STUDIES ON ENERGY EXPENDITURE IN WALKING AFTER STROKE

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Göteborg 2008

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ISBN 978-91-628-7533-6

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ABSTRACT

Aims: The aims were to assess energy expenditure during different conditions, evaluate measurement methods and assess physical activity after stroke.

Methods: In total 51 persons with stroke >6 months previously (mean age 56) and 24 reference persons participated. In study I, oxygen consumption (VO_2), heart rate (HR) and perceived exertion were measured at treadmill walking with 0% and 30% body weight support (BWS) in 9 stroke and 9 reference subjects. Study II evaluated VO_2, HR, gait speed and perceived exertion in 10 subjects with stroke walking with and without a carbon composite ankle foot orthosis. Measurement of VO_2 was compared to the Physiological Cost Index (PCI), a HR based estimate of energy cost, in study III, where 20 stroke and 16 reference subjects participated. In 11 of the stroke subjects, measures were also compared from walking with and without an orthosis. Study IV quantified the energy cost indoors and outdoors by the PCI and the 6 minute walking distance. Physical activity, walking habits and perceived difficulties were also assessed by questionnaires in 31 persons at a median of 8 years after stroke.

Results: Overall, the subjects with stroke walked with lower speeds and higher energy cost compared to reference subjects. With 30% BWS, VO2 was lower than with 0% BWS, in both the stroke and healthy subjects. Furthermore, HR and perceived exertion were lower with 30% BWS in the stroke group. The energy cost in walking with ankle foot orthosis was statistically, although not clinically relevant, lower and the speed was higher compared to unbraced walking. Energy cost measured by VO_2 and PCI mean values did not differ significantly between test and retest, but the differences in PCI were large in the stroke group. VO_2, age, sex and group assignment could explain 53% of the variation in the PCI. VO_2 but not PCI could detect a statistically significant difference in energy cost of walking with and without an orthosis. Persons with stroke a long time ago walked with increased energy cost and decreased distance as compared to reference values. Two-thirds experienced walking difficulties and 50% showed reduced walking habits. Walking difficulty and Body Mass Index were associated with energy cost and walking distance. The latter was also associated with physical activity level, but no relation with physical environment was found.

Conclusions: Body weight support might decrease energy demands of walking both in stroke subjects and healthy persons. Hence, gait training with BWS may be feasible in case of low physical capacity. An ankle foot orthosis might reduce the energy cost and increase walking speed after stroke. The PCI showed limited reliability and validity after stroke and was not sensitive enough to detect a difference in energy cost when an orthosis was applied. Thus, for research purposes, measurement of VO_2 is preferable. Late after stroke, walking ability was impaired, walking difficulties seemed to predict the energy cost, and perceived difficulties and physical activity level were associated with walking distance.

Key words: Gait, rehabilitation, assessment, physical therapy, oxygen consumption, body weight support, orthotic devices, physical activity

ISBN 978-91-628-7533-6

LIST OF ORIGINAL PAPERS

This thesis is based on the following four papers, which will be referred to in the text by Roman numerals:

I. **Danielsson A, Sunnerhagen K S**.
Oxygen consumption during treadmill walking with and without body weight support in patients with hemiparesis after stroke and in healthy subjects.
Archives of Physical Medicine and Rehabilitation 2000;81:953-7.

II. **Danielsson A, Sunnerhagen KS**.
Energy expenditure in stroke subjects walking with a carbon composite ankle foot orthosis.
Journal of Rehabilitation Medicine 2004;36:165-8.

III. **Danielsson A, Willén C, Sunnerhagen KS**.
Measurement of energy cost by the Physiological Cost Index in walking after stroke.
Archives of Physical Medicine and Rehabilitation 2007;88:1298-303.

IV. **Danielsson A, Willén C, Sunnerhagen KS**.
Energy cost, walking habits and physical activity late after stroke.
Manuscript.

CONTENTS

ABBREVIATIONS

AFO	Ankle foot orthosis
BMI	Body mass index
BWS	Body weight support
BWSTT	Body weight supported treadmill training
ECG	Electrocardiography
HR	Heart rate
HRV	Heart rate variability
PASE	Physical Activity Scale for the Elderly
PCI	Physiological Cost Index
RER	Respiratory exchange ratio
SIS	Stroke Impact Scale
6MW	Six minute walk test
VCO_2	Carbon dioxide production
VO_2	Oxygen consumption
$VO_{2\ max}$	Maximal oxygen uptake
$VO_{2\ peak}$	Peak oxygen uptake

INTRODUCTION

Stroke

A stroke is defined as rapidly developing symptoms of focal or global loss of cerebral function lasting more than 24 hours or leading to death, with no apparent cause other than vascular [179]. A stroke can be classified as ischemic (85%) or hemorrhagic (15%) [141]. In Sweden, approximately 30 000 persons suffer acute stroke every year [141] and about 100 000 persons have disabilities following stroke. Stroke is the leading cause of long-term neurological disability in the adult population, the somatic disease that uses the major part of inpatient hospital days and the disease for which the remaining consequences after discharge require much of the community care offered. The median age for stroke onset in Sweden is 76 years and 20% are younger than 65 years of age [141]. The incidence is almost equal for men and women, but women are five years older than men at onset and almost twice as many men as women are struck before the age of 65 years. Approximately 20% die within six months [83]. Risk factors for stroke are similar to those for cardiovascular disorders and both genetic and environmental factors may contribute. Known risk factors are age, hypertension, atrial fibrillation, diabetes mellitus, smoking and physical inactivity; hypercholesterolemia, obesity and stress also increase the risk [150].

The consequences of a stroke can be extensive since several brain functions may be affected giving impairments in many organ systems. All three domains of body structure and function, activity and participation described by the International Classification of Functioning, Disability and Health (ICF) [180] may be affected by a stroke. Muscle and sensory functions, the autonomic nerve system, postural control, ambulation, speech, cognition, emotional and behavioral functions may be impaired with varying severity. The ability to carry out activities of daily life, e.g. transfers, walking and participation in social life, often become impaired.

Impaired muscle function is one of the most prominent consequences after stroke. Damage to the motor cortex disrupts motor and sensory pathways, causing contra lateral hemiparesis. A reduced central drive decreases the number of functioning motor units, alters the muscle fiber recruitment pattern and reduces firing rates [78]. Impairment of upper extremity function has been found in 69% and of the lower extremity in 65%, at admission [83] and after six months in half of stroke survivors [85].

The precise knowledge about recovery of motor function after brain injury is an evolving field. Restitution includes resorption, restoration and plasticity [9]. Plasticity is documented at the molecular, synaptic, cellular, network and cortical system levels [124] and there is evidence for neuronal growth programs being turned on early after an infarct. Substitution depends on external stimuli such as practice with an affected limb during rehabilitation and includes functional adaptations of neural networks and relearning of motor skills. Rehabilitative training of the affected limb has been found to preserve and enlarge cortical representation, and behavioral experience is considered to be central for adaptive processes in the neural system. Compensation aims to improve the mismatch between the individual's impaired skills and the demands of the individual or the environment and includes change of behavior, assistive devices, accommodation and assimilation [9]. Rehabilitation can be defined as an active and dynamic process by which a disabled person is helped to acquire knowledge and skills in order to maximize physical, psychological and social function [8] and a comprehensive team approach is advantageous for persons who have suffered a stroke [153].

Walking

Human walking can be described as "a method of locomotion involving the use of the two legs, alternately, to provide both support and propulsion" [170]. *Walking* involves the walking process whereas *gait* signifies the manner or style of walking [170] but the expressions are often used synonymously. *Locomotion* is the action of moving from one place to another. *Ambulation* is the action of walking, moving about. Walking is a complex activity that comprises almost all body structures and functions. Basic physical conditions are limb muscle strength, length and flexibility, joint mobility and stability, nerve function, sensory motor integration, motor control and coordination of postural and limb muscle activity, and circulatory and metabolic functions.

Walking requires a highly integrated sensorimotor network. The central nervous system controls basic rhythmic movements involved in the gait cycle and evidence for the presence of a spinal generator for locomotion has been derived from studies by Grillner [60] and Barbeau and Rossignol [6] in a variety of vertebrates. These central pattern generators activate network units coordinated for a proper timing of muscle groups and produce stereotyped locomotion patterns, rhythmic activation patterns, functional modulation of reflex action and execute other rhythmic movements [149]. The brainstem activates the spinal network to initiate locomotion and coordinates activation patterns, weight support and propulsion [149]. The basal ganglia, cerebellum, several cortical areas and hippocampus are involved in the control of walking with sensory feedback provided by joint and muscle receptors, vision and vestibular systems. Sensory feedback modulates locomotor output to the actual context, and newer research findings assume that afferent input to the sensory cortex is important [37].

Normal human gait has a symmetrical, alternating movement pattern and gait is usually described on the basis of phases of the gait cycle divided into a stance and a swing phase [149, 170]. Gait can be studied from many different perspectives. Measurement methods are used to describe state and change, to discriminate between the normal and the pathological, to predict future state and to evaluate the outcome of interventions [47]. Any analysis of state or change is limited by how we measure and measurement methods must be reliable and valid for the purpose. In the clinical setting comfortable and fast walking speed, distance and stair climbing are suitable, reliable quantitative measures of walking ability. Observational kinematical gait analysis takes qualitative aspects into account but has low reliability. Walking endurance can be estimated by the distance walked for a certain amount of time [91] and the subject's perceived exertion or difficulty in walking can be rated with a Borg scale [15]. There are ordinal scales for classification of walking ability from the activity perspective [134] or need of assistance [72].

In laboratory settings accurate data can be collected by advanced systems. Kinematical analysis describes motion [170] and focuses on details of the movement, linear and angular displacements of body segments, speeds and accelerations [172]. Muscle activation patterns and muscle fatigue state can be studied with electromyography. Kinetic analysis is the study of gravity and ground reaction forces, muscle and joint reaction forces, moments and masses [170, 172]. An altered gait pattern often affects the energy expenditure, which should also be considered in gait analysis. Measurement of energy expenditure will be described in a following chapter.

Walking speed is a function of step length and step frequency. Step length relates to body height and body height to speed in normal persons [157]. The freely chosen step rate gives the self-selected or comfortable walking speed, which is on average 1.4 m/s [149] and decreases with increasing age [157]. Men walk with greater stride length [170] and thereby faster than women [157, 168].

Walking after stroke

The extent of recovery depends on the severity and location of the stroke and the initial degree of paresis and/or walking ability is related to recovery of walking [81]. In the Copenhagen stroke study, 63% had no independent walking ability at admission [81]; after six months 22% of the survivors still had no walking ability and 12 % needed assistance [83]. Independent walking (no personal assistance, walking aid might be used) was achieved at the end of rehabilitation by 34% of the survivors who were dependent on admission [81]. Of the patients with initial leg paralysis, 21% achieved walking function whereas 79% did not and only 10% regained independent walking [163]. Optimal walking function was achieved in six weeks by 80% and within 11 weeks by 95% of the survivors [81]. Weight bearing and standing balance capacity in the acute stage was seen to be related to functional walking level after one year [173]. Spontaneous recovery is generally considered to occur within the first three months [82] but improvements in walking have been demonstrated by intervention programs long after onset [1, 41, 126].

Hemiparesis involves an asymmetrical gait pattern [89, 178] and, depending on the loss of postural and voluntary movement control, muscle weakness, over activity and spasticity, different pathological gait patterns can be seen [170]. Electromyographic abnormalities are seen both on the affected and non affected side [89]. Common features of hemiparetic gait involve reduced weight bearing on the paretic leg, impaired hip and knee stability, reduced hip extension, increased knee flexion or hyperextension during stance. During the swing phase, insufficient hip and knee flexion and reduced ankle dorsiflexion often involve dragging of the toes, hiking of the pelvis and circumduction. In addition, trunk and arm movements are altered. The deviations result in asymmetry in temporal and distance parameters with decreased stance time on the paretic leg and short step length [178].

Walking speed and distance

Walking speed is correlated to the degree of gait abnormality and is significantly correlated with temporal parameters [145]. Self-selected and maximum walking speeds correlate strongly with hip flexor and plantar flexor strength, as well as with knee extensor strength, motor and sensory function and balance [74, 120, 125]. Since walking speed is related to motor function, different studies show variable values. Healthy persons' self-selected speeds vary from 1.0 to 1.67 m/s [157, 168] and maximum speeds from 1.64 to 2.51m/s [157]. After stroke, mean walking speeds of 0.5 m/s, less than half of normal, are reported [168] but can be as low as 0.1 m/s [134].

Perry et al. used walking speed for classification of community walking ability in patients with speeds ranging from 0.1 to 0.8 m/s [134], where the slowest speeds implied physiological walking for exercise purposes only and those walking at 0.25 m/s were restricted to household ambulation. Restricted community ambulation required walking speeds of 0.40 to 0.79 m/s and unrestricted community ambulation at least 0.80 m/s. Only 18% achieved unlimited community ambulation [134]. In another study of patients living at home [101], with a mean gait speed of 0.8 m/s, about 60% could access shopping malls and other places in the community. Walking distance in the acute stage was limited to 10% of the distance of normal elderly, and to 40% in the chronic stage after stroke [137]. The 6-minute walk (6MW) has been used as an endurance measure where the subject is instructed to walk as far as possible for a period of 6 minutes [151]. In a population based study [20] the average 6MW distance was 659 m, with males walking 59 m further than females. 6MW distances after stroke ranging from 200 in a sub acute [137] to 400 m in a later stage [48] have been reported.

Energy expenditure

Definitions

- Energy expenditure: oxygen consumption (VO_2) per time unit, expressed as mL VO_2/kg/min
- Oxygen cost: oxygen cost per unit distance; VO_2/kg/min divided by walking speed/min, expressed as VO_2/kg/m.
- Energy cost: metabolic cost per unit distance expressed either as VO_2/kg/m or Physiological Cost Index (PCI) expressed as heartbeats/m.

Biomechanics and energy of walking

The goal of walking is progression of the body in the forward direction. Potential energy stored in the muscles in the form of ATP is converted to mechanical energy at the tendon [172]. Positive work occurs during concentric and negative work during eccentric muscle contraction. The sum of positive and negative work gives the metabolic cost for movement activities, and level walking has equal amounts of positive and negative work whereas uphill locomotion involves more positive work [172]. Limb motion is based on the need to maintain a symmetrical, low amplitude displacement of the center of gravity in the vertical and lateral directions, which conserves kinetic and potential energy. At the end of swing the center of gravity is posterior to the forward leg and during stance the center of gravity elevates over the leg by the generation of forward kinetic energy. Forward kinetic energy converts into potential energy during stance and is reconverted into kinetic energy in late stance as the center of gravity passes ahead of the foot and forward speed increases. In late swing the leg decelerates and prepares for heel strike; this energy is transferred into forward propulsive force acting on the pelvis [168]. The lift work during the vertical displacement was found to be a determinant of energy consumption in a study of normal subjects [88]. Smooth advancement of the body enables energy transfer between successive steps with the least mechanical and physiological energy expenditure and an almost constant total mechanical energy level. Muscle activity is most efficient with minimal change in length and when concentric activity is minimized, and elastic recoil of stretched muscles contributes to efficiency [168]. Efficiency is not only an expression of how well metabolic energy is converted to mechanical energy, but also of how well the neural system can control the energy transfer [172]. The metabolic cost of walking is determined by mechanical work and can be differentiated into support of body weight 28%, generation of propulsion 48%, swinging the legs 10% and lateral stabilization 6% [56]. The remaining energy cost is accounted for by ventilation and circulation [55]. Carrying loads increases the energy demands [56] and obesity may result in a 10-15% or even a 50% increase in energy needs per kg body mass [18].

Disturbance of the gait cycle and the energy conserving mechanisms results in increased energy expenditure. The vertical loading forces and patterns as well as joint moments and mechanical muscle work are altered and the exchange of potential and kinetic energy is reduced [172, 178]. Excessive muscle contraction, increased muscle tone [168], co contraction, work against gravity and altered joint moments mean increased total mechanical work that can contribute to decreased efficiency [35, 61]. A person with a gait disability will adapt by compensatory gait substitutions to minimize the energy expenditure [168], e.g. an increase in step width, which is frequently seen as a compensation for balance impairment, raises energy consumption [39].

Energy expenditure and energy cost

Energy cost can be calculated by biomechanical techniques for work or power analysis [172]. Metabolic energy expenditure can be estimated with indirect calorimetry derived from the amount of O_2 required or CO_2 expired, which reflects the release of energy in the cells and gives an estimate of aerobic energy production [171]. Consumption of 1 mL O_2 corresponds to an energy expenditure of 5 calories and 1 calorie is equivalent to 4.19 joule. Energy expenditure can also be expressed as MET (metabolic equivalent), the ratio of exercise metabolic rate to resting metabolic rate; 1 MET = resting metabolic rate [171].

Respiratory gas exchange is measured by the volumes of O_2 (VO_2) and CO_2 (VCO_2) that enter and leave the lungs during a given period of time. The golden standard method is breath-by-breath analysis with continuous registration of expired gas flow [171].

The basal metabolic rate, the minimum level to sustain vital functions in waking state, is related to fat-free mass. Activity level, age, sex, size, weight and body composition influence the energy expenditure; with increased physical intensity, energy demands increase and consequently respiration, gas exchange and HR increase. After several minutes at a constant sub maximal workload, the energy demands of the tissue are met and a steady state for physiological parameters is achieved.

The power requirement, the rate of O_2 consumption (energy expenditure), is expressed as mL O_2 consumed per kg body weight per minute. In the supine position, the basal metabolic rate and the resting value are about the same, in seated rest, an average person consumes about 2.8 mL/kg/min and quiet standing requires 3.5 mL/kg/min [168]. The maximal aerobic capacity ($VO_{2\,max}$) is the highest O_2 uptake an individual can attain during exercise and indicates aerobic fitness.

The energy expenditure of walking varies both among individuals and within the same person depending on the circumstances: body weight, walking speed, surface texture [131] and gradient [183]. Walking requires less than 50 % of VO_{2max} in normal subjects. The utilization of VO_{2max} during walking at self-selected speed rises with age from 28% in childhood to nearly 48% at 75 years of age [168]. There is no significant difference in walking VO_2 between men and women but a decline with age [168]. Walking at the self-selected speed (1.33 m/s) was reported to require 12.1 mL/kg/min on average for adults 20-59 years of age; the fast walking speed required 18.4 mL/kg/min. After stroke, VO_2 may be 10 mL/kg/min, lower than normal [168] due to low walking speed. In a study six months after stroke, 69% of VO_{2max} was required in walking at sub maximal level [111].

Anaerobic metabolism is seen as a rise in the ratio of VCO_2 to VO_2, the respiratory exchange ratio (RER). RER > 0.90 indicates anaerobic activity; RER > 1.0 indicates strenuous exercise with a shortage of O_2. Normally RER is below 0.85 at self-selected and 0.92 at fast speeds [168].

The physiological work (energy cost) is the amount of O_2 consumed per unit distance walked and reflects the total energy required to perform the walking task. In normal gait, the energy cost at level walking depends on the speed [168] and the relationship can be determined by an equation relating O_2 cost to speed with a U-shaped curve with a minimum at the average self-selected walking speed which is around 1.3 m/s [168]. The self-selected speed requires the least muscle activity and is thereby the most economical for each individual [61, 168, 182]. A low walking speed implies increased energy cost [168] and, after stroke, the difference from normal energy cost increases with decreasing speeds [182]. After stroke, the self-selected speed falls within the range where the energy cost versus speed is not optimal as compared to normal values, although the speed might be optimal given a movement disorder. The energy cost in healthy persons at self-selected speed has been stated to be 0.15 mL/kg/m [168] to 0.18 mL/kg/m [29] whereas for stroke subjects 0.27 [168] to 0.40 mL/kg/m [29] are reported. An increase in energy cost may be caused either by an increased VO_2 per time unit or by a low walking speed with normal VO_2. In case that the speed is low but the O_2 rate normal, the person will not experience exertion or fatigue [168].

Stationary and portable systems for gas analysis are available, but the equipment is costly and employment is cumbersome and requires special training. Thus the method is in general unavailable in the clinical setting. HR is related to O_2 consumption at sub maximal workload in persons with normal cardiac function [183]; measurement of HR during exercise can therefore be used as an indirect method for estimating energy expenditure, as HR rises in direct proportion to the increase in walking speed [171]. The relationship between HR and O_2 consumption is dependent on the individual capacity of oxygen transport [183] and HR is higher in women than in men [168].

One method for estimating energy cost using measurements of HR is the Physiological Cost Index (PCI) [104]. The PCI is calculated from the difference in working and resting HR divided by the walking speed. The PCI value reflects the increased HR required for walking and is expressed as heart beats per meter. The method can be administered in a clinical situation with easily accessible, inexpensive equipment. PCI has been tested for validity and reliability in healthy and patient populations with inconsistent results and has been most frequently used in children with disabilities. Linearity between VO_2 and HR has been confirmed in healthy children and in children with cerebral palsy [142]; the correlation between PCI and VO_2 has been found to be high [44, 25]or moderate [16] and, in contrast, non significant in a newer study in healthy adults [57]. A recent study of 17 stroke subjects found a high correlation between O_2 cost and PCI [50] . PCI is generally measured at the self-selected, comfortable walking speed, which is considered to be a reliable measure [176], and measurement is performed either on the ground or on a treadmill. Although measurement at steady state is recommended, a high test-retest reliability was reported in young women at both steady state and non steady state conditions [5]. The intra- and interrater reliability was acceptable in healthy adults [57] but only moderate in a study of children with cerebral palsy [77]. A more recent study found a high reliability in persons with brain injuries and stroke [115].

Physiotherapy

Physiotherapy approaches

The importance of early, intensive training has been emphasized even more in recent years with increasing knowledge about recovery after brain injury [9]. Different theories for regaining motor control have been developed, but no physiotherapeutic approach has yet been proven superior to another. In the early stage of rehabilitation compensatory training of the non-paretic side and bracing dominated. During the1960s the Bobath [13] method, also called the Neurodevelopmental technique, was developed. The method has been classified as reflex-hierarchical and emphasizes inhibition of excessive muscle tone and stimulation of muscle activity to facilitate normal movement patterns. The method further described by Davies [33] is still much employed in many parts of the world. Another reflex-orientated method that emphasized recovery and control of movement synergies was developed by Signe Brunnström in the 1970s [19]. In the 1980s, Carr and Shepherd [22] introduced a movement science theory that took into account neurophysiology, neural plasticity, biomechanics, muscle physiology, neuropsychology and theories for skill acquisition and stressed that the patient must be active in solving his motor problems. This approach was called the Motor Relearning Programme (MRP) [23] and has been classified as task oriented as it emphasizes training of functional tasks in environments meaningful to the patient. Task oriented practice is based on a dynamic model of learning where the therapeutic interventions are specific to the task being trained [149], which is considered important for improvement [36]. MRP is widely used in stroke rehabilitation today [138]. In the most recent years, "forced use", called Constraint Induced Therapy, preceded by Taub's concept of "learned nonuse", has received increasing interest. The aim is to increase use of the paretic limb with intensive training while use of the nonparetic limb is restricted [177].

Walking training after stroke

Walking is a part of many activities in daily living and restoration of walking ability is of great importance to patients and their relatives [14]. Thus much time and effort in physiotherapy are spent on gait training. Several strategies to optimize walking have been employed. The goal is activation of muscles in the paretic limb rather than adaptive compensation with the unaffected side. Motor requirements vary with the task and the environment [22, 149] and exercises must be tailored to current ability and be demanding enough to stimulate progression [21]. In gait training features like surface texture and interaction with objects or conditions are parts of the physical environment that can be manipulated by the therapist to promote a variety of movement patterns [22].

There is evidence for gait training being effective for improvement of gait function [162]. Early after injury the emphasis is on restoring the prerequisites for walking and gait quality while in later stages meeting environmental demands is stressed [69]. Different approaches for gait training may include task specific mobility exercises, treadmill walking with or without body weight support (BWS) [69], gait machine/robot training [69], sometimes combined with functional electric stimulation [100] and strength training. Orthoses and walking aids are used for facilitation or safety. No concept for gait retraining has been found to be superior to another [43], but intensive training with functional mobility tasks enhances walking ability [43] and a high intensity has been found to be important for carry over to functional tasks [93].

Walking training on treadmill with body weight support

Fig 1.

Treadmill walking training is considered to be task-oriented, since the whole gait cycle is trained repetitively [148]. It can also be considered as a form of "forced use" involving weight bearing and muscle activation with many repetitions. The treadmill has been suggested to stimulate repetitive, rhythmic stepping, limb symmetry and coordination in stroke subjects as compared to over ground walking [64]. Body weight supported treadmill training (BWSTT) is provided by a suspension system with a harness, which helps to maintain an upright position, enables weight bearing on the paretic leg and prevents falling. The theoretical background of this therapy involves entrainment of spinal and supraspinal pattern generators [59] and was shown by Barbeau et al [6] to facilitate the re-education of a near normal gait pattern in spinalized cats. The unweighting in combination with the treadmill stimulation is intended to facilitate automatic, normal gait patterns. Weight bearing, stepping and balance can be trained simultaneously, and by reducing BWS, weight bearing is progressively increased. The concept of BWSTT suggests that the need of physical support from another person is reduced, although physical assistance from one or two persons is often needed [122]. In humans, the method was introduced for training patients with incomplete spinal cord injury and has frequently been proposed as a promising method for walking retraining after stroke [7, 69]. BWSTT has also been tried for patients with cerebral palsy [147], multiple sclerosis [52], Parkinson's disease [112] and orthopedic problems [68, 75, 80, 109].

The appropriate BWS level is considered to be as low as possible while still producing the most normal gait pattern. After stroke, 30% BWS has been considered to give enough support without negatively affecting the gait pattern [66] and up to 40% BWS has been most frequently used after stroke [65, 92, 122, 175]. A more upright posture, increased hip and knee extension during stance [66], symmetry and spasticity improvements [67] were seen with BWS compared to over ground walking. Speed is gradually increased in BWSTT as walking ability improves and speed and BWS level are to some extent exchangeable. Training at faster treadmill speeds has been shown to be beneficial for over ground gait speed [43, 140], and training with BWS at higher speeds has led to further improvements than training at the self-selected speed [94, 154].

In a few randomized controlled trials concerning effects on walking ability after stroke BWSTT has been compared with full weight bearing treadmill walking [175], over ground walking [122] and over ground walking with paretic leg bracing [92]. These studies were carried out at subacute stages but there are indications that neural function [37, 181] and gait speed [155] can be improved by BWSTT in a chronic phase as well. The effectiveness of treadmill training and/or BWS after stroke was analyzed in a Cochrane review [114] that concluded that treadmill training with or without BWS was at least as effective as other gait interventions. A clinical hypothesis is that BWSTT is a way to increase the amount of practice. For dependent walkers, BWS is a prerequisite for the treadmill to be used and may be the only means of practicing walking [114]. Treadmill training after stroke has been found beneficial for muscle performance, balance, cardiovascular function and energy cost [108], and BWSTT may improve cardiorespiratory fitness [31, 116].

Energy expenditure with BWS

At the time of the present study, knowledge of the effects of BWS on energy expenditure in stroke subjects was lacking. In SCI [174] and amputee subjects [75], lower HR with increasing BWS levels was found. Experiments with simulated gravity reduction [46] have shown decreased energy expenditure, but a BWS level of 15% gave no reduction in energy cost in healthy persons [105]. Another trial [56] showed no decrease in VO_2 when body weight was reduced by 25%, whereas 50% gave a significant decrease. A recent a study of healthy persons showed a lower VO_2 with 20-40% BWS compared to full weight bearing [160].

Our experience of training with BWS is that some persons find the harness and the suspension uncomfortable, which could increase the energy expenditure because of stress, although theory would suggest the opposite. Knowledge about the energy demands of a method in use for gait re-education is important for safety reasons in view of stroke patients' possible cardiac comorbidity, low physical capacity and low stress tolerance at an early stage of rehabilitation.

Walking with ankle foot orthosis (AFO)

An orthosis is defined as an externally applied device used to modify the structural or functional characteristics of the neuro-musculo-skeletal system [87]. The primary function is to control abnormal motion of one or more of the body segments but allows normal motion when possible.

It may reduce pain, correct deformity, reduce weight load, control range of movement, modify tone and reset abnormal stretch reflexes by providing a sustained muscle stretch. There has been some controversy about the use of orthoses in stroke rehabilitation; some theories have proposed that orthoses prevent facilitation of normal movements [87], although this opinion has changed [98]. The most prevalent orthosis used after stroke is the ankle-foot orthosis (AFO) and one study reported that 22% of the stroke patients at a rehabilitation unit were discharged with an AFO [158]. The main aim of an AFO is to support the ankle in dorsiflexion and stop excessive plantar flexion preventing foot drop or toe drag during the swing phase and facilitate initial heel contact. It also provides mediolateral stability during stance. There are various designs, materials and features of AFOs. Some designs aim at having a dynamic component at the push off phase. Depending on the construction, plantar flexor activity or knee stability can be influenced [96, 97, 113]. Improved kinematical, kinetic, temporal and distance parameters, as well as muscle activation patterns and balance, have been described in stroke patients walking with an AFO [24, 99, 164]. Perceived difficulty and self-confidence may also improve [164].

Fig. 2

Energy expenditure with AFO

The opinions on effects of AFOs on functional outcome are inconsistent [99] and the clinical significance of changes reported has been questioned [34]. The improved walking velocity with an AFO as compared to unbraced walking seen in some studies [34, 49, 54, 99, 164] may involve a reduction in energy cost. To our knowledge, only two studies report reduced energy cost with the use of an AFO [28, 49]. A Cochrane review concerning the effects of orthotic devices for abnormal limb posture after stroke or non progressive cerebral causes of spasticity is ongoing [87]. The effects on energy cost and walking speed of a standard carbon composite ankle foot orthosis, frequently used after stroke in our clinic, have not previously been documented.

Aerobic capacity and physical activity after stroke

Secondary to the paresis, muscle tissue undergoes a number of changes that affect muscular performance and thereby contribute to low fitness levels. Muscle atrophy where the muscle area may be 20% lower in the paretic compared to nonparetic side and increased intramuscular fat area, result in a lower proportion of lean muscle mass thereby decreasing the amount of metabolically active tissue [78]. Changes in muscle fiber composition to more fatigable fibers, reduced oxidative capacity [78], a lower degree of capillarization [156] and reduced blood flow have been seen in the paretic leg [78].

Signs of cardiovascular disease have been observed in 30-75% of stroke patients even in the rehabilitation phase [79, 144]. The autonomic function can be affected by the brain lesion, and inactivity may involve secondary impairments of circulatory function. Structural lesions in the nervous system resulting in changes in vagal and/or sympathetic activity may contribute to an altered HR response to exercise. The HR variability (HRV), a measurement of beat-to-beat changes in HR reflecting the capacity to adapt to environmental demands, has been found to be impaired, indicating autonomic cardiac dysfunction, primaly in early stages, but even six months after stroke [90], particularly right-sided cerebral lesions may involve reduced HRV [27, 121]. Correlations between HRV and VO_2 peak and HR at rest have been seen in the first month after stroke [84].

Cardiovascular deconditioning may involve risks for metabolic abnormalities, such as diabetes or impaired glucose metabolism, seen in up to 80 % of stroke patients in the chronic phase [79], which increases the risk for recurrent stroke or cardiovascular disease. It has been proposed that elevated intramuscular fat may be associated with insulin resistance and that insulin resistance is more pronounced in fast muscle fibers [78]. A reduction in exercise capacity after stroke could be due to impaired cardiovascular, respiratory or neuromuscular functions. A sedentary lifestyle e.g. due to high energy expenditure in ambulation, involves a risk for further decline in aerobic fitness and muscle function. In a sub acute stage four to six weeks after stroke, peak VO_2 at cycle ergometry was 51% of normative values [86]. A treadmill exercise test one month after stroke showed $VO_{2\ peak}$ levels of 60% of the normative values of sedentary persons, which increased to 71% after six months without specific aerobic training [107]. In one study, $VO_{2\ peak}$ was related to the Barthel index, but no statistical differences between subjects with/without beta blockers were found [106]. Another study showed $VO_{2\ peak}$ values approximately one-third of normal in subjects with mild to moderate hemiparesis six months post stroke [111].

There are not many reports concerning the level of habitual physical activity after stroke. When measured by a step activity monitor, the ambulatory activity in a chronic phase was found to be extremely low [111]. Many factors may be related to the physical activity level, e.g. muscle strength, balance, cardiovascular fitness, cognitive function, fatigue, mood, environment and social support. Inactivity is a risk factor for stroke, and thus the premorbid physical activity level may be low. Five years after stroke, walking capacity measured by 6MW distance was still decreased as compared to normal and was strongly correlated with health related quality of life measured by SIS [118]. The importance of aerobic exercise after stroke for cardiometabolic health [79] and cognitive functions [70] is currently emphasized in the literature.

AIMS

The overall aims were to assess the energy expenditure in walking during different conditions, to evaluate measurement methods and to assess physical activity after stroke.

Specific aims were to:

- Measure and compare the energy expenditure of 30% BWS and full weight bearing treadmill walking in stroke and healthy subjects
- Measure and compare the energy expenditure and walking speed with and without a carbon composite AFO in stroke subjects.
- Investigate the reliability and validity of the Physiological Cost Index (PCI) compared to VO_2 measurement in stroke and healthy subjects.
- Investigate whether the energy cost of walking is associated with physical environment, perceived difficulties or physical activity late after stroke.

SUBJECTS AND METHODS

Study populations

An overview of the groups included in the different studies is given in Fig 3. All participants were recruited from the Rehabilitation Medicine Unit at Sahlgrenska University Hospital. The clinic provides comprehensive rehabilitation to persons of working age living in the area of Göteborg. Persons with a stroke diagnosis admitted for rehabilitation between 1995 and 2001 and fulfilling the inclusion criteria were asked to volunteer to be participants in the studies. As reference groups, staff members, relatives or friends were asked to volunteer. A total of 51 persons with stroke and 24 reference persons participated in the studies. Demographic and clinical characteristics are given in Table 1. All subjects received verbal and written information and gave their informed consent. All studies were approved by the Ethics Committee of the University of Gothenburg.

Inclusion criteria

First time stroke at least six months previous to the study, 18-65 years of age at onset and independent walking ability with/without a walking aid or an orthosis. (Studies I-IV)
Additional criteria: Study I – Stroke subjects should have experience of walking training with BWS. Study II - Participants should have been prescribed and habituated for at least three months to walking with a carbon composite AFO. Study IV: Participation in a previous study (of home rehabilitation) at the clinic [11].
Reference persons were included by the criteria of self-perceived good health and absence of walking problems (Studies I and III).

Exclusion criteria
In stroke subjects: unstable heart condition or severe communication problems (Studies I-IV).
Reference persons were excluded if they had cardiovascular disease (Studies I and III).
Pain or musculoskeletal problems affecting gait (Studies I, II and III).

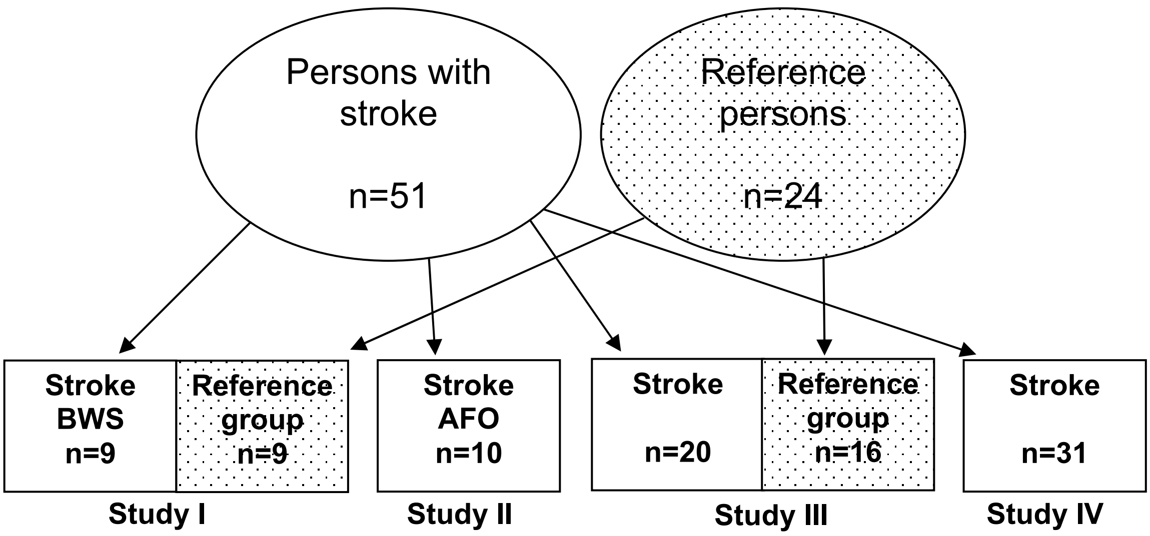

Fig 3. Study population

Table 1. Summary of demographic and clinical characteristics of the study populations

	Study I		Study II	Study III		Study IV
	stroke	reference	stroke	stroke	reference	stroke
n	9	9	10	20	16	31
Women/Men	3/6	3/6	2/8	3/17	5/11	9/22
Age, mean (min-max) (y)	56 (42-66)	57 (42-65)	52 (30-63)	54 (30-63)	48 (33-64)	60 (36-73)
Weight, mean (min-max) (kg)	79 (52-95)	75 (58-95)	76 (63-90)	79 (51-99)	75 (55-100)	81 (52-130)
Height, mean (min-max) (m)	1.73 (1.57-1.82)	1.76 (1.62-1.87)	1.76 (1.61-1.88)	1.77 (1.61-1.88)	1.77 (1.57-1.95)	1.73 (1.43-1.89)
Body Mass Index (mean) (min-max)				25 (19-30)	24 (20-29)	27 (20-37)
Cerebral infarction/ haemorrhage	6/3		5/5	11/9		18/13
Right/left/bilateral hemisphere lesion	3/6		5/5	12/8		15/15/1
Time since stroke, median (min-max) (mo)	15 (7-28)		16 (7-96)	19 (7-96)		101 (84-120)
Ankle foot orthosis (n)	2		10	15		7
Walking aid (n)	6		7	13		14
Cardiovascular disease (n)	4					20
Betablocker (n)			3	5		15

Equipment, measurements and instruments

Data were collected by the author (I-IV) together with a biomedical analyst or research nurse who performed the gas analysis (I-III). Outcome variables were chosen to give both an objective measure and the subject's perception, with intention to measure on different ICF levels [117]. An overview of measurement methods is shown in Table 2 and results of functional assessments at baseline are given in Table 3.

Table 2. Overview of measurement methods. X = outcome measure, x = descriptive

	Study I	Study II	Study III	Study IV
Body structure and function				
Oxygen consumption, gas analysis	X	X	X	
Electrocardiography	X	X	X	
Heart rate monitoring (Polar)				X
Physiological Cost Index			X	X
Borg Category Ratio Scale (CR10)	X	X	X	X
Fugl-Meyer Sensorimotor Assessment	x	x	x	x
Functional Ambulation Categories	x			
Modified Ashworth Scale		x		
Self-Administered Comorbidity Questionnaire				x
Activity				
30-m walk test	x			
6-minute walk test				X
Physical Activity Scale for the Elderly	x			X
Walking Habit Score				X
Participation				
Stroke Impact Scale, mobility section				X

Gas analysis and electrocardiography (I, II and III)

The energy expenditure and HR were estimated with a stationary, computerized system for breath-by-breath analysis [71] and electrocardiography (ECG) (Medical Graphics Cardiopulmonary Exercise Testing System, Medical Graphics Corp, St Paul, MN, USA). Gas exchange was recorded by measuring expired gas flow and expiratory O_2 and CO_2 concentrations. The system was calibrated before each measurement. A face mask covering the participant's nose and mouth was used; the mask was connected to a valve for gas exchange. HR was monitored with ECG via three chest electrodes. The system gave continuous information, breath-by-breath, on levels of VO_2, VCO_2, RER, ventilation and HR. Mean values given every 30 s were used for further calculations. VO_2 was divided by walking speed for estimation of energy cost per distance.

The participants were asked to refrain from nicotine and caffeine intake for one to two hours before the test. Each measurement was preceded by ten minutes of seated rest for habituation to the mask before the valve was attached and baseline registration started. The methods errors of VO_2 calculated in study I were between 4.5% and 10.1%.

Treadmill (I, II and III)

A motorized treadmill (Fig 1, TR Spacetrainer, TR Equipment AB, Box 116, 57322 Tranås, Sweden) was used for the walking measurements in studies I-III. The treadmill size was 0.5 x 1.6 m and speeds between 0 and 2 m/s were eligible with a stepless increase. A handrail was mounted in front of the walkway, and the subjects were allowed to use a light balance support if needed. All participants wore their own preferred walking or training shoes. The participants were habituated to walking on the treadmill under the different conditions for five to ten minutes prior to data collection.

Body Weight Support (I)

The treadmill was attached to a weight supporting apparatus (Fig 1) and BWS could be set at any level between 100% and 0%. The suspension system followed the vertical displacement of the body so that the selected BWS level was held constant throughout the gait cycle. For BWS, the subject wore a modified climber's harness with adjustable belts around the pelvis and thighs. The shoulder straps of the harness were attached to a point centered above the subject's head.

Ankle foot orthosis (II, III)

A standard, carbon composite AFO (Toe-off, Camp Scandinavia, Helsingborg, Sweden) (Fig 2) individually fitted for each person was used.

Heart rate monitor (IV)

HR was measured with a Polar HR monitor (Polar Electro Oy, Professorintie 5, FIN-90440 Kempele, Finland) with storing function. The transmitter was attached with a chest belt and the HR was stored every five seconds.

Physiological Cost Index (III, IV)

Prior to the first trial, the test person rested seated in silence for about five minutes to achieve stable resting HR. Resting HR was then logged each minute during the following five minutes.
In study III, HR was registered by ECG and walking HR was registered during five minutes of treadmill walking at the pre determined individual, self-selected speed, which was held constant throughout the test. In study IV, HR was measured with a Polar heart rate monitor. Over ground walking was performed at the self-selected speed on an oval, 30-m indoor track and a 30-m outdoor, level track for six minutes. The distance was registered to the closest meter. A seated rest of five to ten minutes was carried out between the tests.
To obtain the PCI value, the mean HR of the last 2.5 (study III) or five (study IV) minutes at rest and the last three minutes at work, was calculated. The distance covered during the over ground test was divided by time to give the speed in meters/min.

$$PCI = \frac{HR_{at\,work} - HR_{at\,rest}}{Gait\,speed\,(m/min)}$$

30 m walk test (I)

Self-selected and maximum walking speeds were calculated from the time measured with a stopwatch, for walking 30 m on a level surface in a corridor [103]. The participants wore their preferred walking shoes and assistive devices were used if necessary. Measurement of self-selected walking speed has been shown to have high reliability and validity in stroke patients [176]. Reference values from a Swedish urban population sample are available [157].

6-minute walk test (IV)

Walking was performed both on a 30-m indoor track in a silent corridor and on a 30-m outdoor, level track on bare ground in a quiet garden. Tests were performed during spring or early autumn at different weather conditions except in heavy rain. A cone at each end marked the track. The subject was instructed to walk and pass around the cones during a period of six minutes at his/her self-selected speed and was allowed to stop if necessary. No encouragement was given except that the subject was given information about the remaining time every minute. After six minutes, the subject was asked to stop and rate perceived exertion. The distance was registered to the closest meter. The test-retest reliability for 6MW has been shown to be high in subjects >6 months after stroke [42, 48].

Borg CR10 (I-IV)

Individuals' perceived exertion or difficulty in walking has been shown to correlate well to the work load. The perceived exertion was rated on the 12-point Borg Category Ratio Scale (CR 10) [123] ranging from 0 to 10. In study I, the participant was asked every two minutes to point at a number on the scale. In studies II-IV, the rating was carried out immediately at the conclusion of the walking test.

Fugl-Meyer Sensorimotor Assessment (I-IV)

Motor and sensory functions in the lower limb were assessed according to the Fugl-Meyer Assessment of sensorimotor recovery after stroke [51], which is a three-point ordinal scale with subsections for the upper and lower extremity functions. The maximum motor score for the lower limb is 34, indicating normal movement control. Excellent reliability and validity have been demonstrated [53]. In the present study, the sensory function in the paretic leg was classified as "impaired" or "not impaired", compared to the non affected side.

Modified Ashworth Scale (II)

Muscle tone was rated on the 6-point Modified Ashworth Scale [161], an ordinal scale ranging from 0 to 5 where 0 indicates no increase in muscle tone and 5 indicates rigid tone. The validity and reliability of this scale is considered to be limited [135].

Functional Ambulation Categories (I)

Functional walking ability with regard to need of assistance from another person was classified according to the Functional Ambulation Categories (FAC) [72], a 6-point ordinal rating scale in which 0 indicates non functional, dependent walking and 5 indicates independent walking on all surfaces. A strong relationship between FAC and temporal distance parameters has been shown in stroke subjects.

Physical Activity Scale for the Elderly (I, IV)

The physical activity level was scored by the Physical Activity Scale for the Elderly, a questionnaire that has been shown to be valid and reliable in an elderly community-living population in the USA [166]. The instrument may be administered by self-reporting or in an interview. A 12-item scale measures the number of hours per day spent on leisure, household and occupational activities during the most recent week. Each item has an activity weight that is multiplied by amount of time spent, giving a score where a higher value means higher physical activity level. The highest score obtained in the original study on elderly persons was 360 [166]. The questionnaire has been translated into Swedish; reference values from a Swedish urban population sample 40-69 years of age in ten year cohorts for men and women respectively (unpublished data from our laboratory) were used for comparison.

Walking Habit Score (IV)

The Walking Habit Score of a questionnaire for individuals with a transfemoral amputation [62] comprises five questions regarding outdoor walking distances during the last three months. Data from healthy reference persons are available [62]. In study IV, the subjects were interviewed and the answers were dichotomized into one group that was considered having reduced walking habits for the reason that they never or only once a week walked 500 m and one group, that walked more.

Stroke Impact Scale (IV)

The Stroke Impact Scale (SIS) [40] is a stroke specific comprehensive measure of health outcomes developed from the perspective of both the patient and caregiver. SIS comprises the dimensions of strength, hand function, mobility, activities of daily living, emotion, memory, communication and social participation. In study IV, perceived walking difficulties were assessed by four items of the mobility section of the SIS (3.0, Swedish version, interview), and the answers were dichotomized into one group with and one group without perceptions of walking difficulty.

Self-Administered Comorbidity Questionnaire (IV)

Comorbidity refers to diseases unrelated in etiology or causality to the principal diagnosis [146]. The Self-Administered Comorbidity Questionnaire (SCQ) [146] comprises 12 medical problems and gives the possibility to add three conditions. The subject is asked whether he/she has the problem, whether treatment is given and whether the problem limits activities. The instrument has been tested for validity and reliability in inpatients at medical and surgical care units [146]. SCQ was used in study IV in an interview. The presence of cardiovascular disease, pulmonary disease, diabetes, musculoskeletal pain and depression was reported in this study.

Table 3. Results of functional assessments at baseline

	Study I		Study II	Study III		Study IV
	stroke	reference	stroke	stroke	reference	stroke
Fugl-Meyer Sensory Motor Assessment, leg motor score, 0-34, median (min-max)	23 (11-33)		20 (16-23)	22		29 (20-34)
Sensory function impaired/normal (n)	5/4		5/5	10/10		
Functional Ambulation Categories, 0-5, median (min-max)	4 (3-5)					
Modified Ashworth Scale, 0-5, median (min-max)			4 (2-4)			
Physical Activity Scale for the Elderly, median (min-max)	29 (2-191)	237 (108-293)				115 (31-241)

Procedures

Walking with and without BWS (I)

Energy expenditure was measured by VO_2 at 0% BWS and 30% BWS in randomized order, first at the self-selected and then at the maximum speed. Each walking trial lasted for four to six minutes and the test session comprised a total of four trials. The trials were repeated with BWS conditions in the reverse order once within one week. The methods error was calculated. Nine persons with stroke and nine healthy reference persons participated.

Walking with and without AFO (II)

For each person, one speed at walking without (speed I) and one with (speed II) the AFO were determined on the treadmill during a habituation session. Two measurements of energy expenditure (Fig 4) were carried out with and without the AFO in randomized order at speed I (comparison A). A third measurement was made with the AFO at speed II (for comparison B). Each walking trial lasted for five minutes. The measurements were repeated in reversed order once within one week. Ten persons with previous stroke participated.

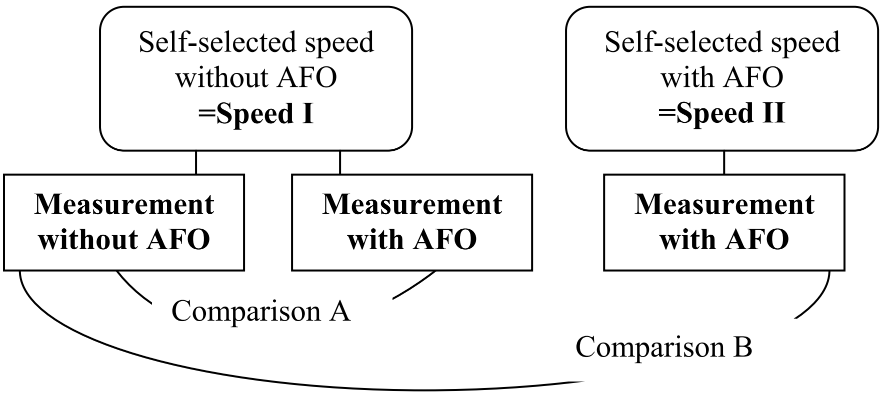

Figure 4. Speeds, trials and comparisons with and without AFO.

Measurement of energy cost by the PCI compared to VO_2 (III)

VO_2 and HR were measured during treadmill walking at the individual self-selected speed on two identical sessions within one week. Energy cost was assessed by VO_2 and PCI. Twenty subjects with stroke and 16 healthy persons participated. A second measurement was carried out without the AFO in 11 stroke subjects walking with an AFO. The test order was randomised.

Energy cost, walking habits and physical activity late after stroke (IV)

The energy cost was estimated by the PCI. A portable HR monitor was used during performance of the 6MW test and distance was registered. One indoor and one outdoor 6MW were performed in randomized order, and data were analyzed for influence of location and test order. Interview questionnaires were employed to assess walking habits, physical activity level, perceived walking difficulties and comorbidity. Regression analyses were performed for PCI and 6MW regarding associations with the other variables. Thirty-one persons with stroke participated.

Statistics

For descriptive statistics, mean values were given for interval and ratio data when the median and mean values were close and a normal distribution could be assumed whereas median values were used for ordinal data and skew distributions. Non parametric methods were used for data with small samples, non normal distribution and nominal or ordinal data. Parametric methods were used for normally distributed interval or ratio data. In study III the "95% range for change" was calculated as 1.96 x SD for the differences between the two measurements [57]. In the regression analysis in study IV, independent variables that correlated with the dependent variable ≥0.3 were included. The independent variables were checked for multicollinearity [127] and in the case of inter-correlation ≥0.7 only one variable was retained. P-values <0.05 were considered statistically significant. Statistical calculations were made by StatView (Study I), SPSS (Study II-IV) and SAS (regression for repeated measures, Study IV) software. An overview of statistical methods is presented in Table 4.

Table 4. Overview of statistical methods.

	Study I	Study II	Study III	Study IV
Dahlberg formula[32]	x			
Wilcoxon's sign rank test	x	x	x	x
Mann-Whitney U-test	x		x	x
T-test			x	x
Bland- Altman plot [12]			x	
Intraclass Correlation ($ICC_{2,1}$)			x	
Linear regression			x	x
Linear regression for repeated measures				x

RESULTS

Study I. Body weight support and energy expenditure

The energy expenditure measured as VO_2, was significantly lower with 30% BWS compared to 0% BWS, both at the self-selected and maximum walking speeds, in both the stroke and the reference groups (Fig 5). The stroke group had a lower walking speed and significantly lower VO_2 than the reference group ($p<0.001$). The stroke group had significantly lower HR with 30% BWS compared to 0% BWS, at both speeds. There was no significant difference in oxygen consumption between the two measurement sessions, and the methods error was within the acceptable level of 10%. The reduction in VO_2 was approximately 13% and 15% for stroke vs. 9% and 10% for the healthy subjects at their self-selected and maximum speeds, respectively.

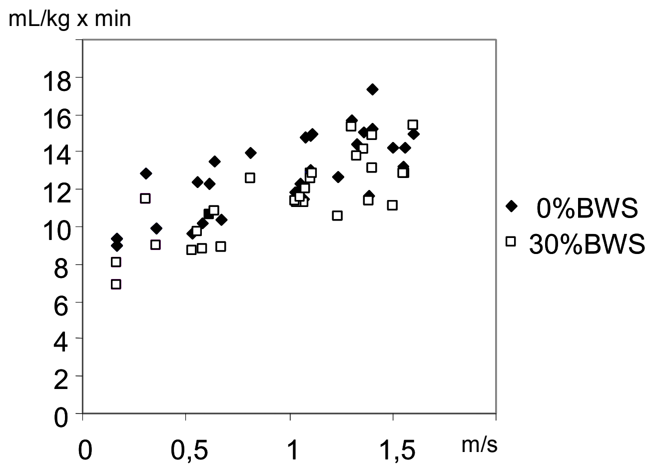

Fig 5. Walking speeds and VO_2 with 0 and 30% BWS, all subjects.

Study II. Energy expenditure with/without AFO

The results from the three trials are shown in Table 5 and Fig 6. The mean self-selected walking speed was 20% higher ($p = 0.027$) with the ankle foot orthosis than without.

Comparison A: (Unpublished data) Walking at Speed I with an AFO was 4% less energy demanding (VO_2 mL/kg/min) ($p=0.028$) than walking without an AFO at the same speed. The energy cost at speed I was also significantly lower with the AFO ($p = 0.037$) than without. HR or perceived exertion did not differ between the two conditions.

Comparison B: There was no significant difference in energy expenditure (VO_2 mL/kg/min) between walking at speed I without an AFO and speed II with an AFO. However, the energy cost, was 12% lower ($p=0.024$) with the AFO. HR and perceived exertion showed no difference between the two conditions.

Table 5. Walking speed, VO_2, energy cost, heart rate and perceived exertion with/without AFO

		Walking speed m/s mean (95% CI)	VO_2 mL/kg /min mean (95 % CI)	O_2 cost mL/kg/m mean (95 % CI)	HR beats/min mean (95 % CI)	CR10 median
Speed I	Without AFO	0.27 (0.20, 0.35)	8.6 (7.8, 9.4)	0.58 (0.43, 0.74)	85 (76, 93)	2
	With AFO	0.27 (0.20, 0.35)	8.2 * [A] (7.5, 8.9)	0.56 * [A] (0.41, 0.71)	84 (76, 93)	2
Speed II	With AFO	0.34 (0.21, 0.47)	8.8 (7.8, 9.8)	0.51 * [B] (0.36, 0.65)	85 (76, 94)	2

[A] Comparison without/with AFO at speed I, [B] Comparison without AFO at speed I/ with AFO at speed II, * $p < 0.05$
CR10 Category Ratio Scale 0-10, perceived exertion

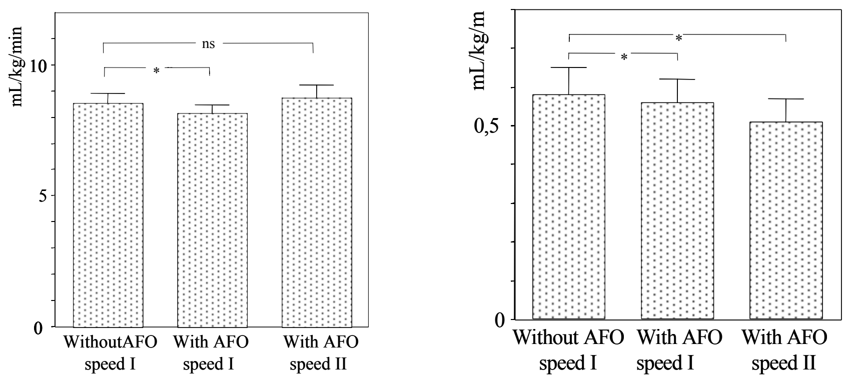

Figure 6**.** Oxygen consumption per minute (left chart) and oxygen cost per distance (right chart) during walking at different speeds and without/with AFO. Comparison A: without/with AFO at speed I, Comparison B: without AFO at speed I/with AFO speed at II. Mean values with SEM.

Study III. Measurement of energy cost by the Physiological Cost Index compared to oxygen uptake

Both the VO_2 and PCI measures showed an energy cost twice as high in the stroke group than in the reference group. The test-retest analysis showed no statistically significant differences between the two occasions in any variable except for resting HR in the healthy group. The ICC coefficients for PCI were 0.86 and 0.57 and for VO_2/m 0.98 and 0.87, for stroke and healthy respectively. Despite the low mean differences in PCI and VO_2 between the tests, the error interval for PCI was larger than for VO_2, particularly in the stroke group. The “95% range for change” [57] indicating the size needed to be a “true” change is shown in Table 6. The linear regression of PCI in a model including sex, age, group assignment and VO_2 could explain 53% of the variation.

In the subgroup of eleven persons with stroke measured both with and without an AFO, the VO_2 cost but not the PCI was statistically significantly lower with the AFO. The difference was small and probably not clinically relevant as the perceived exertion did not differ.

Table 6. The “95 % range for change” indicating a “true” change [57]

		SD differences (Test 1-2)	Change needed (absolute value)	% change needed
PCI	Stroke	0.285	0.56	74
	Reference	0.087	0.17	53
VO_2 mL/kg/m	Stroke	0.045	0.09	22
	Reference	0.020	0.04	21

Study IV. Energy cost, walking habits and physical activity late after stroke

There were no differences in PCI or 6MW distance between the indoor and outdoor situation or regarding test order. PCI and 6MW distance were correlated to motor function (Fig 7).

A regression model of PCI including sex, Body Mass Index (BMI) and “perceived difficulty” explained 24% of the variation (although not significantly) with the largest contribution (a tendency to significant) being perceived difficulty. Regression of 6MW distance in a model including BMI, PASE and perceived difficulty explained 48% of the variation (p=0.002). The PASE score and “perceived difficulty” contributed significantly in this model.

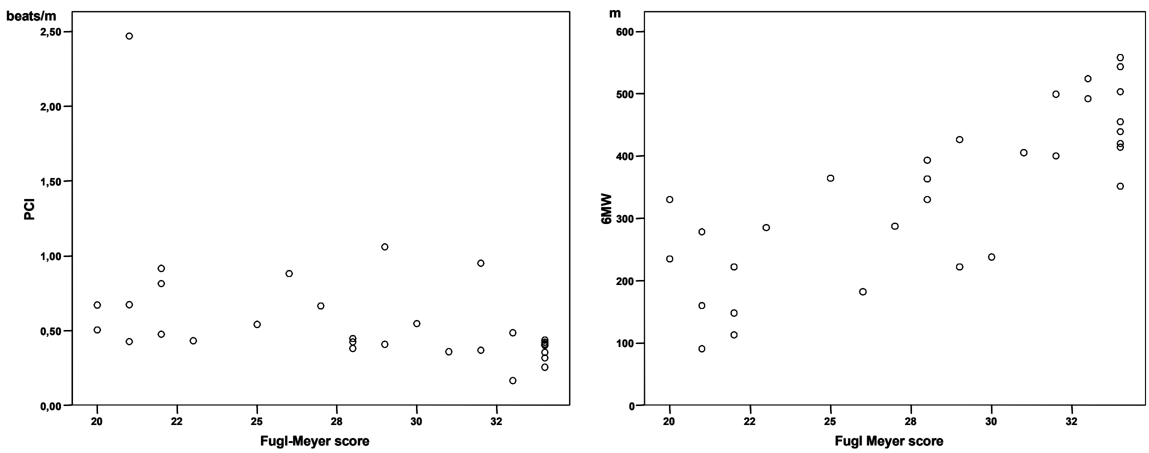

Fig 7. PCI and 6MW vs. Fugl-Meyer Sensorimotor Assessment motor score (leg section)

DISCUSSION

General discussion

The aims of these studies were to assess the energy expenditure during different walking conditions, compare different measurement methods and assess physical activity in a stroke population. The way in which different interventions used in stroke rehabilitation affect the energy cost is important knowledge since this patient group has low physical capacity especially in the early stage. In later stages a high energy expenditure of movement may hinder daily activities and health promoting physical activity. The main and most reliable outcome measure of energy expenditure is VO_2. However, the measurement equipment is expensive and cumbersome and unavailable in most clinical settings. It is therefore of interest to investigate a clinically suitable method for estimating energy cost, and one such method is the Physiological Cost Index based on heart rate measurement and walking speed. The method is easy to administer and has been used in different patient groups although its reliability and validity for a stroke population was not established at the time of the present work. The findings in the present studies demonstrate that measurement of energy expenditure of walking after stroke is reliable, however methods based on HR suitable for clinical use, may have lower reliability than direct measurement of VO_2.

Knowledge about energy demands of different interventions should be used to obtain the best possible circumstances for persons with walking disabilities. Providing BWS or using an AFO may be advantageous for walking training and daily walking for longer distances and at higher speeds. Persons with large motor deficits or low walking speeds may benefit most by a reduced energy demand. Higher walking speeds and longer distances are desirable not only for daily activities but also for exercise of cardiorespiratory function.

The importance of regular physical activity for prevention of cardiovascular disease has been highlighted in recent years and, while several studies show very low aerobic capacity after stroke, there are not many reports on physical activity level. We therefore wanted to explore whether the energy cost of walking was associated with walking habits and general physical activity several years after stroke. As a complement to objective measures, the self-reported activity level and perceived difficulties were explored. Self-report is a feasible way to investigate activity and participation. Cardiorespiratory fitness is often very low after stroke and, for physical health prevention as well as for enhancement of cognitive function efforts should be made to support regular physical activity in all phases following stroke.

Study population

This study population is not representative of all with stroke; however the subjects who were available can be considered representative of Swedish stroke patients below 65 years of age admitted to a rehabilitation unit. In this age group the proportion of men is higher, as is the incidence of haemorrhagic stroke. Still, the generalizability of the results is limited since the study groups were selected by convenience and the samples were small. The requirements for inclusion in studies I and II were extended to involve experience of the methods being studied, which limited the number of subjects available even further. As the consequences of a stroke may be very different, there was a large variation in functional performance between the subjects included. There were also large variations in time passed since the stroke.

Statistics

The nature of the present studies was mostly explorative; for this reason no calculations of sample size needed for statistical power were undertaken since we had no hypotheses about the size of the change that could be expected. In study III the sample size was considered satisfactory for analysis of correlation with a power of 0.8. In study IV the population available was limited to a certain number of persons from a previous study, and thus power calculation was not meaningful. During the study period, a development from simple non parametric significance testing to more advanced statistical analyses can be noted. This reflects both increased personal knowledge and a general trend seen in statistical analyses in rehabilitation studies.

In study III the use of correlation coefficients for reliability testing was considered unsatisfactory [4] since a large variation between subjects may give a false high correlation coefficient. In addition to the Intraclass Correlation Coefficient, we therefore chose to use Bland-Altman plots to describe the differences between the two tests. For validity testing, linear regression was considered more informative than calculation of the correlation coefficient.

The number of independent factors allowed in the regression analyses in study IV was limited due to the sample size. We decided to include the three variables with the highest correlation with the dependent variable and in the case of multicollinearity between independent variables, we included one.

Energy expenditure with and without BWS

Breath-by breath analysis is considered to be the golden standard for measurement of energy expenditure. The reliability is high as long as the system is calibrated accurately. Environmental factors may affect the measurement and dietary factors may contribute to erroneous interpretation of RER. Test-retest reliability in stroke subjects at sub maximal walking tests with similar systems has been shown [30, 38, 42]. In study I we calculated the methods error and found it to be below 10%, which was considered acceptable.

The incentive for this investigation was our clinical experience that some persons felt discomfort from the harness or the suspension, and felt walking with BWS unnatural. Regarding the facts that stroke patients in the early phase may be stress sensitive and may have impaired cardiac function and low physical capacity, we considered it important to investigate the energy demands of this exercise method. In theory, the energy expenditure should be lower with 30% BWS than with full weight bearing.

The 30% BWS level was chosen since it was the most frequently used in our clinic and is also recommended from kinematical aspects [69] in the early phase after stroke. We found that both stroke and healthy subjects had lower VO_2 when 30% BWS was provided, regardless of walking speed. The difference in VO_2 between the two BWS conditions was approximately 1.3 ml/kg/min for the stroke subjects who rated their perceived exertion one scale step lower with BWS. This difference corresponds to a 15% reduction in VO_2 in the stroke group. The difference in the healthy subjects was somewhat lower and they reported no change in perceived exertion. The size of the difference in energy expenditure is in line with other findings [26]. To our knowledge there are no data on what size of a change in VO_2 can be considered clinically relevant, but a difference of 15% might have some impact in a person with low aerobic capacity. We did not investigate whether there might be a threshold level for BWS where the energy expenditure is reduced; according to other studies 20% seems to be critical for a reduction [26, 75] at least in healthy persons. A threshold value might be different in different populations. In our study, the stroke subjects had significantly lower HR with BWS, which has also been reported in other patient groups [75, 174].

Treadmill walking with BWS after stroke may imply a safe way to achieve task-specific gait training for longer distances or at higher speeds than over ground. It has also been suggested to improve aerobic fitness [116], an issue currently emphasized.

Energy expenditure of walking with/without AFO

The hypothesis that walking with a carbon composite AFO would imply a reduced energy cost was partly supported by the present study. When walking at the same speed, VO_2 was 4% lower with the AFO than without, a difference that cannot be considered clinically significant. At such a low walking speed the energy consumption was so low that the AFO probably did not make much difference. This measurement was carried out to see which effect the orthosis itself had on the energy expenditure. To mimic a real situation, the subjects' possible walking speeds with and without the AFO were determined, which resulted in one lower speed without and a significantly higher speed with the AFO, in six of the subjects. No difference in energy expenditure was seen when the absolute values of VO_2 of these two conditions were compared. The energy cost at this comparison was 12 % lower with the AFO, however, which can be explained by the higher speed that could be achieved with the orthosis. In terms of the level of energy expenditure found in this study, this difference is probably not important from a clinical point of view.

However, the mean walking speed, increased by 0.07 m/s with the AFO, and this was 20% faster than without the AFO. There is little knowledge about the size of a clinically relevant change in gait speed. Perry described a change in 0.2 m/s as relevant after stroke [134] and a change of 0.1 m/s was considered meaningful in older subjects with hip fracture [128] . The clinically meaningful change may vary depending on the initial baseline score. A slow walker is presumed to benefit from a small change more than the case in which the initial speed is rather fast.

The effects of AFOs on energy cost reported in the literature are scarce and sometimes inconsistent, mainly demonstrated in small study samples without randomization. Small reductions in energy cost compared to unbraced walking were seen with two other types of AFOs than used in this study [28, 49]. A study of an orthosis affecting the whole leg reported an immediate decrease in VO_2 of 10% which was further decreased after three weeks of familiarization [159]. Increase in walking speed may have contingent effects on the energy cost, but the reports on effects of AFOs on walking speed are inconsistent [54, 99]. It is plausible that an orthosis affects gait more or less depending on the level of motor function or actual walking speed. We measured at two speeds but it might be of interest to assess the energy expenditure with and without an orthosis at various speeds or relate the effects to the level of motor function. Safety might be the most important reason for prescribing an AFO. Self confidence, safety [34], symmetry and dynamic balance may be improved [164]. It is of importance to evaluate different aspects of an orthosis for each individual, and measures may be helpful in the motivational process for using an aid.

Energy cost assessed by the PCI

Disadvantages of gas analysis are that the systems are expensive and require special knowledge to handle and are therefore in general unavailable for clinical use. The PCI gives a rough estimate of the energy cost of walking. In a recent study [50] of stroke subjects, PCI was concluded to be valid, although the variation between subjects was high in that study as it was in the present. The repeatability of PCI measurements has been questioned [17, 73, 76]. PCI has been suggested to be useful in comparisons within the same individual, but not between subjects [76]. While we found very small mean differences between test and retest, the dispersion of the differences was large in the stroke group. This implies that a large change in PCI would be necessary to be a true change.

The most apparent disadvantage of PCI is that the resting HR may be affected by many factors that are difficult to control. A rise in resting HR may result in a false low PCI value. It is therefore of great importance that the resting HR is measured in a calm environment. Some persons showed a rise in HR towards the end of the resting measurement and stated on questioning afterwards that they had felt impatient. Pharmacological treatment affecting HR is another source of error, but the intake of beta blocker did not seem to affect the PCI values, which was checked by comparing the groups with and without these drugs. PCI may also be affected by aerobic fitness. Polar HR monitors used in the present study are considered reliable [95] except in the case of more severe cardiac arrhythmia and have to our knowledge not been evaluated in persons with stroke. Since no ECG was performed in the present study, arrhythmic disturbances cannot be excluded. However, only one subject had known atrial fibrillation with a frequency within normal boundaries. In summary, despite some positive studies [50], the PCI might not have good validity as a measure of energy cost compared to VO_2.

We found an association between perceived walking difficulties and PCI and could demonstrate that PCI could discriminate between normal and pathologic energy cost on the group level, which was also shown in another study [50]. The method's sensitivity to change must be questioned as in the present study no difference between walking with and without an orthosis could be detected and a large variability was found between test and retest. PCI may be used as a rough assessment of energy cost and may have acceptable test-retest reliability on the same day, but not as good between different days. HR monitoring is not as reliable over days as VO_2 measurement but was found to be acceptable in elderly stroke subjects [38]. The relation to VO_2 has limitations and PCI is not equal to VO_2. PCI may be related to other dimensions of physical performance such as body weight and aerobic fitness, whose significance for the measure has not been investigated. There is still no knowledge about the size of a clinically relevant change in PCI.

Walking test on treadmill

Studying gait on a treadmill is advantageous for control and standardization of speed and required if stationary measurement equipment is used. There are conflicting opinions about whether results obtained at treadmill walking are transferable to over ground walking [2, 3, 119, 165]. A lower walking speed on the treadmill compared to over ground has been noted in healthy persons [3] as well as in persons with stroke [10], which is in line with our experience. A moving surface, a different surface texture and not having control over the speed involve higher balance demands. Familiarization is necessary; in one study six minutes was sufficient to obtain the same kinematics as over ground in younger persons [110] whereas older persons needed more than 15 minutes [167]. In our studies, five to ten minutes were given for habituation. There are also disagreeing reports on whether the energy expenditure differs between treadmill and over ground walking [58, 63, 119, 132, 133, 143].

Energy cost in relation to physical environment

The hypothesis in the fourth study was that the energy cost would be related to the physical activity level, outdoor walking habits or environmental setting. We could not support the hypothesis that the energy cost would be higher when walking on an outdoor track as compared to indoors. Furthermore, we could not confirm the hypothesis that energy cost would be associated with walking habits or physical activity level, but PCI and perceived difficulty tended to be associated and those who perceived difficulties were about the same subjects that reported less frequent walking. Because of our hypothesis based on clinical experience that walking on a rougher surface texture outdoors would be more demanding than on a floor indoors, for persons who have walking difficulties. The rationale for this was that this change in physical environment [22] would imply higher demands on neuromotor processes and thereby be more energy demanding than the indoor setting. Other studies have reported differences in PCI between indoors and outdoors in children with cerebral palsy [139], in stroke subjects differences in gait speed between three environments were found [102] and increased VO_2 was found on high grass compared to asphalt in both amputee and healthy subjects [131]. However, we found no differences in energy cost assigned to the change between the indoor and outdoor environment which could either be due to the subjects' adaptability, little importance of surface texture [168] or a low sensitivity of the measurement method. Since no portable equipment for gas analysis was available in our studies, we estimated the energy cost by the PCI despite the uncertainty about the validity and reliability of the method.

Walking distance

Looking at the distance walked, we found no difference between indoors and outdoors in the 6MW test either. The measure is useful, however, as it reflects ambulatory capacity in daily life and has been employed as an endurance measure in several stroke studies. We found associations between 6MW and BMI, physical activity level and perception of walking difficulties. Other factors not examined may contribute, such as balance, muscle strength and spasticity [129] or VO_2 [130]. It would be tempting to explain walking distance with level of muscle function as the primary cause of all physical disability, and we found an association between the Fugl-Meyer score and 6MW similar to findings in a previous publication [136]. In our study, 6MW distance was 50% of published reference values [20]. The reference values in that study are somewhat higher than in another [45] which could be due to different encouragement. In our study the participants received no encouragement other than being told every minute how much time was left. According to guidelines, the participant should be told to "cover as much distance as possible in 6 minutes" which may give another result than being told to "walk as far as possible during 6 minutes at your self-selected speed". We used the data from the first trial since those are in line with most clinical procedures, but other authors have considered that performance becomes better with practice and have used a second trial for analysis [152].

Self reported walking habits and physical activity

We decided to classify walking a distance of 500 m less than or only once a week as reduced walking habits and found associations between reduced walking habits and motor function, 6MW distance and perception of walking difficulties. Walking habits may also be influenced by other factors such as physical environment and psychological and social factors [169].

The physical activity level as measured by the PASE was somewhat higher in the present study than expected. The PASE was initially developed for elderly persons, so the weighting of the activities may be too high for younger persons and household activities may be underestimated. In contrast, it could be that basic activities are more strenuous for persons with physical disabilities. According to the PASE reports we could see that two-thirds of the participants were physically active to some extent at least 30 minutes per day, five days a week, which is near the recommendations for prevention of cardiovascular disease. In contrast, the walking difficulties reported by two-thirds of the subjects make it likely that this activity did not reach the recommended moderate intensity. No knowledge about a possible relationship between low aerobic fitness and physical activity level or walking habits is available. It is not known how much of a contingent decrease in exercise capacity is due to motor impairments vs. inactivity after stroke. We have no information on the participants' attitudes towards physical activity or the physical activity level before stroke.

Self-reports may be erroneous, particularly in persons with brain injury, but we found a high concordance between objective and self-reported measures. The Stroke Impact Scale is developed for and well documented after stroke, whereas the questionnaire on walking habits and the PASE have not previously been used after stroke. However, the development of the PASE is well documented [166] and, even though it has not been tested for reliability or validity in a stroke population, we have found it useful. Objective measurement of physical activity can be made with accelerometers and may be preferred in some studies, but if exactness is not needed self-report is an easily administered method for obtaining this information.

CONCLUSIONS

- Treadmill walking with 30% body weight support seems to be less energy demanding than walking full weight bearing, in stroke and healthy subjects.
- A carbon composite ankle foot orthosis may decrease energy demands and increase walking speed after stroke.
- The Physiological Cost Index is not as valid and reliable for assessment of energy cost as measurement of oxygen uptake, but can give a rough estimate in persons with stroke. For research purposes, VO_2 is preferable.
- The energy cost of walking several years after stroke showed a tendency to be associated with perceived walking difficulties but not with physical activity level or whether performed indoors or outdoors on level ground. The walking distance was associated with physical activity and perception of walking difficulties.

CLINICAL IMPLICATIONS

- Walking with body weight support may be feasible for early walking training after stroke and enable walking training and aerobic exercise for persons with low physical capacity.
- In persons with low walking speed or increased energy cost of walking, an ankle foot orthosis may enhance walking ability. Individual evaluation of effects of orthoses or walking aids on gait speed and energy cost should be made and evaluated after some time.
- The Physiological Cost Index may be used as a clinically suitable assessment of energy cost on the individual level. If measured on the same day, the reliability may be acceptable.
- Interventions aiming at improving a feeling of safety are important for increased walking distance. Walking training with increased demands in different situations and use of orthotic or walking aids in addition to endurance exercise may enhance walking ability and increase daily physical activity. The level of physical activity after stroke should be assessed and support to find and maintain regular physical activity may be required for general health purposes.

FURTHER QUESTIONS

- Does gait training with BWS initiate early walking ability, enable higher walking speeds, longer walking distances and aerobic fitness after stroke?
- How does the use of orthosis affect motor function, symmetry, walking speed, distance, energy cost and accessibility to different environments? Are persons with a defined motor, balance or walking function more likely to benefit from an orthosis? How is patient compliance with prescriptions of aids?
- Which levels of change in walking speed or energy cost are meaningful for the individual?
- Does the energy cost of walking affect activity or participation? Are there other factors that are determinant for participation?
- Which levels of aerobic fitness can be reached with exercise, with different levels of motor function?
- How can persons with stroke be supported to increase and maintain regular physical exercise?

SAMMANFATTNING PÅ SVENSKA (Summary in Swedish)

Studier av energiförbrukning vid gång efter stroke

Ett förändrat rörelsemönster vid gång är vanligt efter stroke och kan medföra ökad energiförbrukning. Kunskap om energikrav är viktig för att kunna underlätta gång och daglig aktivitet. Syftet med detta arbete var att mäta energiåtgång i olika situationer, utvärdera mätmetoder och få en uppfattning om fysisk aktivitetsnivå efter stroke.

Totalt ingick i fyra olika studier 51 personer med stroke med en medelålder av 56 år och 24 referenspersoner. Energiförbrukning beräknades genom mätning av syrgasupptag, hjärtfrekvens och upplevd ansträngning. Studie I jämförde gång med och utan kroppstyngdsavlastning med hjälp av en sele, på rullband vilket är en träningsmetod som används efter stroke. Att med hjälp av sele gå med kroppstyngden avlastad 30% visade sig vara mindre energikrävande än att gå med full belastning, både för personer med stroke och friska personer. I studie II mättes energiförbrukningen då personer med stroke gick utan respektive med en fotledsskena. Med skena kunde personerna gå lite snabbare och med något lägre energiförbrukning än utan skena. Studie III syftade till att jämföra två metoder för att beräkna energikostnaden vid gång. Mätning av syrgasupptag jämfördes med en mätmetod baserad på hjärtfrekvens (som ger ett indirekt mått på energiförbrukning) och gånghastighet. Mätning av syrgasupptag kräver avancerad apparatur som i allmänhet inte är tillgänglig, medan hjärtfrekvens enkelt kan mätas med ett pulsband vilket finns på de flesta sjukgymnastikavdelningar. Beräkning av energikostnad utifrån hjärtfrekvens visade sig fungera men inte med samma precision som mätning av syrgasupptag. För att få en uppfattning om energikostnad hade något samband med gångvanor och fysisk aktivitetsnivå flera år efter stroke, genomfördes i studie IV mätning av hjärtfrekvens vid gång inom- och utomhus medan personerna gick så långt de kunde på sex minuter. Personerna fick svara på frågeformulär avseende om man upplevde gångsvårigheter, hur ofta man gick bestämda sträckor och i vilken omfattning man ägnade sig åt olika fysiska aktiviteter på fritid och i arbete. Energikostnaden jämfördes med svaren men något säkert samband mellan de använda måtten kunde inte påvisas, däremot sågs ett samband mellan gångsträckan under sex minuter och upplevda gångsvårigheter och fysisk aktivitetsnivå.

Slutsatserna är att det förefaller vara mindre energikrävande att träna gång med hjälp av kroppstyngdsavlastning än utan och att metoden kan vara lämplig vid gångträning för personer med nedsatt fysisk kapacitet efter stroke. Vidare kan användning av fotledsskena underlätta gången så att man kan gå något snabbare och med något mindre energikrav än utan skena. Att mäta pulsökningen vid gång kan ge en grov uppfattning om energikostnad, men metoden kan inte ersätta direkt mätning av syrgasupptag. Energikostnad vid gång kan inte förklaras av underlaget eller den fysiska aktivitetsnivån enbart, däremot kan gångsträcka ha samband med fysisk aktivitetsnivå och upplevelse av gångsvårigheter.

ACKNOWLEDGEMENTS

I wish to express my gratitude to all persons who have contributed to this work. In particular I want to thank:

All my study participants for their interest and generosity with their time, effort and patience.

Katharina Stibrant Sunnerhagen, my supervisor and friend, for always being supportive, optimistic and helpful, willing to take your time even when being busy. You have been guiding me through a long process, with great patience and encouragement.

Carin Willén, my co-supervisor, for friendship, support, guidance and constructive criticism. You have encouraged me to continue at moments of despair.

Gull-Britt Henning and Frida Källman Domack for invaluable technical support and data collection by the gas analysis system.

Anna Ekman for constructive advice and help with statistical analyses.

Gunnar Grimby, for constructive criticism, interest and for sharing knowledge in the fields of physiology, science and writing.

My colleagues in the Rehabilitation Medicine research group, Caisa Hofgren, Ann Björkdahl, Åsa-Lundgren Nilsson, Annika Dahlgren, Beatrix Algurén, Cristane Carvalho, Elisabeth Brodin, Jurgen Broeren, Eva Esbjörnsson, Jerry Larsson, Ingrid Morberg, Margit Alt-Murphy and Eva-Lena Bustrén for friendship, interest, encouragement, discussions and assistance with acute computer problems.

My colleagues at the Physiotherapy department at Rehabilitation medicine and other staff at the Rehabilitation Medicine unit, for interest, help in finding study subjects, support and patience with me occupying rooms, moving things around and not being in place when asked for.

My colleagues and friends in the "Satellite group" group Kerstin Hagberg, Mari Lundberg, Anneli Gutke, Elisabeth Hansson, Gunilla Limbäck Svensson and Pia Thomée for high-qualitative discussions, constructive criticism and many good laughs.

The leaders and administrative staff of the Physiotherapy Unit at the Sahlgrenska University Hospital for paying bills and patiently keeping my time registration updated.

The administrative staff at the Department of Clinical Neuroscience and Rehabilitation, particularly Kirsten Toftered, Ulla Ohlsson and Eva Berglund for help on various issues.

Una Cunningham, Janet Vesterlund and Marc Rosenfeld for revision of the English language. Ylva Sunnerhagen for revision of the Swedish text.

All other friends for support, joyful fellowship and delicious dinners.

My family, Kjell, Agnes and Karin for love, patience and support and for reminding me at times what is significant in life. My mother Elsa, my late father Gunnar and Göran with family for love and care.

Financial support

These studies were supported by grants from the Norrbacka-Eugenia Foundation, the Swedish Medical Research Council (VR K2002-27-VX-14318-01A), the Swedish National Association for the Neurologically Disabled, Axel Linder's Foundation, the Swedish Medical Society (Olle Hööks Foundation), Hjalmar Svensson's Research Foundation, the Foundation of the Swedish National Stroke Association, the Foundation for Neurological Research at Sahlgrenska University Hospital (Insamlingsstiftelsen), John and Brit Wennerström's Foundation for Neurological Research, the Council of Research and Development of Gothenburg and Southern Bohuslän and the Physiotherapy Unit at the Sahlgrenska University Hospital.

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