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

Simmelink, Elisabeth Katharina

DOI:
10.33612/diss.178118244

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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

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One-day low-intensity combined arm-leg (Cruiser) ergometer exercise intervention: cardiorespiratory strain and gross mechanical efficiency in one and two-legged exercise

E. K. Simmelink
T. Wervelman
H. S. de Vries
J. H. B. Geertzen
R. Dekker
L. H. V. van der Woude

Int J Rehabil Res. 2017 Dec; 40(4):347-352

Abstract

This study aims to research whether there is a difference in cardiorespiratory variables and gross mechanical efficiency (GE) in healthy individuals during low-intensity one-legged and two-legged exercise on the combined arm–leg (Cruiser) ergometer and whether motor learning occurs. The outcome of this study will support the use of the Cruiser ergometer in future as a testing and training instrument in the rehabilitation of patients with a lower limb amputation. Twenty-eight healthy men participated in this randomized controlled trial. One group (n=14) used one leg and both arms during the exercise and the other group (n=14) used both legs and both arms. All participants performed a 1-day low-intensity exercise protocol. This included a standardized pretest and post-test of three bouts of 4 min exercise at 40W and an exercise intervention of seven bouts of 2×4 min exercise at 40W. The one-legged and two-legged group differed significantly in the heart rate and GE between the pretest and post-test. At the post-test, the one-legged group showed motor learning. GE improved significantly in both groups over the duration of the three exercise bouts of the pretest, but it did not improve during the post-test. There are differences in cardiorespiratory variables and GE between one-legged and two-legged exercise on the Cruiser ergometer. When using this ergometer in the rehabilitation of patients with a lower limb amputation, it is important to consider these differences and the occurrence of motor learning.

Keywords: amputation, ergometry, exercise test, rehabilitation

Introduction

Patients with a lower limb amputation (LLA) experience problems in maintaining their physical fitness due to inactivity, comorbidities and immobility after surgery[1]. To prevent deconditioning, it is important for these patients to start exercising prior to or as soon as possible after surgery in a safe, comfortable, and efficient manner. A suitable and effective training program should include a form of aerobic exercise[2,3]. In addition, at present, a valid and reliable exercise testing modality to measure the physical fitness of patients with a LLA before they commence training is not available.

The Cruiser ergometer[4] (Enraf-Nonius) is a multi-limb exercise modality that can be used in the rehabilitation training of LLA patients. It is a reliable and valid instrument for measuring the peak oxygen consumption in healthy individuals during an incremental exercise test[5] as well as a suitable modality for submaximal exercise testing[6]. In a pilot study[7], the Cruiser ergometer seemed suitable to measure the physical capacity of patients with a unilateral LLA.

An advantage of the Cruiser ergometer over the often used one-legged cycle ergometer[8,9] is that the Cruiser ergometer can be used early on in the rehabilitation when the patient has not yet been fitted with the prosthesis. Also, assistance of a physiotherapist is not required when using the Cruiser ergometer in this phase. Furthermore, because both the residual limb and the upper extremities are used during exercise on the Cruiser ergometer, more muscle mass is assumed to be involved compared with one-legged cycle ergometry. This may impact cardiorespiratory strain and efficiency during submaximal exercise as well as the maximal cardiorespiratory capacity and oxygen consumption (VO_2 max) as mentioned in earlier research[10,6].

The combined arm-leg movement on the Cruiser ergometer is a different cyclic multi-limb exercise compared with the leg movement on the cycle ergometer. This implicates that the combined arm-leg ergometer may be subject to motor learning, that is, learning through practice. Motor learning effects in cyclic exercise are among others expressed in (increased) gross efficiency and (reduced) metabolic costs of that exercise at submaximal intensities[11,12,13].

Consequently, it is important to understand the physiology of this cyclic exercise and the motor learning effects in terms of submaximal cardiorespiratory variables (oxygen consumption [VO_2 (l/min)], carbon dioxide output [VCO_2

(l/min)], breathing frequency [BF (breaths/min)], maximal ventilation [VE (l/min)], respiratory exchange rate (RER), and heartrate [HR (beats/min)]), gross mechanical efficiency (GE), and physical strain in one-legged and two-legged exercise. Outcomes of one-legged Cruiser exercise may also be influenced by the use of the dominant or the nondominant leg[14].

The aims of this study are as follows: (a) to determine whether there is a difference in cardiorespiratory variables and GE in healthy individuals during exercise on the Cruiser ergometer with two arms and one leg and with two arms and two legs; (b) to determine whether effects of adaptation and motor learning are found after a 1-day low-intensity exercise protocol and whether these effects are different for one-legged versus two-legged exercise; (c) and to determine whether the use of the dominant or the nondominant leg results in a difference in motor learning. It is hypothesized that cardiorespiratory strain will be higher and the GE will be lower in one-legged exercise compared with two-legged exercise on the Cruiser ergometer, especially when the nondominant leg is used. Also, it is expected that cardiorespiratory strain will decrease and GE will increase after the completion of the protocol.

Methods

In this study, 28 healthy male subjects between 18 and 30 years of age were included (Table 1). Exclusion criteria were a BMI greater than 30 kg/m^2 and/or a history of cardiovascular diseases; joint disorders; infections; complaints of the shoulder, back, arm or leg; lung diseases and balance disorders. Participants were screened for the exclusion criteria using the Physical Activity Readiness Questionnaire (PARQ)[15]. All participants signed an informed consent form according to the guidelines of the Declaration of Helsinki. The study was approved by the Ethics Committee of the Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen (registration nr: ECB 22052012).

Research protocol

All subjects performed a 1-day low-intensity exercise protocol that included a standardized pretest and posttest and an exercise intervention. Using a randomized controlled design, the participants were assigned to one of the two groups in order of attendance (*n*=14). One group was instructed to use only one leg and both arms (one-legged group), whereas the other group was asked to use both legs and both arms (two-legged group). This group was further divided into two groups of seven subjects who randomly used either their dominant or non-dominant leg during the exercises. All participants were asked to refrain from stimulants (e.g., caffeine, tobacco) and alcohol for at least 12 h before each test.

On the basis of previous studies[6,1213,16], both the pretest and the post-test consisted of three bouts of 4 min submaximal exercise at 40W and at 50 rpm (Fig. 1), while the Cruiser was set in the 'constant power' mode. Resting heart rate and resting oxygen consumption (VO_2 rest) were monitored while the subjects sat quietly for 3 min on the ergometer before starting the pretest (Table 1). The cardiorespiratory variables, as mentioned in the introduction, were measured during the last minute of each of the three exercise bouts of the pretest and post-test. The GE was afterwards calculated for the three exercise bouts of the pretest and post-test. The perceived exertion was measured during the 2 min rest period between the three bouts of the pretest and the post-test by the local perceived discomfort scale[17]and the rates of perceived exertion (RPE) on a 10-point Borg scale[18]. The intervention consisted of seven exercise sessions of 10 min (2×4 min, with 2 min rest in between) at 40W and at 50 rpm with a 20 min rest in between the sessions (Fig. 1). The 20 min rest interval was chosen on the basis of earlier research[16] and was chosen for practical reasons as the intervention was performed in 1 day.

Table 1: Personal characteristics and physiological values in rest before the start of the pre-test (mean, SD and p-values)

	One leg / both arms (n = 14)	Both legs / both arms (n = 14)	p-values
Age (y)	22.5 ± 2.2	22.4 ± 1.9	0.856
Body height (m)	1.88 ± 0.09	1.85 ± 0.07	0.508
Body mass (kg)	81.1 ± 10.0	83.7 ± 8.4	0.456
BMI (%)	23.1 ± 2.3	24.4 ± 2.3	0.148
VO_2	0.45 ± 0.31	0.35 ± 0.09	0.279
VE	9.7 ± 1.6	9.8 ± 0.6	0.938
BF	12.5 ± 4.9	13.6 ± 4.3	0.528
HR	74.6 ± 9.6	72.9 ± 8.6	0.638
RER	0.82 ± 0.07	0.79 ± 0.06	0.295

Abbreviations: BMI = Body Mass Index; VO_2 = Aerobic capacity; VE = Ventilation; BF=Breathing frequency; HR = Heart rate; RER = Respiratory Exchange Ratio.

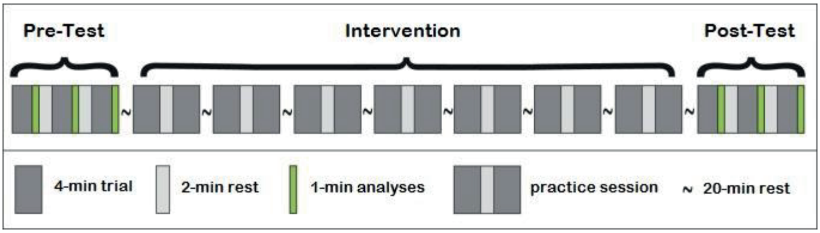

Figure 1. Setup of the 1-day experiment

Figure 2. The Cruiser ergometer (Enraf-Nonius, Delft)

Instruments

The Cruiser ergometer[4] (Enraf-Nonius, 2011) is a combined arm and leg ergometer (Fig. 2). The participant sits on a comfortable seat (low seat height) and places his or her (lifted) feet or foot against a nonmoving, adjustable footrest in front. Participants in the one-legged exercise group placed their inactive leg on a special support connected to the seat. When a patient with an LLA uses the Cruiser ergometer without wearing a prosthesis, the residual limb can be positioned securely on another support especially made for patients with an LLA. When the patient wears a prosthesis, the prosthetic leg can be involved actively in the exercise. The footrest is used to push the sliding seat backwards and the patient can move the seat forwards again by pulling the two-lever arm. In this cyclic process, the sound leg, trunk, and arms are used to provide power output into the ergometer, and thus the patient exercises (an)aerobically. The ergometer was set to operate at a constant power between 35 and 60 rpm. Participants were instructed to maintain 50 rpm. The accuracy of the Cruiser ergometer is ±10% for power output and ± 2 rpm for speed[4].

The cardiorespiratory variables (VO_2, VCO_2, BF, VE, and RER) were measured with the Metamax II (Cortex Biophysik GmbH, Leipzig, Germany)[19]. HR was measured using a Polar chest band. Metabolicpower (P_{met}) was calculated using Eq. (1).

$$(1) \qquad P_{met}(w) = VO_2[\frac{(4.940\ RER+16040)}{60}]$$

GE (%) was derived from the ratio between the mechanical power output (P_o) and the metabolic power (P_{met}), as shown in Eq 2[20].

$$(2) \quad GE\ (\%) = \frac{P_o}{P_{met}} \cdot 100\%$$

Statistics

All statistical analyses were carried out using IBM SPSS statistics 20.0 software; USA. Independent-sample *t*-tests were used to compare the baseline values of group characteristics. A mixed factorial analysis of variance was used to detect significant effects for both groups (one-legged vs. two-legged), test moment (pretest and post-test), and exercise bout (1–3) and to determine the interaction effects between group, time point, and exercise bout. Also, to detect differences in the one-legged group between the dominant versus the nondominant group, a mixed factorial analysis of variance was used. A post-hoc Bonferroni correction was applied to all tests to control for α inflation. The statistical significance level was set at *P* value less than 0.05.

Results

All 28 participants completed the study successfully. No significant differences were found in personal characteristics and physiological values (recorded during the rest period) between both groups (Table 1).

One versus two legs

The one-legged and two-legged group differed significantly regarding GE and HR between the pretest and post-test ($P=0.031$ and $P=0.034$) (Table 2). At the posttest, the one-legged exercise group had improved significantly in all variables compared with the pretest [GE ($P <0.001$),VO_2 ($P < 0.001$), VE ($P <0.001$), BF ($P =0.033$), HR ($P= 0.002$), RER ($P < 0.001$), and RPE ($P = 0.004$)] (Table 2). The two-legged exercise group had improved significantly in VE ($P <0.001$), BF ($P< 0.004$), RER ($P= 0.016$), HR ($P <0.01$), and RPE ($P= 0.003$), while showing borderline nonsignificant changes in GE ($P= 0.143$) and VO_2 ($P = 0.072$). However, no significant interaction effects between both groups and tests were found, indicating no major differences in improvement between both exercise groups after the intervention (Table 2).

Motor learning

GE of the one-legged group increased significantly ($P=0.001$) from 9.2% at the pretest to 10.9% at the posttest, whereas the two-legged group showed a nonsignificant ($P=0.143$) increase, with pretest values of 10.8% and posttest values of 12.2%. VO_2 of the one-legged group decreased significantly ($P<0.01$) from a pretest value of 1.29 l/min to a post-test value of 1.12 l/min. The VO_2 of the two-legged group decreased from 1.16 to 1.03 l/min,but this was a nonsignificant decrease ($P=0.072$). HR decreased significantly between the pretest and post-test in both the one-legged and the two-legged group, as did VE and BF. Thus, the one-legged group showed more motor learning effects than the two-legged group. Both groups improved significantly in GE during the three exercise bouts of the pretest (Fig. 3). However, during the post-test, no significant improvements in GE were observed in the duration of the exercise bouts of the posttest (Fig. 3 and Table 2).

Dominant versus non-dominant leg

Participants in the one-legged exercise group (*n*=14) were further divided into two groups (*n*=7), using either their dominant leg or their non-dominant leg during the exercises. No significant differences in outcome variables were found between the two subgroups, however.

Table 2 Outcome variables of the pre-test and post test for both exercise group

Outcome variables		Scores (mean and SD)		Main effects			Two-way Interaction effects			Three-way Interaction
		Pre-test	Posttest	One leg vs 2 legs	Pretes vs post- test	Exercise bout	One leg vs 2 legs x pre-test vs post-test	Pre-test vs posttest x exercise bout	One leg vs 2 legs x exercise bout	One leg vs 2 legs x pre-test vs posttest x exercise bout
GE (in %)	Total			0.031*	0.004*	0.002*	0.697	0.002*	0.831	0.025*
	One leg	9.2 ± 0.8	10.9 ± 1.7		0.001*	0.083		0.022*		
	Two legs	10.8 ± 2.5	12.2 ± 2.7		0.143	0.011*		0.008*		
VO_2 (L/min)	Total			0.076	<0.001*	<0.001*	0.528	0.007*	0.602	0.103
	One leg	1.29 ± 0.11	1.12 ± 0.14		<0.001*	0.049*		0.066		
	Two legs	1.16 ± 0.26	1.03 ± 0.20		0.072	0.005*		0.041*		
VE (L/min)	Total			0.438	<0.001*	0.002*	0.166	0.002*	0.727	0.397
	One leg	30.5 ± 5.5	26.0 ± 3.1		<0.001*	0.531		0.020*		
	Two legs	29.4 ± 3.8	25.7 ± 2.6		<0.001*	0.479		0.026*		
BF (breaths/ min)	Total			0.46	<0.001*	0.156	0.083	0.082	0.079	0.268
	One leg	20.3 ± 4.8	18.9 ± 4.5		0.033*	0.065		0.071		
	Two legs	22.5 ± 5.0	19.0 ± 4.0		0.004*	0.842		0.211		
HR (beats/min)	Total			0.034*	<0.001*	0.222	0.288	<0.001*	0.672	0.408
	One leg	109.9 ± 12.8	99.1 ± 5.6		0.002*	0.186		0.106		
	Two legs	101.5 ± 9.0	94.1 ± 6.7		<0.001*	0.516		0.004		
RER	Total			0.052	<0.001*	<0.001*	0.057	<0.001*	0.110	0.551
	One leg	0.87 ± 0.04	0.81 ± 0.05		<0.001*	0.036*		<0.001*		
	Two legs	0.82 ± 0.05	0.80 ± 0.03		0.016*	<0.001*		0.033*		
RPE	Total			0.694	<0.001*	0.585	0.120	0.081	0.019*	0.817
	One leg	2.4 ± 1.0	1.2 ± 0.6		0.004*	0.099		0.166		
	Two legs	2.0 ± 1.1	1.4 ± 1.2		0.003*	0.166		0.465		

One versus two legs (mean ±SD scores during the last minute of all three exercise bouts) and the results of a repeated-measures analysis of variance (P values). Main effects for the three main factors (total), 1 versus 2 legs, pre-test versus post-test, exercise bout, and their two-way and three-way interactions. Bonferroni corrected post analyses for all two-legged groups are presented in addition. BF, breathing frequency; GE, gross mechanical efficiency; HR, heart rate; RER, respiratory exchange ratio; RPE, ratings of perceived exertion; VE, ventilation; VO_2, aerobic capacity. *Significant.

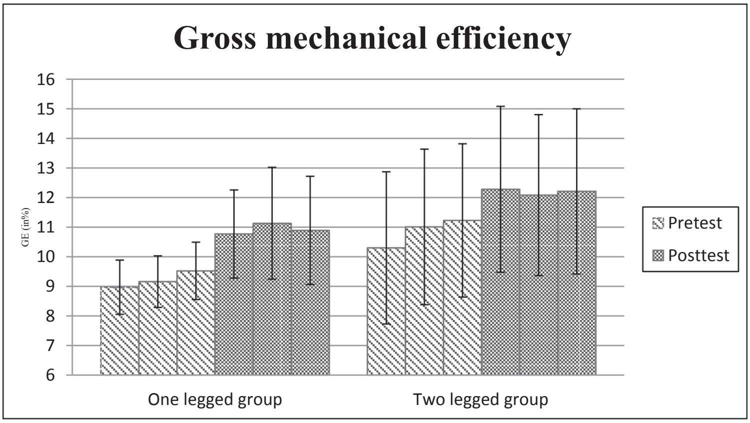

Figure 3: Mean scores and SD of the gross mechanical efficiency during each of the exercise bouts (1-3) for the pre-test and post-test for both groups (n = 14).

Discussion

This is the first study to research the differences between one-legged and two-legged exercise on the combined arm-leg (Cruiser) ergometer. Our study adds to earlier research on the Cruiser ergometer[5,6,7] by showing that one-legged and two-legged exercise on the Cruiser ergometer results in significant differences in HR and GE between the pre- and posttest. The maximum HR during one-legged exercise was higher and one-legged exercise was less efficient than two-legged exercise. After performing a 1-day low-intensity exercise protocol on the Cruiser ergometer, the one-legged exercise group improved significantly in all outcome variables. The two-legged exercise group improved significantly in VE, BF, RER, HR, and RPE, while showing borderline nonsignificant changes in GE and VO_2. GE improved significantly in both groups during the three exercise bouts of the pretest, but it did not improve during the post-test Therefore, it seems motor learning occurs after exercising on the Cruiser ergometer in the short and intermediate term. Furthermore, one-legged exercise on the Cruiser ergometer leads to a greater improvement in motor learning than two-legged exercise. In the one-legged exercise group, no influence of the dominant leg on the outcome variables was found.

Our findings are similar to those reported by Ogita et al.[21], who compared one-legged and two-legged exercise on the cycle ergometer. They found that VO_2 was higher in low-intensity one-legged cycling than in low-intensity two-legged cycling. This is probably because of the fact that postural control muscles have to be more active because of the asynchronic and initially somewhat unbalanced movement[22,23]. Because one-legged exercise requires greater effort, HR was higher compared with two-legged exercise. The same results were found in this study. During one-legged exercise on the Cruiser ergometer, less muscle mass is used, which means that the postural control muscles need to work harder to stabilize the trunk. This could explain why a higher cardiorespiratory strain and a lower GE were found for one-legged exercise compared with two-legged exercise.

Several studies have reported on the increase in GE following practice, which is thought to be indicative of the underlying process of motor learning[11,24,25]. In this study, a significant increase in GE was demonstrated in the one-legged group and a borderline nonsignificant increase in the two-legged group. Cardiorespiratory strain was significantly reduced, especially in one-legged exercise, after practice. Metabolic strain and energy expenditure are reduced with practice when the task constraints remain unchanged[11]. It seems that exercising on the Cruiser ergometer is subject to a process of improved coordination and adaptation, that is, motor learning. To be able to reach a stable metabolic energy expenditure, some practice on the Cruiser ergometer is needed. The motor learning effect was found to be greater for movement with two arms and one leg than for movement with two arms and two legs.

The aforementioned increase in GE can be explained by better coordination of the arms and leg, reduced co-contractions of the dynamic and postural control muscles, and more efficient mechanical power input while exercising on the Cruiser ergometer. A difference was found between both exercise groups for the first 12 min of the exercise protocol. Whereas the two-legged group showed motor learning during the second exercise bout, in the one-legged group motor learning only took place from the third exercise bout onward, 4 min later (Fig. 3). These findings could indicate that one-legged exercise is a more complex movement that requires more (practice) time before motor learning can occur. To our knowledge, this is also the first study to investigate motor learning processes during the first 12 min of exercise on the Cruiser ergometer.

Vegter et al.[13,16] researched the increase in mechanical efficiency during the first 12 min of wheelchair propulsion. The healthy, able-bodied participants in their study increased their mechanical efficiency, indicating that less energy was used to maintain a constant speed and power output. This corresponds with findings from the present study, which demonstrated that motor learning already occurs soon after the start of the more difficult types of exercise. Our findings suggest motor learning did not take place during the posttest. An explanation might be that sometime during the intervention period a steady state was reached, after which no additional motor learning took place. However, given that this study did not measure GE during the intervention period, it is not possible to confirm this.

Another aspect that might influence motor learning is amputation of the dominant leg, which, consequently, does not contribute to the exercise. To test this hypothesis, the one-legged group was further divided into two subgroups in this study. No difference was found, however, between use of the dominant leg or nondominant leg and the occurrence of motor learning. This is in accordance with a review on leg preference in running and cycling[14], which showed that previous studies failed to find a general association between functional asymmetry and lateral preference for the lower limbs. No relationship was found between asymmetries and performance in this study.

A limitation of this study is that only male participants were included. This homogeneous population was chosen to enable comparisons with other research in this area with also only male participants. Previous research[6] showed that female participants exercised seemingly more efficiently on the Cruiser ergometer at identical submaximal absolute power output levels compared with male participants.

Another limitation concerns the lack of data on the seven exercise sessions of the intervention between the pretest and post-test. Therefore, no conclusions can be drawn on outcome variables during the intervention. Future research is needed to clarify at what point during the intervention period a steady state is reached with respect to metabolic costs and GE. Furthermore, to determine whether this steady state is final or only temporary, future studies should consider using a longer intervention period.

Conclusion

This study showed a difference in cardiorespiratory strain and GE between one-legged and two-legged exercise on the Cruiser ergometer. The one-legged and two-legged group showed an increase in GE after the intervention and thus seemed to indicate motor learning. This increase in GE, however, can be mainly attributed to the one-legged group. Motor learning was not influenced by use of dominant leg or nondominant leg. Further research on the use of the Cruiser ergometer in the rehabilitation of patients with a LLA should not only consider differences in cardiorespiratory variables and GE between one and two-legged exercise, but also potential consequences of adaptation over time. Further research should also explore motor learning effects and adaptation in these patients during various periods of practice.

From a clinical perspective, the experimental results suggest that unilateral leg exercise on the Cruiser ergometer is highly feasible, is somewhat more straining, and yet less efficient, and it requires a period of adaptation (in which motor learning takes place) to become familiar with the exercise configuration. Low-intensity practice provides such a period of adaptation, which leads to optimization of efficiency and reduction of metabolic costs at a given power output. This should be taken into account when using the Cruiser in novices for training and/or exercise testing.

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.

References

1. Blume P, Salonga C, Garbalosa J, et al. Predictors for the healing of transmetatarsal amputations: Retrospective study of 91 amputations. Vascular 2007; 15: 126-133.
2. Chin T, Sawamura S, Shiba R. Effect of physical fitness on prosthetic ambulation in elderly amputees. Am J Phys Med Rehabil 2006; 85:992-996.
3. 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.
4. Enraf-Nonius, Delft, the Netherlands: operating instructions Cruiser 2011.
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. Simmelink EK, Borgesius EC, Hettinga FJ, Geertzen JH, Dekker R, van der Woude LH. Gross mechanical efficiency of the combined arm-leg (Cruiser) ergometer: A comparison with the bicycle ergometer and handbike. Int J Rehabil Res 2015;38: 61-67.
7. 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.
8. Wezenberg D, de Haan A, van der Woude LH, Houdijk H. Feasibility and validity of a graded one-legged cycle exercise test to determine peak aerobic capacity in older people with a lower-limb amputation. Phys Ther 2012;92: 329-338.
9. Wezenberg D, de Haan A, Faber WX, Slootman HJ, van der Woude, LH, Houdijk H. Peak oxygen consumption in older adults with a lower limb amputation. Arch Phys Med Rehabil 2012;93:1924-1929.
10. Bostom AG, Bates E, Mazzarella N, Block E, Adler J. Ergometer modification for combined arm-leg use by lower extremity amputees in cardiovascular testing and training. Arch Phys Med Rehabil 1987;68:244-247.
11. Sparrow,W.A., Newell,K.M. Energy expenditure and motor performance relationships in humans learning a motor task. Psychophysiology 1994;31: 338-346.
12. 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.
13. Vegter RJ, de Groot S, Lamoth CJ, Veeger DH, van der Woude LH. Initial skill acquisition of handrim wheelchair propulsion: A new perspective. IEEE Trans Neural Syst Rehabil Eng 2014;22: 104-113.
14. Carpes FP, Mota CB, Faria IE. On the bilateral asymmetry during running and cycling - a review considering leg preference. Phys Ther Sport 2010; 11: 136-142.
15. 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.
16. Vegter RJ, Lamoth CJ, de Groot S, Veeger DH, van der Woude LH. Inter-individual differences in the initial 80 minutes of motor learning of handrim wheelchair propulsion. PLoS One 2014;9: e89729.

17. van den Berg R, de Groot S, Swart KM, van der Woude LH (2010). Physical capacity after 7 weeks of low-intensity wheelchair training. Disabil Rehabil 2010;32: 2244-2252.
18. Borg GA (1982) Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982;14: 377-381.
19. Medbo JI, Mamen A, Welde B, von Heimburg E, Stokke R (2002). Examination of the metamax I and II oxygen analysers during exercise studies in the laboratory. Scand J Clin Lab Invest 2002; 62: 585-598.
20. 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.
21. Ogita F, Stam RP, Tazawa HO, Toussaint HM, Hollander AP. Oxygen uptake in one-legged and two-legged exercise. Med Sci Sports Exerc 2000;32:1737-42
22. Sargeant AJ, Davies CT. Forces applied to cranks of a bicycle ergometer during one- and two-leg cycling. J Appl Physiol Respir Environ Exerc Physiol 1977;42:514-518.
23. Neary PJ, Wenger HA. The effects of one- and two-legged exercise on the lactate and ventilatory threshold. Eur J Appl Physiol Occup Physiol 1986;54: 591-595.
24. Almasbakk B, Whiting HT, Helgerud J. The efficient learner. Biol Cybern 2001; 84: 75-83.
25. Vegter RJ, Hartog J, de Groot S, Lamoth CJ, Bekker MJ, van der Scheer JW et al. Early motor learning changes in upper-limb dynamics and shoulder complex loading during handrim wheelchair propulsion. J Neuroeng Rehabil 2015;12:26.