Combined arm-leg ergometry in persons with a lower limb amputation

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General introduction

A lower limb amputation (LLA) is one of the main patient categories in rehabilitation medicine, with reported incidence rates showing considerable global variation, ranging from 3.6 to 69.4 per 100,000 person-years[1]. The incidence of diabetes mellitus (DM), global average age, ethnic differences and social deprivation all influence the incidence of amputation worldwide. More than 90% of the lower limb amputations in the United States and Western European countries are related to peripheral arterial disease and DM[2,3]. Other causes of amputations are cancer related, trauma related or because of congenital deficiencies[1]. The age-standardized incidence rate of first ever dysvascular LLA in Northern Netherlands in 2012–2013 was 7.7 per 100,000 person-years[4].

Many persons with a LLA due to peripheral arterial disease have had severely limited physical activity for weeks to months, sometimes years, prior to the amputation as a result of gangrene, osteomyelitis, pain or vascular claudication[5-7]. In addition, having a LLA results in a severe decline in physical fitness. This decline is caused by physical inactivity due to bed rest during hospitalization prior to and after the operation, a reduced ability to perform daily activities with a LLA[8] and the prevalence of co-morbidities, especially cardiovascular diseases[9].

> *Mr. X, 62 years old, has undergone a lower limb amputation because of peripheral arterial disease. After surgery he starts with rehabilitation. His main goal of rehabilitation is to walk with a prosthesis because he wants to reintegrate into his work as a teacher and wants to play golf. Before the amputation, he went through a period of inactivity of several months because of pain. Consequently, Mr. X experienced a decline in physical fitness. The physiotherapist involved wants to start an exercise training program to improve physical fitness. He needs to know the level of physical fitness at the start of the rehabilitation and has to make choices with regard to training intensity and duration.*

Lower limb amputation often leads to long-term disability. It has a major impact on almost every aspect of a person's life in the domains of the International Classification of Functioning, Disability and Health (ICF) (Fig. 1). It affects the body functions and structures and level of activities and participation[10,11]. For example, the function and/or structure of the leg is affected by the LLA, resulting in a change in gait and walking ability (activity) and probably in changes in work, family or sport participation. These different effects are in turn dependent on environmental (physical and social) and personal characteristics. Rehabilitation is one of those environmental factors designed to impact functionality of people with a disability. The main purpose of rehabilitation is to restore function and to regain optimal levels of functioning, participation and quality of life[12].

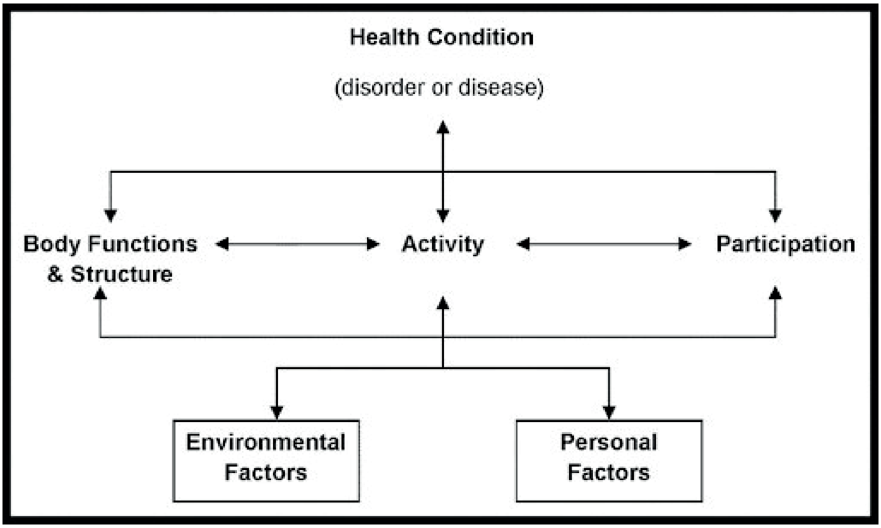

Figure 1. ICF model: International Classification of Functioning, Disability and Health[11].

Energy cost of ambulation after a lower limb amputation

Walking ability after a LLA is multidimensional defined and can be influenced by many different aspects, such as disease characteristics, personal and environmental factors. A relevant personal factor that may seriously impact walking ability is physical fitness. Physical fitness has been defined in several ways, but a generally accepted definition is the ability to carry out daily tasks with vigor and alertness, without undue fatigue, and with ample energy to enjoy leisure-time pursuits and meet unforeseen emergencies[13]. In relation to physical fitness, two other terms are often used; physical activity and exercise. Physical activity is defined as any bodily movement produced by the contraction of skeletal muscles that results in a substantial increase in caloric requirements over resting energy expenditure[13]. Exercise is a type of physical activity consisting of planned, structured, and repetitive bodily movement done to improve and/or maintain one or more components of physical fitness[13]. Physical fitness is composed of various elements that can be further grouped into health-related components (cardiorespiratory endurance, body composition, muscular strength, muscular endurance and flexibility) and skill-related components (agility, coordination, balance, power, reaction time and speed)[13]. Poor physical fitness influences the progress of rehabilitation in a negative way[14]. In addition, the energy cost of walking with a prosthesis is much higher compared to walking with two healthy legs. Energy cost of walking tends to rise with the level of amputation[15]. Rehabilitation in persons with a LLA is about relearning and training ADL (activities of daily living) and ambulation, preferably to regain walking ability and daily functioning, generally with the help of assistive technology. It requires practice to create controlled, comfortable, efficient and safe ambulation and ADL. Often the physical strain during rehabilitation is insufficient to elicit potential improvements in cardiorespiratory fitness. It is suggested that gait training with a prosthesis should be accompanied by some kind of endurance exercise training to improve the overall cardiorespiratory and muscular parts of physical fitness[6,14]. Individualized training requires individualized goal setting, based on valid, reliable and specific exercise capacity tests. In order to determine individual cardiorespiratory fitness in persons with a LLA, a safe, valid and specific exercise test, testing equipment and testing environment are essential.

Cardiorespiratory fitness and ergometry

The cardiorespiratory fitness or aerobic exercise capacity can reliably be measured in healthy individuals by determining the peak oxygen uptake (VO_2 peak)[16]. The VO_2peak can be directly measured by a peak exercise test or calculated from a submaximal exercise test[17]. Submaximal exercise tests are terminated when a certain percentage of the predicted maximal heart rate is reached. The oxygen uptake during the course of the test is recorded and the data are used to estimate VO_2peak based on a predicted, age and gender corrected, peak heart rate. Especially in persons with a LLA submaximal exercise testing can be unreliable[17]. The peak oxygen uptake cannot be reliably estimated from submaximal oxygen uptake and heart rate data when persons with a LLA take medication that influences the exercise capacity[18]. ß-Blockers for instance are known to reduce heart rate and systolic blood pressure[19]. In addition, persons with a LLA may have altered blood pressure and heart rate responses to exercise[18]. For these reasons VO_2peak cannot be predicted reliably from the submaximal oxygen uptake and heart rate. Given these conditions, VO_2peak of these persons has to be determined in an actual peak exercise test.

In order to measure the VO_2peak validly and reliably, it is important to apply a reliable testing protocol that involves the largest possible active muscle mass during exercise[16]. When using a large muscle mass during testing, more oxygen is consumed which allows a more reliable estimate of VO_2peak and heart function. This in itself is a challenge in persons with a LLA. Different ergometers were used in the past to evaluate aerobic capacity in persons with a LLA like a motor driven treadmill (only in those with walking ability with a prosthesis), unilateral bicycle ergometer, arm ergometer, rowing ergometer or a combined arm-leg ergometer[20-22]. Exercise testing via arm ergometry can provide useful data to generate a safe upper extremity exercise program[23]. However, arm ergometry is less specific in ambulant LLA, while it excludes functional leg muscle mass and does not stress the cardiovascular and the respiratory system as much as regular leg cycling or treadmill walking exercise. During arm ergometry peak oxygen uptake will be 50 to 70% of peak oxygen uptake during bicycle ergometry[24-26]. For reaching higher levels of VO_2 in persons with a LLA, it is attractive to use both arms and the unaffected leg. The use of a bicycle ergometer with one leg[27] is limited in applicability as persons with a LLA often need help to make the cycling movement with one leg, it is more difficult to maintain balance, and the muscle mass of only one leg is applied. Combined arm-leg ergometers have the advantage that a person applies a large muscle mass, since arms, trunk as well as leg(s) are contributing to peak power production.

A pilot study[28] showed that combined arm-leg ergometry with the Cruiser ergometer (Fig. 2), is appropriate to test the cardiorespiratory fitness in persons with a unilateral LLA. The main advantages of the Cruiser ergometer are that persons with a LLA can safely perform the test in a relatively low sitting position with proper back support and with support for the residual limb, while using one leg, both arms and trunk, without external help (e.g. a therapist). The Cruiser ergometer allows a combined cyclic action of the trunk and arms that push and pull both handles in an synchronous manner, while the sliding seat is pushed and pulled back and forth by the actions of the leg(s), trunk and arms. Persons with a LLA require the use of a balance-securing leg support for the amputated leg that connects to the frame under the seat.

Figure 2. The Cruiser, a combined arm-leg, ergometer with the special purpose leg support.

Gross mechanical efficiency and learning effects

The combined arm-leg movement on the Cruiser ergometer is a different cyclic multi-limb exercise compared with the oftentimes well-trained leg movement on the bicycle ergometer. Most people in the Netherlands are used to cycling. The movement on the Cruiser ergometer is for most people an unknown form of cyclic multi-limb exercise. This implicates that the movement may be subject to natural motor learning, i.e. learning through practice. With natural motor learning in cyclic motor actions, the movement becomes more smooth and efficient, reducing energy cost, while optimizing technique of movement and force production. In learning a (novel) cyclic exercise (e.g. walking, cycling, wheelchair propulsion) the underlying motor learning processes can be monitored adequately with physiological measures such as energy cost and gross mechanical efficiency (GE) during submaximal exercise intensities[29,30]. Assuming that biological systems inherently seek for optimal motor performance in terms of strain and metabolic costs, novel users of the Cruiser ergometer may be subject to motor learning. They inherently learn to fine-tune the arm trunk and leg movements, force production and muscle activation patterns in timing and co-contraction thus optimizing metabolic costs at a given power output and muscle effort. From that perspective, it is important to understand the physiology of a novel cyclic task, such as Cruiser ergometry, and the motor learning effects in terms of submaximal cardiorespiratory variables, GE and perceived exertion. Submaximal cardiorespiratory variables are heart rate, oxygen input, carbon dioxide output, breathing frequency, ventilation and respiratory exchange rate. The rate of perceived exertion is a psychophysiological outcome that can easily be determined by asking the patient at the end of the exercise test to score their level of exertion on a 10 point Borg scale[31]. The GE is defined as a percentage of external work (work output (W)) performed in relation to the total metabolic production of energy (internal metabolic power produced by the subject) which can be determined during steady state submaximal exercise from the oxygen uptake and respiratory exchange ratio (RER)[32]. Gross mechanical efficiency is indicative of the whole body task efficiency and may help elucidate potential learning or skill requirements. A high efficiency is important in the effective use of limited energy resources in many patient groups and may be helpful in preventing mechanical overuse[33,34]. Gross mechanical efficiency is dependent on the work load, speed, the detailed characteristics of the task (use of arms or legs or both, their rhythm and whether or not the task is simple or complex), the amount of active muscle mass and coordination of the movement, as well as individual training status.

Exercising on the Cruiser is a cyclic exercise, and assumed as a somewhat complex movement, in which arm and leg movement have to act together over time and in repetition. Because of the seemingly complex nature of combined arm-leg movement, it is imaginable to find motor learning effects when the exercise is repeatedly practiced, as is for instance seen in manual wheelchair studies[29,35-37]. For the Cruiser ergometer it has not been tested yet whether or not learning effects are prominent when exercising on it. One-legged Cruiser exercise is expected to be more complicated than two-legged exercise, due to stability issues and a lower muscle mass involved. As such a lower GE and higher physical strain are expected in one-legged Cruiser exercise compared to two-legged exercise at the same external power output and speed.

Cardiopulmonary exercise testing and exercise prescription

The Cruiser ergometer can potentially be used both as a training as well as an exercise testing device. However, a suitable test protocol for the Cruiser ergometer to measure the peak aerobic capacity in persons with a LLA is up to now not available. Also no publications are available about the optimal practice or training dose for Cruiser ergometry during rehabilitation after a LLA.

Clinical cardiopulmonary exercise testing protocols for leg ergometry are used for evaluation of exercise intolerance and exercise-related symptoms and for measuring the peak aerobic capacity[16]. With these results the optimal individual training dose can be defined. This can be related to a percentage of maximal exercise capacity or maximal heart rate or linked to the concept of the so-called lactate threshold[38]. For instance, the three-phase model of lactic acid accumulation with two ventilatory thresholds can be used for exercise prescription[39]. There are many names for these thresholds. The most commonly used semantics are anaerobic threshold and respiratory compensation point (Wasserman) or first (VT1) and second (VT2) ventilatory threshold[39]. We prefer in this thesis the VT1 and VT2. The level of the ventilatory thresholds is age, exercise modality, and protocol specific[16]. The VT1 and VT2 increase with age when expressed as percentage (%) of VO_2max predicted. Arm exercise results in lower ventilatory thresholds compared to leg exercise and bicycle ergometry results in lower (5-11%) values versus treadmill exercise[16]. The determination of the VT1 and VT2 is also protocol specific, while the best protocol to reach the peak exercise capacity within 10-12 minutes has to be individually chosen. The determination of the VT1 and VT2 is helpful as an indicator of level of fitness, for safe and efficient exercise prescription, and to monitor the effect of physical training[38]. When using the Cruiser ergometer for exercise testing in persons with a LLA, it is important that evaluation of undiagnosed exercise intolerance, exercise-related symptoms and determination of peak aerobic capacity is possible in a feasible, safe, reliable and valid way. In addition, with the results of the exercise test, individual prescription of the optimal training dose during the rehabilitation program after a LLA should be possible.

Aims of the thesis

The general aim of this thesis is to determine whether the Cruiser ergometer is clinically applicable as an instrument for cardiopulmonary exercise testing in persons with a LLA.

In this respect, the sub-aims of this thesis are:

- To compare and understand the physiology of submaximal cyclic exercise on the Cruiser ergometer, regular cycling and treadmill handcycling on cardiorespiratory variables, gross mechanical efficiency (GE) and perceived exertion in healthy persons.
- To study potential motor learning effects during low-intensity submaximal steady state one-legged and two-legged practice on the Cruiser in healthy persons with respect to GE and cardiorespiratory strain.
- To establish the repeatability and validity of peak exercise testing on the Cruiser ergometer in a population of healthy persons.
- To determine the feasibility, safety, and reliability of (sub)maximal exercise testing on the Cruiser ergometer in a study population with a LLA.
- To determine the inter-observer and intra-observer reliability of the first (VT1) and second (VT2) ventilatory thresholds in subjects with a unilateral LLA and healthy subjects during a peak exercise test on the Cruiser ergometer.

Based on the outcomes of this thesis, future work is intended to lead to the development of an elaborated exercise test protocol for persons with a LLA using the Cruiser ergometer. In addition, in future, based on an individual exercise prescription for persons with a LLA , Cruiser ergometer-based training programs will be developed to improve the physical fitness during and after rehabilitation.

Thesis outline

In **chapter 2** the GE, cardiometabolic strain and perceived exertion of low-intensity Cruiser ergometer exercise is described and compared with leg cycling and hand cycling. Ten healthy men and 12 healthy women enrolled in four discontinuous submaximal graded exercise tests on respectively the Cruiser ergometer, a bicycle ergometer, a handbike on a motor driven treadmill and again the Cruiser ergometer.

In **chapter 3** we explored in a low-intensity practice study among healthy individuals whether differences exist in cardiorespiratory variables and GE comparing one-legged and two-legged exercise on the Cruiser ergometer and whether motor learning occurs over time.

In **chapter 4**, the repeatability and validity of peak exercise testing on the Cruiser ergometer was established. Thirty healthy volunteers carried out three incremental exercise tests, once on the bicycle ergometer and twice on the Cruiser ergometer. The repeatability of the Cruiser ergometer peak exercise test was assessed by studying the mean values of the test-retest and the validity by studying the mean values of the bicycle and the two repeated Cruiser ergometer tests.

In **chapter 5** the feasibility, safety, and reliability of (sub)maximal exercise testing on the Cruiser ergometer was established. Seventeen persons with a LLA performed one submaximal exercise test and three maximal exercise tests on the Cruiser ergometer.

In **chapter 6** the inter-observer and intra-observer reliability of determining the ventilatory thresholds in subjects with a LLA and healthy subjects during a peak exercise test on Cruiser ergometer were described. Two observers determined two ventilatory thresholds of the exercise tests performed in the studies described in chapters 4 and 5.

In **chapter 7** the main findings of the previous chapters are recapitulated and discussed. Based on the information deduced from the reported studies, future research recommendations are formulated. Finally, recommendations are provided for a protocol for persons with a LLA for an exercise test on a Cruiser ergometer in rehabilitation practice.

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