Shephard, 1995). When integrated in daily life on a regular basis as exercise and/or transportation mode, hand cycling may eventually improve the level of independent living, social participation and quality of life.

Hand cycle training

In the current thesis, subjects were generally untrained and - especially in early phase of rehabilitation - inexperienced in hand cycling. As suggested by Hjellnes et al. (1986) and in the introductory chapter of current thesis, arm cranking (and also hand cycling) seems to be an unskilled task, which should be recommended early after injury for endurance training rather than wheelchair training. Compared to hand rim wheelchair exercise, a larger and more balanced muscle mass is involved, assumingly at a lower mechanical load, which makes it a safe mode of exercise for untrained vulnerable persons with SCI.

An interval-training protocol was used as this was found to be extremely suitable for persons with a low physical capacity (Butcher and Jones, 2006; Tordi et al., 2001; 1998). From a pilot study it was seen that untrained subjects with tetraplegia had to stop already after only a few minutes of continuous hand cycling as a consequence of extreme muscle fatigue. The small active muscle mass, imbalance in muscle group strength and the disturbed blood supply were factors assumed to contribute to this early muscle fatigue. Personal observations make clear that especially the untrained subjects with tetraplegia needed (short) rest periods in between short bouts of hand cycling. Also frequent periods of recovery are considered to reduce the repetitive strain on the musculoskeletal system and thus the occurrence of overuse injuries (Bonninger et al., 2005). Interval training (if sustainable) at a higher intensity but same total work load, has been shown to elicit greater physiological change than continuous aerobic training at a lower constant intensity (Butcher and Jones, 2006). All the subjects in the present studies with SCI and of different age, lesion levels and training status, were able to train satisfactory with the interval-training protocol (Chapter 5, Appendix 1).
Training intensity can be imposed and monitored using different indicators: heart rate, oxygen uptake, power output, or through subjective indicators such as the score on a Borg-scale. The continuous monitoring of power output with a power measuring system, commonly used for cycling, may be very suitable in hand cycling as it allows training at percentage of peak power output (McLean et al., 1995). However, at the time of the experimental study (Chapter 4) the validity and reliability of power measuring systems (e.g. Powertap, Ergomo and SRM) commonly used for cycling (Bertucci et al., 2005; Paton and Hopkins, 2006), were not yet evaluated in low-intensity hand cycling. Measuring VO₂, although reliable, is not practical since it requires ambulant and expensive instrumentation. Therefore it was decided to use heart rate monitors together with a Borg-scale.

A training intensity of 60-80% heart rate reserve (HRR) was imposed in persons with chronic tetraplegia which was within the range of the guidelines for continuous exercise of the ACSM of able-bodied persons (Pollock, 1998) and previous upper body training studies in persons with SCI (Chapter 2) (Valent et al., 2007b). Several studies (Bar-On and Nene, 1990; Goosey-Tolfrey and Tolfrey, 2004; Hjeltnes, 1977; Hooker et al., 1993; Schmid et al., 1998; Tolfrey et al., 2001) showed strong individual linear HR-VO₂ relationships in those with paraplegia and consequently training on heart rate appeared to be valid for this group. The data on individuals with tetraplegia in Chapter 4 however, showed that a reliable linear relationship between HR and VO₂ was found in half of the subjects with tetraplegia. The lack of a reliable relationship in the other half may be explained by the disturbed sympathetic innervation resulting in a restricted peak heart rate and an inadequate blood circulation. In agreement with McLean et al. (1995), it is concluded that heart rate may not reflect the exercise intensity adequately in all persons with tetraplegia and those with high thoracic lesions (>Th5). Therefore, the individual HR-VO₂-relationship should be investigated to evaluate the appropriateness of heart rate as indicator of exercise intensity. Possibly in future, with the standard evaluation of the autonomic nervous system in addition to the ASIA (Krassioukov et al., 2007) more knowledge will become available on the severity of autonomic dysfunction and its influence on the oxygen uptake-heart rate-relationship.
Discussion

The complementary use of the easy applicable Borg-scale was previously recommended in persons with tetraplegia (McLean et al., 1995) and paraplegia (Grange et al., 2002). The present study however, showed some limitations of the Borg-scale in persons with tetraplegia who, in general, appeared to be more affected by local muscle fatigue, while the Borg-scale evaluates general perceived exertion. Based on their results also Lewis et al. (2007) concluded that the Borg-scale may not be a valid index of perceived exertion in persons with paraplegia or tetraplegia. Moreover they also emphasized the importance of discriminating peripheral from central cues when using the Borg-scale.

In conclusion, hand cycling is assumed to be a safe exercise mode and interval training is regarded a useful protocol to train physical capacity in persons with SCI. The actual training intensity in persons with SCI appears to be reasonably reflected by a large target heart rate range (60-80%HRR) together with a Borg-scale. Especially in persons with tetraplegia however, hand cycle training on basis of percentage peak power output must be seriously considered as an alternative.

Hand cycle testing

To test peak exercise capacity adequately in persons with SCI, especially with tetraplegia, several factors are important such as test mode (wheelchair propulsion, arm cranking or hand cycling) and test protocol (continuous/discontinuous and work rate increments).

The untrained to moderately trained subjects with tetraplegia scored relatively high VO$_{2\text{peak}}$-values during a discontinuous hand cycle exercise test: 1.08 ± 0.36 L·min$^{-1}$ (Chapter 4) and pre- and post-training values of 1.31 ± 0.40 and 1.43 ± 0.43 L·min$^{-1}$ (Chapter 5) respectively. This is in agreement with Janssen et al. (2001) who also found higher values during hand cycle testing in subjects with tetraplegia than previously reported. Previous studies evaluating persons with chronic tetraplegia (of different training status) during peak wheelchair exercise (Coutts and McKenzie, 1995; Coutts et al., 1983; Dallmeijer et al., 1997; Gass et al., 1980; Janssen et al., 2002; Lasko-McCarthey and Davis, 1991; Schmid et al., 1998) and/or peak arm crank exercise (Goosey-Tolfrey et al., 2006; Hopman et al., 1998; 2004; Jacobs et al., 2002a; McLean and Skinner, 1995), reported substantially lower mean values ranging from 0.70-
Discussion

1.03 L·min\(^{-1}\) with the exception of the high post-training values in the arm crank study by Di Carlo (1988).

In general, personal (age, gender, rehabilitation and/or training status) and/or lesion characteristics (lesion level and completeness) may explain some of the variation in VO\(_{2\text{peak}}\)-values. It is most likely however, that differences in A) test protocols (discontinuous/continuous and work rate increments) and/or B) test modes (arm cranking, wheelchair or hand cycling) may be responsible for this variation.

A) Continuous and discontinuous arm work yielded comparable results in able–bodied subjects and persons with paraplegia (Rasche et al., 1993; Washburn and Seals, 1983). However, based on the physiology of persons with tetraplegia (Chapter 1) and the results of a pilot study in this particular group it was decided that a discontinuous protocol should be more appropriate to prevent the occurrence of local muscle fatigue and ability to continue the test. A protocol of 2 minutes hand cycling with 30 seconds recovery in between and small increments of 2-5 W (as was recommended by Lasko-McCarthey and Davis (1991)) was applied (Chapters 4 and 5). It was assumed that in persons with tetraplegia this protocol would lead to higher VO\(_{2\text{peak}}\)-values than a continuous protocol.

B) An other factor that may be responsible for differences in VO\(_{2\text{peak}}\) is the mode of testing: in the current thesis as well as in the only other study comparing hand cycle and wheelchair propulsion (Dallmeijer et al., 2004b), a hand cycle test yielded higher VO\(_{2\text{peak}}\) and PO\(_{\text{peak}}\)-values than the wheelchair test. In previous research comparing arm crank and wheelchair exercise in able-bodied subjects and subjects with paraplegia (Gass et al., 1995; Glaser et al., 1980a; Martel et al., 1991; McConnell et al., 1989; Sedlock et al., 1990; Wicks et al., 1983), most authors also reported higher values of peak power output in arm crank exercise than in wheelchair exercise but no differences in VO\(_{2\text{peak}}\). It is questionable however, whether results of previous arm crank exercise studies can be generalised towards today’s hand cycling and more specifically to persons with tetraplegia. It is important to focus more closely on possible differences between arm crank exercise and modern hand cycling (when performed by persons with SCI and especially tetraplegia). At least two aspects of the difference between arm crank exercise and hand cycling seem to
be important: 1) the positioning of the crank axis (interfacing) and 2) the mode of cranking: asynchronous or synchronous.

1. In previous studies on arm crank exercise in tetraplegia the positioning of the crank axis was often mid-sternum (McLean and Skinner, 1995) or at shoulder level (DiCarlo, 1988; Goosey-Tolfrey et al., 2006; Hopman et al., 1998; 2004), whereas in modern hand cycling a trend is seen that the axis is positioned as low as possible which is allowed by the curved cranks (Figure 6, Chapter 1) and often just below the sternum. A lower positioning of the axis may result in a better (peak) exercise performance in persons with tetraplegia for whom it is very strenuous to push above shoulder level against gravity.

2. In contrast to modern hand cycling, arm crank exercise has generally been performed asynchronously. Several studies have been performed comparing asynchronous with synchronous arm crank exercise (Glaser et al., 1980b; Hopman et al., 1995; Marineck and Valencic, 1977; Mossberg et al., 1999) and hand cycling (Abel, 2003; Bafghi et al., 2008; Dallmeijer et al., 2004a; Goosey-Tolfrey and Sindall, 2007; Van der Woude et al., 2000; Van der Woude et al., 2007). The results are not uniform in arm crank exercise but in hand cycling all studies found higher levels of peak performance and efficiency in the synchronous mode. This corresponds with the general preference for synchronous hand cycling in sport (Janssen et al., 2001) and daily life (Valent et al., 2007c). An explanation may be that, in contrast to asynchronous hand cycling, no energy costs are needed during synchronous hand cycling to prevent steering movements of the crank set while transferring power into propulsion (Abel, 2003; Bafghi et al., 2008; Dallmeijer et al., 2004a; Van der Woude et al., 2007). Another advantage of synchronous hand cycling is a better trunk stability: during the push-phase the reaction forces are directed perpendicular to the back rest, while asynchronous hand cycling causes rotation of the trunk along a longitudinal axis when one arm is extended and the other one flexed (Bafghi et al., 2008). Therefore, in contrast to asynchronous hand cycling, upper body muscles do not need to be active to stabilise the trunk. This is especially favourable for persons with higher thoracic or cervical lesions who lack active trunk and
(partly) arm muscles. Subjects with tetraplegia in the current studies never complained of sideward trunk instability during synchronous hand cycling while this is often experienced in practise during asynchronous cranking. The only trunk stability problem that some subjects experienced was falling forward in the pull-phase, which we were able to solve with a belt around the thorax. In synchronous hand cycling, upper body muscles are apparently used more efficiently: less muscle activity is needed to prevent trunk instability and unwanted steering movements (Van der Woude et al., 2007). Moreover, depending on lesion level, active trunk muscles may contribute to the propulsion by moving the trunk forward and/or backward.

In conclusion, synchronously hand cycling with a relatively low crank axis seems to be more suitable for persons with tetraplegia than hand rim wheelchair propulsion or asynchronously arm crank exercise. Therefore, this favourable hand cycle motion and the discontinuous test protocol may explain the relatively high VO$_{2\text{peak}}$ and PO$_{\text{peak}}$ values in this particular group. Future studies should corroborate these notions of an optimum hand cycle interface.

Over-use injuries and hand cycling

Especially persons with tetraplegia are at a higher risk of developing musculoskeletal pain as a consequence of physical activity. The (partial) paralysis of thoraco-humeral muscles and imbalance in shoulder muscles, may lead to potential overuse of functional muscles (and other tissue) (Curtis et al., 1999; Powers et al., 1994). Persons with tetraplegia generally report a relatively low level of daily activity together with a higher prevalence of shoulder pain (Curtis et al., 1999). From the current studies, hand cycling during or after clinical rehabilitation did not have adverse effects in persons with paraplegia or tetraplegia: no increased pain to the upper extremities as a consequence of hand cycling was found (Chapter 3, 5, 6). This is in agreement with a recent study that evaluated the effect of arm crank training on shoulder pain in subjects with SCI (Dyson-Hudson et al., 2007). As in the current study, the authors avoided potentially injurious positions such as extreme internal rotation and abduction as well as extreme flexion and extension and a hand position above shoulder level. Also in a study on arm crank exercise in subjects with tetraplegia
by (Klefbeck et al., 1996) the cranks were adjusted so the highest point of the hand grips was at shoulder level, which is according to guidelines on shoulder preservation (Bonninger et al., 2005; Requejo, 2008). The risk of over-use injuries however, is always present in this particularly vulnerable group and therefore hand cycling should be performed with an adequate ergonomic interface, gear ratio, propulsion technique as well as an adequate training intensity, frequency and/or duration.

In conclusion, it was found that hand cycling in a well-adjusted hand cycle and with an individually matched interval training protocol does not provoke any adverse effects in persons with tetraplegia during and after clinical rehabilitation.

**Trainability of persons with a low physical capacity**

It is notable that the dropout rate in the presented studies was substantial, not as a consequence of the training but mainly due to other health complications such as pressure sores and urinary tract infections. This indicates the vulnerable general condition of this specific group (Ginis and Hicks, 2005). The dropouts tended to have a lower physical capacity at the start of training. However, non-compliance due to aforementioned health complications also occurred in subjects who completed the training period. From the current thesis and from international literature it is clear that the high prevalence of secondary complications appears to have a large and negative influence on general fitness (Post et al., 1998). The problem is that due to the negative consequences (bed-bound period) of a medical complication, it is difficult to maintain regular physical fitness. If these persons succeed in attaining and maintaining a higher level of physical fitness, would this help to prevent or reduce the occurrence of secondary complications in the future (Haisma, 2008)? In other words: can the debilitative cycle in persons with a low physical capacity be interrupted or reversed?

In the introduction of this chapter we mentioned the deviating physiological and cardiovascular mechanisms in persons with tetraplegia (Figoni, 1993; Krassiovkov and Claydon, 2006). The trainability of the central and peripheral cardiovascular system will be discussed in persons with tetraplegia:
Discussion

In previous studies in subjects with tetraplegia (DiCarlo, 1988; Hjeltnes and Wallberg-Henriksson, 1998; McLean and Skinner, 1995) and in the current thesis mostly positive effects on peak power output, but to a lesser extent on VO$_{2\text{peak}}$, were found (Table 1). According to Figoni (1993), Hoffman (1986), Hopman et al. (1998) no evidence is available to support the presence of central cardiovascular training effects from arm exercise. Nevertheless, we found a tendency of an improved oxygen pulse in persons with tetraplegia, suggesting a potential for central improvements. Moreover, it was concluded that subjects with tetraplegia attained relatively high VO$_{2\text{peak}}$-values during hand cycling. It remains unknown however, whether energy levels required for hand cycling are high enough to induce a central cardiovascular training effect in persons with tetraplegia. It is most likely that peripheral adaptations occurred such as an improved ability of muscles to extract oxygen or an increased muscle mass, as is supported by a study by Hopman et al. (1998). Harvey (2008) stated that the increased ability to extract oxygen is one of the key factors increasing VO$_{2\text{peak}}$ in all persons with SCI. For example, due to changes in muscle metabolism (e.g. increase in mitochondria, improved glycogen storage and synthesis) and/or a higher density of capillaries, less lactic acid is accumulated resulting in a delayed onset of muscle fatigue (Harvey, 2008). Besides these adaptations, a training effect may be expressed in an improved technique (coordination) resulting in less co-contraction of muscles.

In the present study (Chapter 5) mostly untrained subjects were included. It is possible that the 8-12 weeks of training lead to more peripheral (muscle) training effects, whereas a longer training period may lead to increased muscle endurance and eventually to some additional central effects. This is explained by a long-term adaptation-process of the small active muscle mass to the imposed specific load; this process needs to be gradual to allow recovery and adaptation to the increasing load over time: e.g. from practise it is seen that endurance athletes with tetraplegia, who adopted regular training (with wheelchair or hand cycle) as a lifestyle, are able to improve physical performance over years. Besides peripheral (muscle) adaptations, possibly also some minor (but clinically relevant) adaptations to the central cardiovascular system have gradually occurred over these years but this hypothesis is not confirmed as no studies focussed on the long-term aerobic training effects.
However, in a group of well-trained athletes with SCI, including persons with tetraplegia (Abel et al., 2003), the energy turnover during both hand cycling and (more straining) wheelchair racing were found to be high enough to induce cardiovascular training responses, comparable to able bodied persons, and probably to help prevent cardiovascular diseases (Paffenbarger et al., 1993). Unfortunately, studies on physical capacity in wheelchair athletes are mostly cross-sectional (comparing with inactive persons) while athletes and non-active controls are hardly ever followed over a long period (Shephard, 1988). Therefore, selection of the fittest in most published studies cannot be ruled out while it is interesting to know if both athletes and inactive persons with tetraplegia can benefit from long-term regular physical training and thus may be able to deal better with the strain of daily life.

It may take a lot of extra time and effort to turn the tide in those with the lowest physical capacity, especially during rehabilitation. The few subjects with tetraplegia, who trained hand cycling regularly during a long period of active rehabilitation, seemed to benefit with considerable gains at discharge (Chapter 6). A relatively long period of rehabilitation may be favourable for a higher degree of independence of persons with tetraplegia, as is supported by data by Post et al. (2005). On the other hand, a more recent study of Haisma et al. (2007) showed that a long period of rehabilitation was not associated with higher fitness levels: In the Dutch centres the duration of rehabilitation seems to be more determined by waiting time for arranging post-discharge facilities instead of reaching rehabilitation goals. Therefore, after reaching the basic rehabilitation goals, aerobic training (e.g. hand cycling) indeed should be continued until (and after) discharge to prevent deconditioning during the final – often ‘waiting’ phase of rehabilitation (Haisma et al., 2007). In a study by O’Neill and Maquire (2004) a high proportion of patients perceived sporting activity as beneficial for rehabilitation with increments in fitness, quality of life, confidence and social contact. In addition, after discharge, patients may face a less adapted environment and acquired skills may appear more strenuous and difficult to put in practice than it was during rehabilitation (Haisma, 2008). To conclude, hand cycle training in spinal cord injured persons with a low physical capacity, should focus on achieving physical fitness AND functional hand cycle use in the own environment to ensure a sufficiently high degree of
Discussion

independence and participation. Nonetheless, this particular group appears to be at higher risk of health complications, which may seriously interrupt training programs.

Limitations of the studies

In the current thesis no randomized controlled trials (RCT) could be conducted due to the small and heterogeneous sample sizes available in the experimental settings, and complexities of daily practice. This seems to be a more general problem in research on persons with SCI (Ginis and Hicks, 2005). It was possible however to compare the hand cycling subjects with control subjects from the epidemiological study (Chapters 3 and 6). They were selected retrospectively and on matched characteristics. The use of a regular care control group would have been more optimal. In the experimental study of Chapter 5, effects of a hand cycle training period were compared with a non-training period. It may be stated that, in contrast to most previous upper body training studies in persons with SCI, an effort was made in the current thesis to compare with non-training control subjects with SCI.

The effects of hand cycle training would have been more outspoken when evaluated with a hand cycle test. The effect of training was evaluated with a wheelchair test (in Chapters 3 and 6) because of its relevance for daily life and because experimental and control subjects were familiar with hand rim wheelchair propulsion but not with hand cycling. Moreover, a positive effect of hand cycle training on wheelchair peak performance was hypothesized, based on studies that found a transfer from arm crank training effects to wheelchair performance (DiCarlo, 1988; Sedlock et al., 1988).

A training frequency of twice a week was considered to be feasible in the experimental study during clinical rehabilitation (Chapter 6). Due to (temporarily) health problems, the subjects were not able to attend all sessions. In the busy rehabilitation program it was not always possible to make up for a missed training, resulting in a lower actual training frequency than planned. Consequently, the contrast between the hand cycling and control group in this study was smaller than expected.

It is likely that a longer period of training in the experimental studies during (Chapter 6) and after clinical rehabilitation (Chapter 5) would have resulted in
larger gains in our primary and secondary outcomes. A longer training period however, may result in a higher drop-out and non-compliance of subjects with SCI due to complications (Davis et al., 1991; Hicks et al., 2003). This may be especially the case in (untrained and/or older) persons with tetraplegia who are often tormented by secondary complications.

**Clinical implications**

Hand cycling appears to be a safe mode of exercise and mobility to train physical capacity in persons with SCI. This applies especially to those with a low physical capacity: persons during clinical rehabilitation and those with tetraplegia.

From findings in literature (Butcher and Jones, 2006; Tordi et al., 2001) and from this thesis it can be concluded that interval test and training-protocols are very suitable to prevent the occurrence of early local muscle fatigue and soreness. The interval-protocol is expected to allow more people with tetraplegia to complete the training program.

To impose an adequate strain during hand cycle training, monitoring of intensity is important. For persons with tetraplegia, training at a percentage of $P_{O_{peak}}$ may be more suitable than training at percentage of HRR or Borg-scale. Recently, power measurement systems (the SRM-system) have been used in hand cycling in able-bodied subjects (Van der Woude et al., 2007) and in arm cranking in athletes with tetraplegia (Goosey-Tolfrey et al., 2006). During early clinical rehabilitation of persons with SCI and especially those with tetraplegia, it is important to start at a low intensity and to build up the training load gradually. In this phase, arm crank systems (or roller ergometers) are advised because it is possible to start with a very low initial power. It is important however that the axis of the crank set is positioned as low as possible and that the hands remain below shoulder level during the full cycle (Bonninger et al., 2005). To prepare adequately for future hand cycling a synchronous (instead of a asynchronous) mode should be installed. In persons with tetraplegia, it is recommended to start with a few hand cycle bouts (e.g. 5x1 minute within 30 minutes of rest) during early clinical rehabilitation. Subsequently, a gradual increase in duration and repetition of hand cycle bouts and training sessions can be allowed. Eventually, after approximately 2 months, the protocol described in Chapter 5 can be used
Discussion

( Appendix 1). In addition, functional hand cycle use should be trained especially in subjects with tetraplegia to ensure continuation of safe and independent hand cycling in the own environment after rehabilitation.

In The Netherlands hand rim wheelchairs are often prescribed together with an add-on hand cycle unit for outdoor mobility in persons with SCI with lesion level C5/C6 and below. In their clinical practice guidelines (Bonninger et al., 2005), recommend powered mobility when wheelchair propulsion is too strenuous. A valuable addition to these guidelines should be the use of hand cycling for outdoor mobility instead of powered mobility as a physically less straining alternative for hand rim wheelchairs yet allowing daily exercise. From a health perspective, the use of powered wheelchairs should be prevented as it may deteriorate physical fitness, especially in persons who are not likely to exercise.

If the strain imposed by the environment is high (e.g. hills) and/or the physical capacity is low, even after a training period, the hand cycle-unit may be equipped with an electric power support, e.g.¹

Different coupling systems exist which make it possible to attach the hand cycle unit independently to the wheelchair. However for persons with a C5-lesion this may be too strenuous and therefore powered wheelchairs may appear to be the final solution, enabling independent in- and outdoor mobility and thus participation. Nonetheless, with a little help from others, those who are not entirely independent in use of the hand cycle as a mobility device may still benefit from hand cycling for sport and recreation.

Furthermore, individuals should be made familiar with all available exercise options and accessibility of facilities in the own environment (e.g. fitness, circuit resistance training, hand cycling, wheelchair racing, quad-rugby and swimming). In addition, hand cycling offers an opportunity to recreate or exercise with peers or with able-bodied friends or family members who like to (Nordic) walk, jog, skate or cycle. Although not investigated in the current thesis, being able to participate independently in physical (outdoor-) activities, with others or alone, is likely to have a positive effect on self-esteem and well-being (Giacobbi, 2008; Nash, 2005).

¹ www.speedy.de, www.doubleperformance.nl
Based on these arguments, it is a challenging task to motivate and help individuals with SCI to adopt a physically active lifestyle during clinical rehabilitation and remain physically active after clinical rehabilitation and thus to maintain a long-term physically and mentally healthy lifestyle (Ditor et al., 2003; Fernhall et al., 2008). As is suggested by the ACSM: “Exercise = medicine”. Especially after a period of illness or due to the consequences of a complication, it is of utmost importance to regain physical fitness (through active mobility or exercise and sport) carefully and gradually.

**Future research**

There is a need for training studies with the highest possible methodological quality in the field of upper body training (e.g. hand rim wheelchair, arm cranking, hand cycling, circuit resistance training etc.) in persons with SCI. An urgent need for randomized controlled training studies on the effects of training exists for spinal cord injured persons with a low physical capacity during clinical rehabilitation, in untrained or older persons and especially those with tetraplegia. The focus should be on underlying mechanisms responsible for adaptations to training in these vulnerable groups.

A relatively long training period may be needed to find substantial training effects, although non-compliance and dropout may seriously limit results. Therefore, to ensure large subject groups, multi-center collaboration may be needed to reach sufficient statistical power.

In future research on hand cycling and other upper body training modes, the effects of different training protocols (e.g. form, intensity, frequency, duration) should be compared on outcomes of physical capacity in persons with SCI. Of particular interest are studies comparing training forms such as interval, endurance and strength training protocols or combinations (e.g. circuit resistance training).

Differences between exercise modes (wheelchair exercise, arm crank exercise, hand cycling and circuit resistance training) should be subject of study. The focus however, should not only be on the effects on physical capacity but certainly also on the occurrence of upper body over-use complaints when comparing different protocols or training modes.
Future research should focus on mechanical load and physiology during hand cycling and the effects of adjustments to the ergonomic hand cycle-user interface: e.g. based on observation, it is assumed that a low position of the crank axis is favourable for persons with tetraplegia but so far this has not been investigated. Eventually this should result in specific training guidelines for (un-)trained persons with different levels of SCI.

Furthermore, it would be interesting to study the effects of regular hand cycle use or training on the level of social participation and quality of life.

To conclude, future research is needed on early training interventions (e.g. hand cycling) and on protocols that ensure continuation of exercise after the clinical rehabilitation period, as part of a physically active, healthy lifestyle in persons with SCI.
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References


Summary
Summary

Following spinal cord injury (SCI), the loss of motor (sensory and autonomic) function leads to a reduced physical work capacity and may hinder physical activity or exercise at an adequate level in order to maintain fitness and health in daily life. Moreover, persons with SCI are prone to secondary health complications. Especially for those with tetraplegia, who essentially have an extremely low active muscle mass and a (partly) disturbed blood circulation due to paralysis and autonomic dysfunction, it is difficult to engage in physical activity. Not many easy accessible, not too strenuous exercise modes are available or can be performed independently by persons with high lesions or those with recent spinal cord injury. In the current thesis the focus was on the synchronous\(^1\) hand cycle add-on unit, as exercise mode. This type of hand cycle unit can be attached to the own hand rim wheelchair with slight adaptations. Hand cycling is assumed to offer an adequate alternative exercise mode for persons with SCI to improve physical capacity during and after clinical rehabilitation.

The introductory Chapter 1 describes SCI and the consequences for health and physical capacity. Physical capacity is defined as the joint ability of muscles and respiratory and cardiovascular systems to attain a peak level of activity. The relation between physical capacity, functioning, participation and quality of life is outlined. The hand cycle is described as well as its use as exercise and mobility mode around the world. The interface characteristics and mechanical efficiency of hand cycling are compared with hand rim wheelchair propulsion and conventional arm cranking. The favourable characteristics of hand cycling, especially for persons with tetraplegia, are described. Chapter 1 concludes with an outline of this thesis. Chapter 2 describes a systematic review of the international literature of the effects of upper body exercise and training on physical capacity in persons with SCI. The gains on the main outcomes PO\(_{\text{peak}}\) and VO\(_{2\text{peak}}\) are compared between arm crank exercise, wheelchair exercise and alternative modes such as resistance training and quad rugby. Due to the relatively low number of studies and the limited methodological quality (the lack

\(^1\)Although also used in current thesis, the commonly used definitions ‘synchronous’ and asynchronous are less appropriate. Synchronous refers to the correct definition in-phase (phase-angle of 0\(^\circ\)), whereas asynchronous refers to out-of-phase (angle of 180\(^\circ\)).
of randomised controlled trails), it was not possible to draw definitive conclusions on training effects for different lesion groups or training modes. Average relative gains on \( P_{\text{O}_\text{peak}} \) and \( V_{\text{O}_2\text{peak}} \) were found to be between 10-30% in studies with predominantly pre-post-training design. Most studies were performed in persons with paraplegia, while gains in the few studies on persons with tetraplegia were mostly positive but not uniform. The results of the relatively few studies with an acceptable quality seem to support the view that upper-body exercise may increase the physical capacity of people with SCI. None of the studies however focussed on the effects of hand cycle training.

In the past decade, hand cycling as an exercise therapy has become part of the rehabilitation program in The Netherlands. In Chapter 3, an epidemiological study is described in which the influence of hand cycle use on physical capacity during (and in the year after) clinical rehabilitation was studied. The outcomes of physical capacity between hand cycling and non-hand cycling individuals, after correction for baseline-values and confounders (lesion and personal characteristics) were compared. A significantly larger increment in \( V_{\text{O}_2\text{peak}} \), \( P_{\text{O}_\text{peak}} \) and elbow extension strength was found in subjects with paraplegia who were hand cycling during clinical rehabilitation, compared to those who were not. The small and heterogeneous study groups may have hampered the finding of positive results of hand cycling in persons with tetraplegia. In the post-rehabilitation period, out of all outcome measures, only a positive effect on elbow extension strength was found and only in subjects with paraplegia.

The ACSM-training guidelines recommend heart rate as indicator of exercise intensity in persons with SCI. However in practise, some individuals with tetraplegia encounter problems when training according to heart rate due to a disturbed autonomic nervous system. A disturbed autonomic nervous system may influence the heart rate-oxygen uptake (HR-\( V_{\text{O}_2} \)) relationship. The cross-sectional study in Chapter 4 addresses the question whether heart rate reflects the actual aerobic training intensity based on the assumed linear HR-\( V_{\text{O}_2} \) relationship between the oxygen uptake and heart rate and whether training according to heart rate is appropriate in persons with tetraplegia. The heart rate-oxygen uptake relationship appeared linear in less than half of the subjects and an individual analysis of this relationship is necessary to determine whether heart rate can be used to quantify exercise intensity. In conclusion, the use of
Summary

Heart rate to prescribe training intensity should be reconsidered in persons with tetraplegia. Suggested alternatives for exercise intensity monitoring - perceived exertion and ambulant power output readings - should be evaluated experimentally in near future.

Chapter 5 outlines the effects on physical capacity and health-related quality of life in subjects with tetraplegia following a structured hand cycle interval-training program. Pre- (t1) and post (t2) outcome measures on physical capacity and health-related quality of life were compared. In addition, double baseline data (t0, t1) were available for a subgroup. A significant improvement after the structured hand cycle training on physical capacity as reflected by PO\text{peak} and VO\text{2peak} was found. Except for shoulder abduction, no significant effects were found on muscle strength, pulmonary function or health-related quality of life. Despite dropouts and non-compliance (due to common health and practical problems), untrained subjects with tetraplegia were able to improve their physical capacity through regular hand cycle interval training.

In Chapter 3 hand cycling during clinical rehabilitation was studied with an observational analysis and thus without a controlled training protocol. Therefore, Chapter 6 addresses an experimental study on the effects of a structured hand cycle training program during rehabilitation of subjects with paraplegia or tetraplegia. The results are compared with matched control subjects from the cohort group receiving usual treatment described in Chapter 3. Tendencies for improvement were found in wheelchair capacity, reflected by PO\text{peak} and oxygen pulse after additional hand cycle training. Significant effects on shoulder exo- and endo-rotation strength were found but no improvements on pulmonary function. Additional hand cycle training during clinical rehabilitation seems to show similar or slightly favourable results on fitness and muscle strength compared with usual treatment. The heterogeneous subject group and large variation in training period (and number of training sessions) may explain the lack of significant effects of additional hand cycle training on wheelchair capacity. Moreover, the contrast between hand cycling and regular treatment during clinical rehabilitation is relatively small.

Finally, in Chapter 7, the main findings and conclusions of this thesis are summarized and discussed. Practical implications for the design and prescription of hand cycle training- and rehabilitation programs for individuals
Summary

with SCI are discussed. Suggestions are given for future research in order to optimize physical training protocols for persons with SCI, and especially for persons with tetraplegia. The main conclusions of the current thesis were that structured hand cycle training leads to mainly significant improvements in physical capacity, reflected by improvements in $P_{O_{\text{peak}}}$ and to a lesser extent in $V_{O_{2\text{peak}}}$, compared to usual care in persons with SCI during and after clinical rehabilitation. Some improvements in peak arm muscle strength were found compared to usual care and no consistent improvements in pulmonary function were found that could be attributed to hand cycling only. No over-use injuries as a consequence of hand cycle training were reported. In conclusion, hand cycling offers a safe exercise and mobility mode to maintain and train physical capacity in those with SCI, already in early rehabilitation.
Samenvatting
Samenvatting

Het verlies van motorische (sensorisch en autonome) functies als gevolg van een dwarslaesie leidt over het algemeen tot een verlaagde fitness als wel een verminderd niveau van fysieke activiteit in het dagelijks leven. Het is door de beperkte spiermassa dan ook lastig voor personen met een dwarslaesie om fit en gezond te blijven, mede gezien het feit dat zij extra gevoelig zijn voor secundaire gezondheidsklachten. Bovenaan geldt vooral voor personen met een tetraplegie vanwege de geringe actieve spiermassa van de armen en romp en de verstoorde bloedsomloop als gevolg van autonoom disfunctioneren. Er zijn maar weinig laagdrempelige, niet al te zware trainingsvormen beschikbaar die bovendien onafhankelijk uitvoerbaar zijn door personen met een tetraplegie of door personen die recent een dwarslaesie kregen. Handbiken is daarop een uitzondering.

Dit proefschrift is gericht op training met de synchroon1 (de parallele cranks bewegen in fase) aangedreven aankoppelbare handbike. Handbiken wordt beschouwd als een geschikt alternatief trainingsmiddel ter verbetering van de fysieke capaciteit van personen met een dwarslaesie tijdens en na de revalidatie.

In de Introductie (hoofdstuk 1) worden de ingrijpende gevolgen van een dwarslaesie voor de gezondheid en fitheid (fysieke capaciteit) beschreven. Onder fysieke capaciteit wordt verstaan het geheel van spierkracht, ademhalings- en bloedsomloop, dat bijdraagt aan het maximale prestatievermogen. De samenhang tussen fysieke capaciteit, functioneren, participatie en kwaliteit van leven wordt belicht. Vervolgens is de werking en toepassing van de handbike binnen de sport en het dagelijkse leven beschreven. De interface-kenmerken van de handbike en de mechanische efficiëntie tijdens handbiken worden vergeleken met het gebruik van de handbewogen rolstoel en het conventionele armcranken. De gunstige eigenschappen van handbiken, vooral voor personen met een tetraplegie, worden genoemd. Tot besluit wordt in hoofdstuk 1 de indeling van dit proefschrift beschreven.

1 De definitie ‘synchroon’ is gangbaar in de literatuur en wordt dan ook gebruikt in dit proefschrift maar is feitelijk incorrect. Het refereert aan bewegen met parallele cranks en een juiste terminologie is ‘in fase’. Voor ‘asynchroon’ is ‘uit fase’ de correcte definitie.
Samenvatting

In hoofdstuk 2 wordt de literatuur naar de effecten van training van de bovenste extremiteiten op de fysieke capaciteit (POpiek en VO2piek) geëvalueerd bij personen met een dwarslaesie. De trainingseffecten als gevolg van de beschikbare trainingsvormen: arm cranking, handbewogen rolstoel training en alternatieven zoals fitness en quad rugby werden met elkaar vergeleken. Handbiketrainingstudies naar de effecten op de fysieke capaciteit (POpiek en VO2piek) waren echter nog niet beschikbaar in de literatuur. Het was niet mogelijk om verschillen tussen trainingsvormen of protocollen te vinden in deze systematische review doordat er slechts een paar studies zijn met bovendien een beperkte methodologische kwaliteit voornamelijk vanwege het gebrek aan gerandomiseerde, gecontroleerde trials. De relatieve toename in POpiek en VO2piek was gemiddeld tussen 10-30% in de kwalitatief acceptabele studies met vooral pre-post-training designs. De studies werden echter voornamelijk uitgevoerd bij personen met een paraplegie en de enkele studies bij personen met een tetraplegie lieten geen eenduidige resultaten zien. De zienswijze dat training van de bovenste extremiteiten een positief effect heeft op de fysieke capaciteit van personen met een dwarslaesie lijkt te worden ondersteund door de studies van een acceptabele kwaliteit, echter de zienswijze kan niet worden bevestigd.

In de laatste tien jaar is handbike-training een geïntegreerd onderdeel van de Nederlandse dwarslaesierevalidatie geworden. In hoofdstuk 3 is een epidemiologische studie beschreven naar de invloed van handbike-gebruik op de fysieke capaciteit. Na een correctie voor uitgangswaarden en (eventuele) storende factoren zoals laesie- en persoonskenmerken, werden de uitkomstmaten van fysieke capaciteit vergeleken tussen handbikers en niet-handbikers. Gedurende de revalidatie werd een significant grotere toename in VO2piek, POpiek en elleboogextensiekracht gevonden bij de personen met een paraplegie. Bij personen met een tetraplegie werden geen positieve resultaten gevonden, waarschijnlijk omdat er sprake was van een kleine en heterogene groep. In het jaar na de revalidatie werd alleen op de uitkomstmaat elleboogextensie kracht een positief effect gevonden en dit gold alleen voor de personen met een paraplegie. De ACSM –trainingsrichtlijnen adviseren hartslag als een indicator voor de trainingsintensiteit bij personen met een dwarslaesie. In de praktijk worden bij personen met een tetraplegie echter problemen
Ondervonden bij het trainen op hartslag. Onderliggende mechanismen als gevolg van een verstoord autonoom zenuwstelsel kunnen de hartfrequentie-zuurstofopname-relatie in belangrijke mate beïnvloeden. Het cross-sectionele onderzoek in hoofdstuk 4 behandelt de vraag of een lineaire relatie tussen hartfrequentie en zuurstofopname ook daadwerkelijk aanwezig is bij personen met een tetraplegie. Geeft de hartfrequentie de actuele trainingsintensiteit wel goed weer en is trainen op geleide van de hartfrequentie wel geschikt voor deze groep? In dit proefschrift bleek dat bij iets minder dan de helft van de proefpersonen een lineaire relatie bestond. Bij personen met een tetraplegie lijkt het daarom noodzakelijk om de hartfrequentie-zuurstofopname relatie individueel te analyseren om vast te stellen of de hartfrequentie de aerobe inspanningsintensiteit adequaat weergeeft voor de betreffende persoon. Concluderend kan worden gesteld dat het gebruik van hartfrequentie heroverwogen dient te worden bij het voorschrijven van trainingsintensiteit bij personen met een tetraplegie. Mogelijk geschikte alternatieven voor monitoring van de intensiteit zoals de subjectief ervaren fysieke inspanning en vooral ambulante vermogensmeters dienen in toekomstig experimenteel onderzoek verder te worden geëvalueerd.

In hoofdstuk 5 werden de effecten van gestructureerde handbike-interval-training op de fysieke capaciteit en gezondheidsgerelateerde kwaliteit van leven onderzocht bij proefpersonen met een tetraplegie. Na handbike-training werd een significante verbetering van de fysieke capaciteit (PO_piek en VO_2_piek) gevonden. Dit was zowel het geval na analyse van een pre-post-test-design als na analyse van een subgroep waarin handbike-training tevens werd vergeleken met een periode zonder handbike-training. Verder werden behalve een verbetering in de abductiekracht van schouderspieren, geen significante verbeteringen gevonden in spierkracht van de armen, ademhalingsfunctie en gezondheidsgerelateerde kwaliteit van leven. De kwetsbaarheid van personen met een tetraplegie is een algemeen bekend gegeven en bleek tevens uit de hoge uitval van proefpersonen en het aantal gemiste training sessies, beiden als gevolg van gezondheids en praktische problemen. Ondanks deze problemen bleken de relatief ongetrainde proefpersonen met een tetraplegia in staat om hun fysieke capaciteit door handbikeintervaltraining te verbeteren.
Samenvatting

In hoofdstuk 3 werd handbiken tijdens de revalidatie bestudeerd aan de hand van een observationele analyse en dus zonder een gecontroleerd trainingsprotocol. In vervolg hierop behandelt hoofdstuk 6 een experimentele studie naar de effecten van een handbiketraining-protocol bij personen met een paraplegie of tetraplegie tijdens de revalidatie. De resultaten werden vergeleken met een gematchte controlegroep van de longitudinale cohort-groep die is beschreven in hoofdstuk 3. De controlegroep volgde de reguliere behandeling. Een trend voor verbetering na handbike training werd gevonden voor rolstoelcapaciteit, weergegeven door PO\textsubscript{piek} en zuurstofpols. Significante toenames in exo- en endorotatiekracht in het schoudergewricht werden gevonden, maar geen verbetering van de ademhalingsfunctie. In vergelijking met de reguliere behandeling tijdens de revalidatie lijkt toevoeging van handbike-training vergelijkbare, of enigszins gunstigere resultaten op fitheid en spierkracht te geven. De heterogene groep proefpersonen en de grote variatie in trainingsduur (en aantal training sessies) zouden het gebrek aan een significant effect op rolstoelcapaciteit kunnen verklaren. Bovendien is het contrast tussen de handbikegroep en de controlegroep (reguliere behandeling) tijdens de revalidatie relatief klein, vooral vergeleken met de trainingstudie na de revalidatie.

In hoofdstuk 7 worden de belangrijkste bevindingen en conclusies van dit proefschrift samengevat en bediscussieerd. Tevens worden praktische implicaties gegeven voor de uitvoering van handbiketraining en suggesties voor toekomstig onderzoek gericht op optimalisatie van fysische trainingprotocollen (handbiken) in het bijzonder bij personen met een tetraplegie.

De belangrijkste conclusies van dit proefschrift zijn: in vergelijking met niet handbiken (reguliere behandeling) van personen met een dwarslaesie tijdens en na de revalidatie, leidt een gestructureerd handbike-trainingsprotocol tot significante toenames in fysische capaciteit, in PO\textsubscript{piek} en in mindere mate in VO\textsubscript{2piek}. Daarnaast werden enige verbeteringen in spierkracht van de armen gevonden. In geen van de studies werd echter een verbetering in ademhalingsfunctie gevonden die kan worden toegeschreven aan handbiketraining. Er werden geen overbelastingsblessures gerapporteerd die werden veroorzaakt door handbiketraining. De slotconclusie is dat handbiken
Samenvatting

een veilig en geschikt trainings- en mobiliteitsmiddel is om de fysieke capaciteit van personen met een dwarslaesie te onderhouden of te verbeteren, ook al in de vroege revalidatie.
Dankwoord
Dankwoord

Het is al weer bijna 10 jaar geleden dat ik bij Annet Dallmeijer en Luc van der Woude aan kwam met het idee om onderzoek te gaan doen naar handbike-training bij mensen met een hoge dwarslaesie. Als ergotherapeut was ik hierdoor gegrepen in de revalidatiepraktijk en vanuit mijn achtergrond als bewegingswetenschapper wilde ik graag uitzoeken wat de effecten waren op de fitheid van mensen die voorheen hoofdzakelijk aangewezen waren op de elektrische rolstoel voor buitenvervoer. Qua timing had het niet beter gekund want Annet en Luc waren net bezig met de subsidieaanvraag voor een landelijk dwarslaesieonderzoek (beter bekend als het Koepelproject). Een handbikeonderzoek zou kunnen aanhaken bij het landelijk onderzoek en subsidie voor dit extra project zou ingediend kunnen worden bij ZonMw. Hans Slootman (revalidatiearts dwarslaesieafdeling Heliomare) vond het gelukkig ook een erg leuk plan en we gingen aan de slag met het schrijven van een onderzoeksvoorstel. Na een vlekkeloos doorlopen eerste subsidieronde werd ik door mijn toenmalige managers Frans le Fèvre en Ellen Donker beloond met tijd om de tweede meer tijdrovende ronde voor te bereiden. Gelukkig met goed gevolg; een dik jaar later werd de subsidieaanvraag gehonoreerd.

Ik kon daadwerkelijk aan de slag met het handbike-promotie-onderzoek; de eerste drie jaar zou ik er 2 dagen/week aan werken en de tweede drie jaar 3 dagen/week. Ja, we wisten toen al dat ik er flink wat jaren mee zoet zou zijn (en het werd nog langer door minder werken na de geboorte van Luna en Silas). Naast mijn promotieonderzoek was ik 1 dag onderzoeksassistent voor het Koepelproject en 1½ dag ergotherapeut. Als onderzoeksassistent had ik als taak om al onze dwarslaesie-revalidanten te testen i.v.m. het Koepelproject. Als ergotherapeut heb ik echter in die jaren maar een klein aandeel gehad in de behandeling van de revalidanten op onze afdeling. Dit heeft zeker ook betekend dat mijn ET-collega’s Renate Korse, Ellen Kaandorp, Arjan van den Bosch (en later) Maaike Oud soms belast werden met acties voor mijn revalidanten op de dagen dat ik er niet was. Ik besef dat dit voor jullie het werk soms extra druk heeft gemaakt en ik wil jullie dan ook bedanken voor het begrip en de steun al die jaren. Dat laatste geldt uiteraard voor het gehele team. Ik ben vooral ontzettend blij met het feit dat iedereen altijd erg goed heeft meegewerkt om revalidanten te stimuleren om mee te doen met testen en trainingen in het
Dankwoord

kader van het handbikeonderzoek. Verder, wil ik dan ook de verpleging van 2A en 2B noemen die altijd bereid waren om revalidanten in de handbikerolstoel te helpen zetten. De groen-oranje handbike-testrolstoel is zo eigen geworden dat de meesten van jullie geblinddoekt een handbike kunnen aankoppelen en de wielen omzetten.

In het bijzonder wil ik ook Mechteld Hagoort noemen die als een leeuwin waakt over haar handbikes en die altijd heeft gezorgd dat ons handbikepark up-to-date en tip top in orde is. Daarnaast is haar enthousiasme en humor er zeker ook een belangrijke factor in geweest dat (oud)revalidanten graag kwamen handbiken in Heliomare. Ik denk met een glimlach terug aan het swingen op housemuziek tijdens de training en de gezellige BBQ met proefpersonen ter afsluiting van een handbike-trainingperiode. Alle andere trainers en motivators van belang voor het handbikeonderzoek betrokken waren wil ik bij deze ook van harte bedanken. Hierbij denk ik zeker ook aan de Sport en fysiotherapie-afdelingen van het RCA en de Hoogstraat.

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Ik heb voor het handbikeonderzoek uitgebreid gebruik gemaakt van de data uit het koepelproject. Ik wil dan ook mijn medeonderzoeksassistenten bedanken voor de dataverzameling in hun eigen revalidatiecentrum: Sacha van Langeveldt (Hoogstraat), Karin Postma (Rijndam), Jos Bloemen (Hoensbroeck), Ferry Woldring (Beatrixoord), Henny Rijken (Maartenskliniek), Marijke Schuitemaker (het Roessingh). Peter Luthart en Annelieke Niesten (RCA). Ik denk dat wij als groep (samen met Luc, Annet, Sonja en Marcel) ontzettend trots mogen zijn op de inspirerende samenwerking al die jaren en onze bijdrage aan de totstandkoming en uitvoering van het Koepelproject (en het vervolg Spique). Niet eerder zijn op ons vakgebied zoveel interessante publicaties voortgekomen uit een longitudinaal onderzoek.
Erg leuke herinneringen heb ik aan het ISCOS-congres in München waar ik samen met Sonja de Groot, Janneke Haisma en Karin Postma de grootste lol had met de gezamenlijke fysieke en mentale voorbereiding (blouse strijken) op onze presentaties. Daarnaast moet ik bij een Nivea-potje nu altijd meteen aan een gebouw in München denken door de tip die we kregen bij het geocaching.\footnote{Buitensport en spel, waarbij gebruik wordt gemaakt van een GPS-ontvanger om ergens ter wereld een zogenaamde cache (schat) te vinden.} Na het congres in Reykjavik werd onze onderzoeksrelatie nog hechter o.a. door ochtendelijke inspirerende hardlooperciesities, zwavelbaden en vooral een louterende driedaagse trektocht door de IJslandse bergen.

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Dankwoord

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Dankwoord

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Curriculum Vitae
Curriculum Vitae


Van 1997 tot heden (met een onderbreking van een jaar werken en rondreizen in Australië) werkt zij als ergotherapeut en later ook als (promotie)onderzoeker in Revalidatiecentrum Heliomare te Wijk aan Zee.
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