University of Groningen

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

Simmelink, Elisabeth Katharina

*DOI:*
10.33612/diss.178118244

**IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.**

*Document Version*
Publisher's PDF, also known as Version of record

*Publication date:*
2021

Link to publication in University of Groningen/UMCG research database

*Citation for published version (APA):*
Simmelink, E. K. (2021). *Combined arm-leg ergometry in persons with a lower limb amputation*. [Thesis fully internal (DIV), University of Groningen]. University of Groningen. https://doi.org/10.33612/diss.178118244

**Copyright**
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

**Take-down policy**
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

*Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.*

Download date: 19-04-2025

# 2

# Gross Mechanical Efficiency of the combined arm-leg (Cruiser) ergometer: a comparison to the bicycle ergometer and handbike

E. K. Simmelink
E. C. Borgesius
F. J. Hettinga
J. H. B. Geertzen
R. Dekker
L. H. V. van der Woude

Int J Rehab Res. 2015 Mar;38(1):61-67

# Abstract

The combined arm–leg (Cruiser) ergometer is assumed to be a relevant testing and training instrument in the rehabilitation of patients with a lower limb amputation. The efficiency and submaximal strain have not been established and thus cannot be compared with alternative common modes of exercise. A total of 22 healthy able-bodied men (n=10) and women (n=12) were enrolled in four discontinuous submaximal graded exercise tests. Each test consisted of seven bouts of 3 min exercise ranging from 20 to 45W and was performed on, respectively, the Cruiser ergometer, a bicycle ergometer, a handbike, and again the Cruiser ergometer. Cardiorespiratory parameters were measured and rate of perceived exertion was determined. Gross mechanical efficiency (GE) was determined from power output and submaximal steady-state energy cost. Repeated-measures analysis of variance ($P<0.05$) was used to evaluate the effects of exercise mode, exercise intensity, ad sex. No differences in GE and cardiorespiratory strain were found between both Cruiser tests (GE 45W: men 13.0%, women 15.0%) and the bicycle test (GE 45W: men 13.2%, women 14.6%). GEs of handbiking (45W: men 11.2%, women 12.2%) were lower compared with the Cruiser and bicycle test results, whereas cardiorespiratory strain in handbiking was consistently higher. Apart from a lower rate of perceived exertion at the second Cruiser test, no differences were found between the repeated Cruiser tests. It can be concluded that GE and cardiorespiratory strain in submaximal Cruiser exercise are comparable with leg cycling, the repeatability was good, and no obvious learning effects were observed. The results of this study form a base for further research in patients with a lower limb amputation.

**Keywords:** ergometry, exercise testing, gross mechanical efficiency, lower limb amputation, physical strain, rehabilitation, submaximal exercise.

## Introduction

Patients with a lower limb amputation (LLA) experience a decline in physical fitness and higher relative and absolute energy costs during walking[1]. Evidence from Chin et al.[2] suggests that when prosthetic rehabilitation only covers walking with prosthesis, maximal aerobic capacity of patients with a LLA does not improve to the level of able-bodied persons. Therefore, training in prosthetic walking should be accompanied by some forms of endurance exercise training. Before commencing training, an appropriate maximal exercise test is required to determine individual work capacity[3]. At present, different types of ergometers and modes of exercise are available for exercise testing and training in rehabilitation: treadmill walking, wheeling and handbiking, bicycle ergometry, arm-ergometry and combined arm-leg ergometry. Treadmill walking and bicycle ergometry cannot be used in patients with a lower limb amputation without prosthesis or without assistance and are therefore not useful for training and testing in the early phase of rehabilitation when the patient does not have prosthesis yet. When using arm-ergometry for training or exercise testing, the considerably lower muscle mass of the upper body is involved and the $VO_2$ peak will be lower compared to leg exercise tests. The Cruiser ergometer (Enraf-Nonius[4] , Fig.1) might provide the ideal alternative, as it combines cyclic arm and leg exercise in the sitting posture. In the early stage, the residual limb can be securely positioned on a special support for the stump, whereas in a later stage the prosthetic leg can be actively involved. The main advantage of the Cruiser ergometer is the safe and comfortable exercise of a large muscle mass in early rehabilitation. Furthermore, the Cruiser ergometer has been shown a reliable and valid instrument to measure the peak oxygen uptake in healthy individuals during an incremental exercise test[5]. In a previous pilot study Vestering et al.[6] also concluded that peak exercise on the Cruiser ergometer led to a higher load on the cardiovascular and respiratory system compared to arm-ergometry in patients with a LLA.

**Figure 1**: The Cruiser ergometer, a combined arm-leg ergometer.

Apart from its suitability as a testing device, it is currently not known whether the Cruiser ergometer is a suitable training device for patients with a LLA. The exercise on the Cruiser ergometer seems a somewhat complex combined cyclic action of legs and arms that may require a learning period and may initially be slightly less efficient compared to the more common cycling mode. Therefore, before using the Cruiser ergometer as training device, it is important to know the submaximal physical strain, perceived exertion (RPE) and Gross Mechanical Efficiency (GE) of the Cruiser ergometer in comparison to common exercise cyclic exercise modes, as well as its repeatability[7,8].

Exercise on the Cruiser ergometer combines elements of cyclic upper and lower body exercise, such as handbiking, wheeling, rowing and cycling. The optimal values of GE of these exercise forms in literature are in the range of 10-20%, for example, handbiking 6-13%, wheeling 10%, rowing 17-19% and cycling 20% [9,10,11,12] and have been found to be dependent on work load, speed, task, amount of active muscle mass, coordination of the movement and temperature[3,13,14]. We expect to find a GE for the Cruiser ergometer in a similar range[15]. GE is an important measure, because it can be used to evaluate training as well as motor learning effects. Because of the complexity of a combined arm-leg movement, it is imaginable to find small learning effects when the exercise is repeated[16,17.]. When using the Cruiser ergometer as a testing and training instrument it is important to know whether there is a motor learning effect in the movement on the Cruiser ergometer.

Submaximal strain and GE are expected to be different between men and women. It is known that resting oxygen consumption is greater in men than in woman but also that absolute oxygen consumption on the bicycle ergometer is higher in men than in woman[18]. Therefore both men and woman participated in this study.

In the current study, the main goal was to determine the GE, submaximal cardio-respiratory strain and subjective strain in healthy able-bodied men and women during standardized submaximal Cruiser exercise in comparison to exercise on a bicycle ergometer and handbike. In addition the repeatability and motor learning aspects of Cruiser exercise were evaluated.

## Methods

### Participants

A total of 22 healthy participants (10 men and 12 women) were enrolled in the present study (Table 1). Exclusion criteria for participating in this study were as follows: age less than 18 years, a body mass index of more than 30, neuro-musculoskeletal disorders or complaints that could have affected the test, evidence or serious suspicion of cardiovascular diseases, stress or exercise related pain in the chest, pulmonary diseases, viral or bacterial infection for less than 10 days and use of medication for cardiopulmonary diseases[3]. The inclusion and exclusion was screened using the Physical Activity Readiness Questionnaire (PARQ)[19,20]. All participants signed an Informed Consent and all tests were conducted in accordance with the Declaration of Helsinki. The local Ethics Board of the Center for Human Movement Sciences (UMCG) approved the current experiment.

### Procedure and design

All participants performed four discontinuous submaximal steady state exercise tests on four separate days. The four tests were conducted at the same time of the day for each individual, with intervals of approximately one week between subsequent tests. All participants were asked to refrain from stimulants (caffeine, drugs, cigarettes, etc.), exercise and alcohol for at least 12 hours before testing. Each person was asked to have a light breakfast/lunch at least two hours before the exercise test, and normal hydration was requested. Before testing personal characteristics were determined (Table 1).

**Table 1** Personal characteristics (mean and SD)

| | **Age (y)** | **Body height (m)** | **Body mass (kg)** |
|---|---|---|---|
| Men (n=10) | 24.0 (1.8) | 1.86 (0.07) | 79.0 (10.5) |
| Women (n=12) | 22.1 (2.4) | 1.72 (0.06) | 65.8 (10.2) |

All tests started with three minutes sitting on the Cruiser ergometer, bicycle ergometer or handbike in order to obtain a baseline. Each exercise test consisted of seven (20W, 25W, 30W, 35W, 40W, 45W and again 20W) three minutes submaximal exercise bouts. The different cardio-respiratory measures: oxygen consumption ($VO_2$ (ml/ min)), carbon dioxide output ($VCO_2$ (ml/min)), breathing frequency (BF (breaths/min)), maximal ventilation (VE (l/min)), respiratory exchange rate (RER) and heart rate (HR (beats/minute)) were measured during the last 30 seconds of each of the 7 submaximal exercise bouts. Between each two bouts, the participant had a 30 seconds rest period in which the rate of perceived exertion (RPE) was determined on a ten points Borg scale[21]. In each new exercise bout the external work load was increased from zero to the desired work load, within ~5s.

The four exercise tests were conducted on the Cruiser ergometer (Fig 1), bicycle ergometer, the handbike exercise test on a motor driven treadmill and again the Cruiser test in the same sequence for all participants. The second submaximal exercise test on the Cruiser ergometer served to determine its repeatability as well as potential motor learning effects over time.

## Instruments & exercise modes

### Cruiser ergometer

The Cruiser ergometer[4] (Fig 1; Enraf Nonius, Delft, the Netherlands, 2011) is a combined arm-leg ergometer equipped with a comfortable seat. The feet are placed against a non-moving yet adjustable footrest. The footrest is used to push off; this makes the seat move backwards. The participant moves the seat forward again by pulling the handlebars with the arms. In this way, the arms and legs are used simultaneously to provide power output to the ergometer. The resisting load of the ergometer was gradually increased manually. The ergometer was set to operate at the constant power between 35 and 60 revolutions per minute (rpm). Participants were instructed to exercise at 50 rpm. The footrest was adjusted to the individual body height and was fixed for the two Cruiser tests. The accuracy of the Cruiser ergometer for the power output is ± 10 % and for speed ±2 rpm[4].

## Bicycle ergometer

The incremental submaximal bicycle exercise test was conducted on an electronically braked bicycle ergometer (Lode Excalibur, Ergo-line, Groningen, The Netherlands). The participants were instructed to cycle at 50rpm. Saddle and steer position were individually adjusted.

## Handbike

The incremental submaximal handbike exercise test was conducted on a motor driven treadmill (1.25m x 3.00m, Enraf Nonius, Delft, The Netherlands). The attach-unit handbike (mass 25kg; front wheel diameter: 20.9 inch; tire pressure: 8 bar, 800 kPA) consisted of a hand rim wheelchair (Double Performance, RGK Wheelchair Inc., Staffordshire, UK) and Tracker Challenger, a synchronous arm crank unit (Alois Praschberger, Niederndorf, Austria). The gear was held constant during the entire handbike exercise test so that a rpm of 50 was reached at a treadmill belt speed of 5 km/h (=1.39 m/s). During the exercise test the required load was determined using a Powertap (Powertap SL; CycleOps, Saris Cycling Group inc., Fitchburg, Wisconsin, US; sample frequency: 0.2Hz; reliability: ±1.5% between 0 and 1999 W) in the hub of the front wheel and by the use of a pulley system.

The pulley system (Fig. 2) was used to increase the workload during the exercise test on the handbike, on the basis of the individual powertap readings[22]. The load could be gradually increased by adding mass to the pulley system according to the following formula: $PO = (m \times g) \times v$. For instance to increase the load (PO) with 5 W at a velocity of $v = 1.39$ m/s a mass of $m = 0.367$ kg was added.

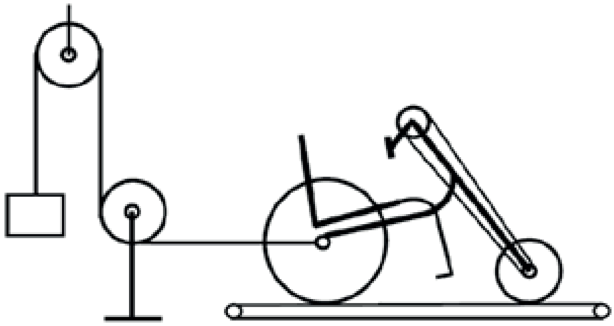

**Figure 2**: Pulley system used for regulation of power output level during the handbike exercise test on the motor-driven treadmill

## Outcome variables

The Oxycon Delta (Jaeger, Bunnik, The Netherlands) was set to measure breath-by-breath the cardio-respiratory parameters ($VO_2$, $VCO_2$, BF, VE and RER). The gas analyzer was calibrated for volume every session with a 3-l-syringe (Jaeger). Room air and a standard gas mixture of 18% $O_2$ and 5.0% $CO_2$ were used to calibrate the sensors. Heart rate was measured by a Polar heart rate monitor (Polar Transmitter Chest Strap, type T34, Polar Electro Nederland bv, Almere, The Netherlands). The metabolic power ($P_{met}$) was calculated using: $P_{met}$(W)=VO2 [(4.940RER+16040)/60][23]. The measured mechanical power output ($P_O$) divided by the calculated $P_{met}$ defined GE (%).

## Statistical analysis

A repeated-measures analysis of varince ($P<0.05$) was performed for each outcome measure to determine main effects between exercise modes (the Cruiser ergometer, bicycle ergometer and handbike). Exercise intensity (power output) was a within-participant factor, sex a between-participant factor.

A repeated-measures analysis of variance ($P< 0.05$) was also carried out on all outcomes for the Cruiser ergometer pretests and post-tests. Pretests and post-tests and exercise intensity were the within-participant factors and sex was again the between-participant factor. The differences in the RPE Borg-scores were assessed by the Wilcoxon signed rank test. A Bonferroni correction was applied in the posthoc testing to control for $\alpha$ inflation.

## Results

All 22 participants successfully concluded the study. RER was well below 1.0 in most tests, with the exception of the handbike test, where in the higher workloads for the female participants RER was slightly above 1.0. For those instances, energy cost and efficiencies were calculated using an RER value of 1.0.

### Three different exercise modes

No differences in GE or cardio-respiratory strain (apart from BF *P*<0.025) were found between both Cruiser tests (mean GE: 13.0 and 15.0% for men and women at 45 W) and the bicycle test (mean GE: 13.2 and 14.6% for men and women at 45 W) (Fig. 3a-d). GE's of the handbike test (mean:11.2 and 12.2% for men and women at 45 W) were significantly lower and cardio-respiratory strain was significantly higher compared to the Cruiser and bicycle tests. As expected, the GE increased throughout the test as external work was increased for all exercise modes (Fig. 3a). Similar main effects of power output were evidently found for the cardio-respiratory outcomes. Considering the RPE at 45W, all participants found the handbike test (RPE of ~3.0) significantly more exerting than the bicycle and Cruiser tests (both RPE of ~2.0).

### Cruiser test-retest

When comparing the GE and cardio-respiratory outcomes [apart from a single difference for RER at 20 W (P= 0,041)] (Fig 3a) of the first and second Cruiser test, no differences were found (range 0.151 > P < 0.888). Remarkably, RPE scores were lower for the second Cruiser test compared to the first test (P < 0.001 for all output levels).

### Sex

For men and women some small differences in GE can be noted (Fig. 3a). On all four modes and levels of power output, women were more efficient than men (P=0.003*)* and $VO_2$ scores were significantly higher in men (P=0.005, Fig. 3c). However, HR (Fig. 3b) and BF (Fig. 3d) of men were lower than that of women. In the resting phase before starting the exercise test $VO_2$ was lower for women than for men for all modes. The $VO_2$ scores in this relative rest condition before the start of the second Cruiser test was 393.0±72.9 ml/min for men and 327.8±90.9 ml/min for women (Fig 4).

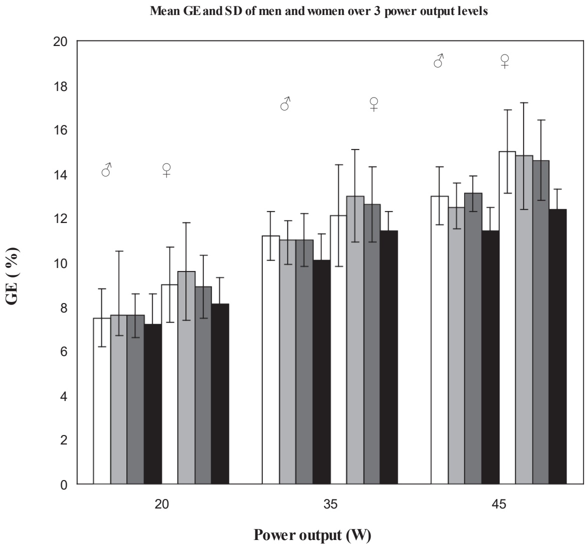

**Figure 3a**

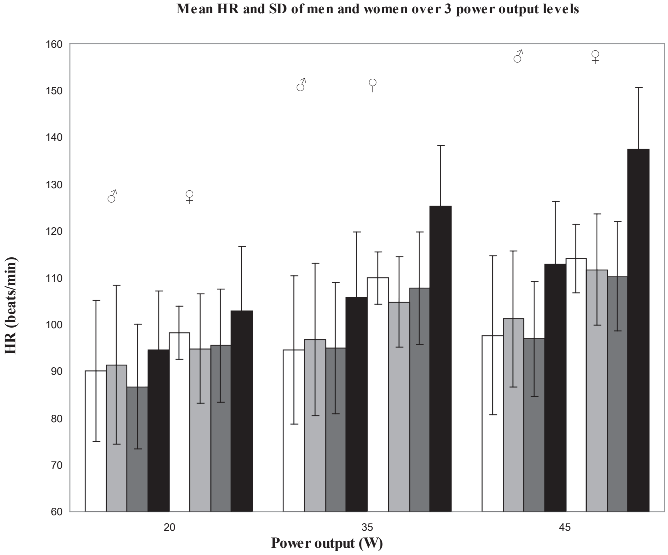

**Figure 3b**

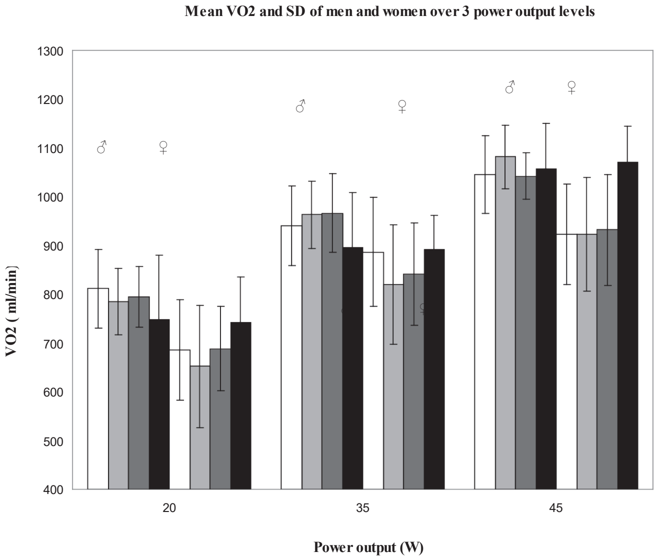

**Figure 3c**

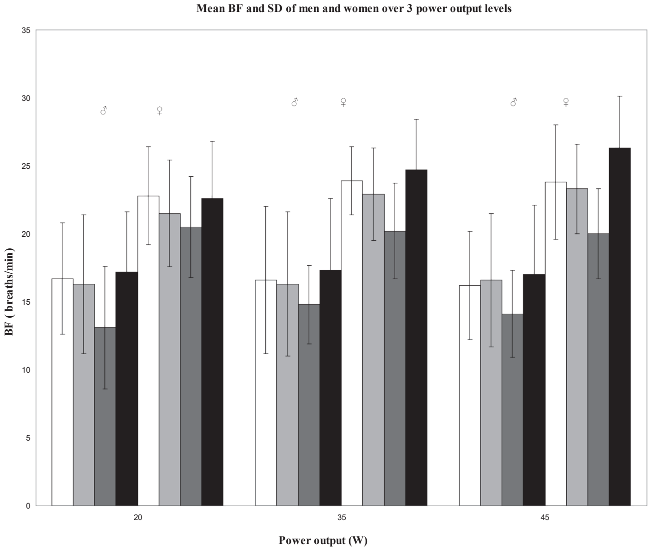

**Figure 3d**

**Figure 3a-d**: Representation of Gross mechanical efficiency (GE; a), Heart rate (HR; b), Oxygen uptake (VO$_2$ ; c) and Breathing freuency (BF; d) (mean ± SD) for men (n= 10; ♂) and women (n= 12; ♀) over 3 different output levels (20, 35 and 45 W) and the three different exercise modes Cruiser pre-test (white) and post-test (light grey), Bicycle test (dark grey) and Handbike test (black). All values were determined during the last 30 seconds of every 3 min submaximal exercise bout

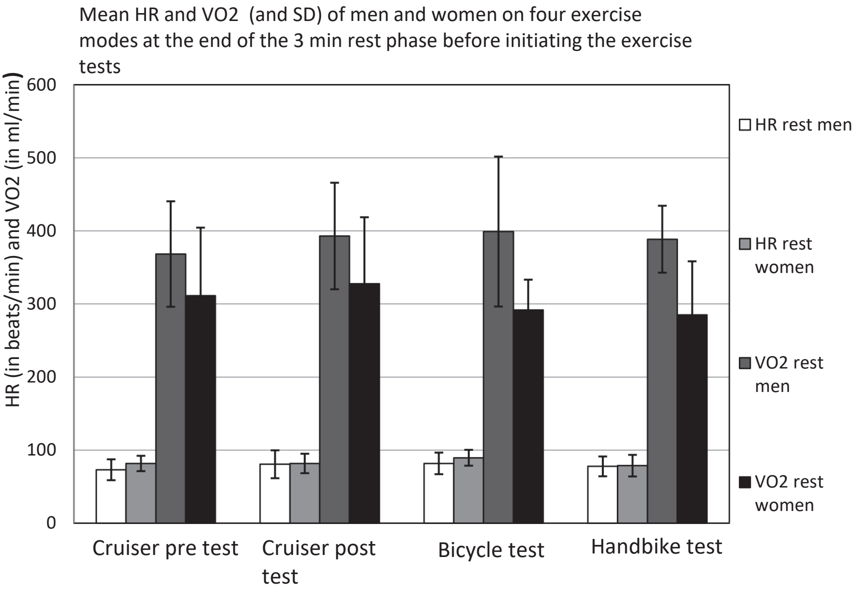

**Figure 4**: Representation of heart rate (HR) and Oxygen uptake ($VO_2$) for males(n=10) and females (n=12) at the end of the resting phase and prior to the start of submaximal exercise test in each of the three different modes. All values were determined during the last 30 seconds of the resting phase

# Discussion

This study shows that under the current experimental conditions and in the able-bodied participants, cardio-respiratory strain and GE during Cruiser ergometry are similar to exercising on a bicycle ergometer at the same range of power outputs (20-45 W). Handbiking at these power outputs is, however less efficient and more straining than Cruiser and bicycle ergometry. The repeatability of Cruiser ergometry was good and no learning effects were observed, other than a lower RPE on the second test. Finally, distinct differences in GE were observed between men and women in GE and cardio-respiratory strain at this range of submaximal power outputs.

## Three different exercise modes; differences and relevance

The intermittent combination of leg and arm exercise generates a similar GE and strain with the Cruiser ergometer as the continued alternating movement of the legs in cycling. The movement on the Cruiser ergometer seems more complex than that for Dutch people well trained in cycling movement. However, both arms and legs, and thereby more muscle mass, can be used during Cruiser exercise. This is a beneficial characteristic of the Cruiser ergometer, in addition to its safe and sitting form of exercise, which can also be performed with one leg. Exercise with the upper body only (handbike) produces a higher strain and lower efficiency[9]. The present study underlined these findings, and as expected, Cruiser ergometry was more efficient than handcycling. An efficiency comparable to that of cycling was shown.

To initiate and continue moving on the Cruiser ergometer the extensor muscles of the upper legs are used to push the participant (and Cruiser seat) backwards. This is beneficial with an amputation because the extensor muscles represent a huge percentage of the active muscle tissue in the upper leg. Ogata and Yano[24] have shown that if the leg muscles are more active during the exercise, the movement is more efficient. In the study of Simmelink et et al.[5], the maximal work load on the Cruiser ergometer was about 200W for healthy individuals. In the current study, seven bouts of 3 min exercise between 20 and 45W were performed by all the participants. This mild exercise level was chosen because patients with a LLA experience a decline in physical fitness because of inactivity and comorbidity. Especially in the period just after the amputation, low intensity exercise is necessary to prevent further deconditioning and start reconditioning. The Cruiser ergometer seems to be a suitable training instrument in this early period of rehabilitation.

The exercise intensity of cycling in this study is relatively low compared with most cycling studies focusing on solely cycling performance. In the literature, it can be found that GE improves at higher work rates[25], which explains why the values for GE in the present study (~14% at 45 W; ~8% at 20 W) are relatively low compared with the values presented in the literature (up to 20% at higher exercise intensities more relevant to cycling). The relative proportion of energy required for basal metabolism is relatively higher at the lower exercising intensities, leading to a lower GE[25]. Ambient temperature might be another important factor influencing GE[13]. However, the present study was carried out in a climate-controlled laboratory keeping exercise conditions the same throughout all testing; thus, we do not expect that this would have affected our results.

## Cruiser ergometer: repeatability and motor learning

Motor learning is often a crucial element in rehabilitation. Novice motor tasks (i.e. wheelchair propulsion and prosthetic walking) often require an extensive motor learning process. In previous research in healthy individuals, significant motor learning effects in wheelchair propulsion emerged after training, expressed in GE and parameters for the propulsion technique[26,27,28]. Although it was expected that exercising on the Cruiser ergometer is a fairly complex and unusual movement, no differences were found between the two Cruiser tests on the seven different power output levels for efficiency and most of the cardiorespiratory outcomes (except for a single RER value and the RPE), indicating that motor learning at these power output levels is short and not a dominant process. Indeed, the Cruiser ergometer seems to be a repeatable instrument at submaximal exercise levels in the healthy population and lower range of power output. The RPE results, initially being higher during Cruiser ergometry, suggest that with a brief practice (seven bouts of exercise of the pretest), exercising on the Cruiser ergometer becomes easier (indicated with the lower RPEs on the post-test). This must be taken into consideration when using the Cruiser ergometer as a testing instrument in patients who have not used the Cruiser ergometer before. To finally evaluate any potential motor learning elements in Cruiser ergometry, it is advised to replicate the work of De Groot et al.[26] and Vegter et al.[28] and systematically monitor the effects of low-intensity practice on the Cruiser ergometer.

## Sex

In this study, it was found that women were seemingly more efficient on the Cruiser ergometer, bicycle ergometer, and handbike compared with men at these submaximal absolute power output levels (Fig. 3a). Men showed a higher $VO_2$ compared with women (Figs. 3c and 4). Also, the $VO_2$ scores in rest for the second Cruiser test were higher for men, 393.0 ± 72.9 ml/min, compared with women, 327.8 ± 90.9 ml/min (Fig. 4). In agreement with these findings, Toth et al.[18] found that resting oxygen consumption was greater ($P < 0.01$) in men (233 ± 23 ml/min) than in women (190 ± 21 ml/min). The $VO_2$ resting scores in our study are somewhat higher than those in the study of Toth et al.[18] because these values were obtained just before the start of exercise and therefore the participants in our study were not completely relaxing. Yet, the results from Fig. 4 are indicative for a higher resting metabolism in men. Absolute oxygen consumption in the study of Toth et al.[18] was higher in men at 10 ($P <0.05$), 20 ($P < 0.01$), and 30 min ($P < 0.01$) of exercise on a bicycle ergometer. The lower GE in men in the current study at the current levels of power output may therefore be explained by their higher resting metabolism. In addition, another aspect may be that the absolute power output levels in the submaximal tests are relatively higher for the female participants than for the male participants as men can reach higher peak power outputs compared with women[29,30,31].

## Recommendations for future research

In this study, only healthy, relatively young, able-bodied individuals participated because they were able to perform the exercise test on these three different ergometers. These results provide a reference base to compare with future results in patients with a LLA of various fitness levels or other rehabilitation populations. Now, future studies can aim to collect data from LLA patients. Before extensively starting to train and test patients with a LLA on the Cruiser ergometer, it is advised that a group of healthy older individuals should be tested, more or less of similar age and physical fitness to patients with an LLA and in the one-leg and two-leg mode. For the current study population we did not need ECG and blood pressure monitoring for the submaximal exercise. To maintain safety throughout training and testing in older vascular amputees, ECG and blood pressure monitoring must be added as variables to the training and testing protocol.

When the participants exercised on the Cruiser ergometer with two arms and two legs, GE was the same as GE on the bicycle ergometer. Further research is necessary to explore whether this will be the same in patients with a unilateral LLA when exercising on the Cruiser ergometer with one leg and two arms. When the GE of exercising on the Cruiser with two arms and one leg is known, protocols for the Cruiser ergometer as a training instrument used by patients with an LLA can be formulated.

## Conclusion

In the present study, it was shown that GE and physical strain in submaximal exercise on the Cruiser ergometer were comparable with cycling exercise. The repeatability of Cruiser ergometry was good and no learning effects were observed, other than a lower RPE on the second test. The advantage for patients with an LLA of the Cruiser ergometer is the safe and comfortable exercise that is possible without prosthesis with one leg and two arms. This is the first study in which GE of the Cruiser ergometer has been described. Further research is necessary to describe training and testing protocols for the Cruiser ergometer in patients with a LLA. The results from this study in a nondisabled population represent a suitable reference base for patients with a LLA.

### Acknowledgements

The authors thank the participants for their effort and the technical service of the Center of Human Movement Sciences UMCG for their support during the project during various periods of practice.

# References

1. Van Velzen JM, van Bennekom CA, Polomski W, Slootman JR, van der Woude LH, Houdijk H. Physical capacity and walking ability after lower limb amputation: a systematic review. Clin Rehabil 2006; 20:999–1016.
2. Chin T, Sawamura S, Fujita H, Ojima I, Oyabu H, Nagakura Y, et al. % $VO_2$max as an indicator of prosthetic rehabilitation outcome after dysvascular amputation. Prosthet Orthot Int 2002; 26:44–49.
3. Fletcher GF, Balady GJ, Amsterdam EA, Chaitman B, Eckel R, Fleg J, et al. (2001). Exercise standards for testing and training: a statement for healthcare professionals from the American Heart Association. Circulation 2001; 104:1694–1740.
4. Enraf-Nonius, Delft, The Netherlands: Operating Instructions Cruiser 2011. Available at: http://www.enrafnonius.nl/index.php?option = com_doc man&task =search_result& Itemid = 61 (No longer available).
5. Simmelink EK, Wempe JB, Geertzen JH, Dekker R Repeatability and validity of the combined arm–leg (Cruiser) ergometer. Int J Rehabil Res 2009; 32:324–330.
6. Vestering MM, Schoppen T, Dekker R, Wempe J, Geertzen JH (2005). Development of an exercise testing protocol for patients with a lower limb amputation: results of a pilot study. Int J Rehabil Res 2005**;**28:237–244.
7. Klute GK, Kallfelz CF, Czerniecki JM. Mechanical properties of prosthetic limbs: adapting to the patient. J Rehabil Res Dev 2001; 38:299–307.
8. Jain NB, Higgins LD, Katz JN, Garshick E. Association of shoulder pain with the use of mobility devices in persons with chronic spinal cord injury. PMR 2010;2:896–900.
9. Van Ingen Schenau GJ, van Woensel WW, Boots PJ, Snackers RW, de Groot G. Determination and interpretation of mechanical power in human movement: application to ergometer cycling. Eur J Appl Physiol Occup Physiol 1990;61:11-19.
10. Hopker J, Jobson S, Carter H, Passfield L. Cycling efficiency in trained male and female competitive cyclists. J Sports Sci Med 2010;9:332–337.
11. Hopker J, Myers S, Jobson SA, Bruce W, Passfield L. Validity and reliability of the Wattbike cycle ergometer. Int J Sports Med 2010;31:731–736.
12. Hettinga FJ, de Groot S, van Dijk F, Kerkhof F, Woldring F, van der Woude L . Physical strain of handcycling: an evaluation using training guidelines for a healthy lifestyle as defined by the American College of Sports Medicine. J Spinal Cord Med 2013; 36:376–382.
13. Hettinga FJ, de Koning JJ, de Vrijer A,Wüst RC, Daanen HA, Foster C. The effect of ambient temperature on gross-efficiency in cycling. Eur J Appl Physiol 2007;101:465–471.
14. Powers S, Howley E . Exercise physiology. Theory and application to fitness and performance. 6th ed. New York: McGraw-Hill 2007.
15. Astrand P, Rodahl K. Textbook of work physiology, physiological bases of exercise. 3rd ed. New York: McGraw-Hill 1986.

16. Almåsbakk B, Whiting HT, Helgerud J. The efficient learner. Biol Cybern 2001; 84:75–83.
17. De Groot S, Veeger DH, Hollander AP, van der Woude LH. Wheelchair propulsion technique and mechanical efficiency after 3 wk of practice. Med Sci Sports Exerc 2002; 34:756–766.
18. Toth MJ, Gardner AW, Arciero PJ, Calles-Escandon J, Poehlman ET (1998). Gender differences in fat oxidation and sympathetic nervous system activity at rest and during submaximal exercise in older individuals. Clin Sci (Lond) 1998; 95:59–66.
19. Chisholm DMM, Collis ML, Kulak LL, Davenport W, Gruber N. Physical activity readiness. Br Col Med J 1975;17:375–378.
20. Cardinal BJ, Esters J, Cardinal MK. Evaluation of the revised physical activity readiness questionnaire in older adults. Med Sci Sports Exerc 1996;28:468–472.
21. Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982; 14:377–381.
22. Arnet U, van Drongelen S, Veeger DH, van der Woude LH. Are the force characteristics of synchronous handcycling affected by speed and the method to improve power? Med Eng Phys 2012;34:78–84.
23. Garby L, Astrup A. The relationship between the respiratory quotient and the energy equivalent of oxygen during simultaneous glucose and lipid oxidation and lipogenesis. Acta Physiol Scand 1987;129:443–444.
24. Ogata H, Yano T. Kinetics of oxygen uptake during arm cranking with the legs inactive or exercising at moderate intensities. Eur J Appl Physiol 2005; 94 (1–2):17–24
25. Moseley L, Jeukendrup AE. The reliability of cycling efficiency. Med Sci Sports Exerc 2001;33:621–627.
26. De Groot S, Veeger HE, Hollander AP, van der Woude LH. Adaptations in physiology and propulsion techniques during the initial phase of learning manual wheelchair propulsion. Am J Phys Med Rehabil 2003; 82:504–510.
27. De Groot S, Veeger HE, Hollander AP, van der Woude LH. Short-term adaptations in co-ordination during the initial phase of learning manual wheelchair propulsion. J Electromyogr Kinesiol 2003;13:217–228.
28. Vegter RJ, Lamoth CJ, de Groot S, Veeger DH, van der Woude LH. Interindividual differences in the initial 80 min of motor learning of handrim wheelchair propulsion. PLoS One 2014; 9:e89729.
29. Andersen LB. A maximal cycle exercise protocol to predict maximal oxygen uptake. Scand J Med Sci Sports 1995;5:143–146.
30. Cook DB, O'Connor PJ, Oliver SE, Lee Y. Sex differences in naturally occurring leg muscle pain and exertion during maximal cycle ergometry. Int J Neurosci 1998; 95 (3–4):183–202.
31. Billaut F, Giacomoni M, Falgairette G (2003). Maximal intermittent cycling exercise: effects of recovery duration and gender. J Appl Physiol (1985) 2003; 95:1632–1637.