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.
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).

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\(^1\) 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 0º), whereas asynchronous refers to out-of-phase (angle of 180º).
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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>
<thead>
<tr>
<th>A = complete</th>
<th>No sensory or motor function is preserved in the sacral segments S4–S5, representing the anal sphincter and peri-anal sensation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>B = incomplete</td>
<td>Sensory but not motor function is preserved below the neurologic level and includes the sacral segments S4–S5.</td>
</tr>
<tr>
<td>C = incomplete</td>
<td>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 = incomplete</td>
<td>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 = normal</td>
<td>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.
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).

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.
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(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).

![Figure 3: Interactions between components of physical capacity by Haisma et al. (Haisma, 2008)](Figure 3: Interactions between components of physical capacity by Haisma et al. (Haisma, 2008))

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 debilitative 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
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](source: 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)
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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.
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**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° 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).
Table 2: Comparison of wheelchair, hand cycle and arm crank exercise

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

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)