Comparison of Peak Cardiopulmonary Performance Parameters on a Robotics-Assisted Tilt Table, a Cycle and a Treadmill

Jittima Saengsuwan[1,2,3]*, **Tobias Nef**[2], **Marco Laubacher**[1], **Kenneth J. Hunt**[1]

1 Institute for Rehabilitation and Performance Technology, Division of Mechanical Engineering, Department of Engineering and Information Technology, Bern University of Applied Sciences, Burgdorf, Switzerland, **2** ARTORG Center for Biomedical Engineering Research, Gerontechnology and Rehabilitation Research Group, Bern University, Bern, Switzerland, **3** Department of Physical Medicine and Rehabilitation, Faculty of Medicine, Khon Kaen University, Khon Kaen, Thailand

* jittima.saengsuwan@bfh.ch

Abstract

Robotics-assisted tilt table (RATT) technology provides body support, cyclical stepping movement and physiological loading. This technology can potentially be used to facilitate the estimation of peak cardiopulmonary performance parameters in patients who have neurological or other problems that may preclude testing on a treadmill or cycle ergometer. The aim of the study was to compare the magnitude of peak cardiopulmonary performance parameters including peak oxygen uptake (VO_{2peak}) and peak heart rate (HR_{peak}) obtained from a robotics-assisted tilt table (RATT), a cycle ergometer and a treadmill. The strength of correlations between the three devices, test-retest reliability and repeatability were also assessed. Eighteen healthy subjects performed six maximal exercise tests, with two tests on each of the three exercise modalities. Data from the second tests were used for the comparative and correlation analyses. For nine subjects, test-retest reliability and repeatability of VO_{2peak} and HR_{peak} were assessed. Absolute VO_{2peak} from the RATT, the cycle ergometer and the treadmill was (mean (SD)) 2.2 (0.56), 2.8 (0.80) and 3.2 (0.87) L/min, respectively ($p < 0.001$). HR_{peak} from the RATT, the cycle ergometer and the treadmill was 168 (9.5), 179 (7.9) and 184 (6.9) beats/min, respectively ($p < 0.001$). VO_{2peak} and HR_{peak} from the RATT vs the cycle ergometer and the RATT vs the treadmill showed strong correlations. Test-retest reliability and repeatability were high for VO_{2peak} and HR_{peak} for all devices. The results demonstrate that the RATT is a valid and reliable device for exercise testing. There is potential for the RATT to be used in severely impaired subjects who cannot use the standard modalities.

Introduction

Maximal oxygen uptake (VO_{2max}) or peak oxygen uptake (VO_{2peak}) is commonly used for the evaluation of physical fitness and for exercise prescription [1–3]. The most commonly used

devices are treadmills and cycle ergometers. The VO_{2max} achieved from cycle ergometry has been observed to be 6–23% lower than from a treadmill [4–6].

There are some limitations to the use of standard devices in neurological patients who have weakness or coordination problem caused by stroke, multiple sclerosis or spinal cord injury [1]. The alternative recommended devices for these patients are a semi-recumbent cycle ergometer or a total body stepper [1], but severely affected patients have limitations that preclude them from using even these devices.

Recent systematic reviews have highlighted the importance of maintaining cardiorespiratory fitness after stroke [7] and spinal cord injury [8], but also emphasise the technical difficulty of implementing testing protocols and training programmes in these populations. Smith et al. included 42 studies in their systematic review of cardiorespiratory fitness after stroke and reported that VO_{2peak} was as low as 26% of that of healthy age- and gender-matched individuals; but, importantly, they noted that "most studies recruited patients with mild stroke" and pointed out that cardiorespiratory fitness is likely substantially lower in more severely affected patients [7]. The reason for inclusion of only mildly-affected patients in the reviewed studies is clear: most studies estimated VO_{2peak} using either a cycle ergometer or a treadmill, exercise modalities which are only usable in the case of mild to moderate impairment.

A robotics-assisted tilt table (RATT) provides the advantage of body support, cyclical stepping and physiological loading for early rehabilitation. These features are necessary for using the RATT for exercise testing and training in patients with severe disability: the body support makes it feasible and safe for patients with severe weakness or balance problems to exercise because the stability of the body is not required; thigh cuffs and foot plates stabilise the weak or spastic extremities and hold them in place. This type of device has been augmented by adding force sensors, work rate calculation and a visual feedback system to guide exercise intensity for exercise testing [9]. In a previous study, it was shown that it is feasible to measure peak cardiopulmonary performance parameters using the augmented RATT [10, 11]. To verify that the device can be used to measure peak cardiopulmonary performance parameters, the RATT should first be compared with the standard testing devices using able-bodied subjects.

The aim of this study was to compare the magnitude of peak cardiopulmonary performance parameters including peak oxygen uptake (VO_{2peak}) and peak heart rate (HR_{peak}) obtained from the RATT, a treadmill and a cycle ergometer. The strength of correlations between the devices, test-retest reliability and repeatability were also assessed.

Materials and Methods

Subjects and general study design

The study was reviewed and approved by the Ethics Review Board of the Canton of Bern in Switzerland (Reference No. 002/12). Written informed consent was obtained from all subjects prior to participation. The study was conducted in Bern University of Applied Sciences from December 2012 to September 2013.

Eighteen normal subjects (10 male, 8 female; Table 1) completed the study by performing 6 maximal exercise tests, with 2 tests on each of the three exercise modalities as described below. No subjects had cardiovascular, pulmonary or musculoskeletal problems that might have interfered with or contraindicated exercise testing.

Subjects performed a total of 6 tests using a treadmill (Venus, h/p/cosmos GmbH, Germany—2 tests), a cycle ergometer (LC7, Monark Exercise AB, Sweden—2 tests) and a RATT (Erigo, Hocoma AG, Switzerland—2 tests). The order of presentation of the tests for each subject was done by computer randomization and the subjects did not know in advance which testing device would be used. Each individual test was done on a separate day, and each test session was

Table 1. Baseline characteristics of subjects (n = 18).

Characteristic	Value—mean (SD)
Age [years]	28.6 (6.3)
Male/Female [n]	10/8
Smoking [%]	11.1
Height [cm]	172.4 (9.9)
Body mass [kg]	69.1 (12.8)
Body mass index [kg/m^2]	22.7 (2.2)
Activity level [14]*	3.4 (1.1)

* level 1: inactive or little activity; level 2: regular ($\geq$ 5 days/ week), low level of exertion ($\geq$ 10 min at a time); level 3: aerobic exercise for 20–60 min/week; level 4: aerobic exercise for 1–3 hours/week; level 5: aerobic exercise over 3 hours/week.

doi:10.1371/journal.pone.0122767.t001

separated by at least 48 hours but not more than 7 days. The time of day for testing was the same for each subject. Participants were instructed to avoid strenuous activity within the 24 hours before testing and not to consume food, nicotine or caffeine at least three hours prior to testing [12, 13].

Experimental procedures

Each incremental exercise test had the same structure. There was 3 minutes of rest, 5 minutes of warm up, a further 3 minutes of rest, and 3 minutes of unloaded movement. The ramp phase followed. Individualized, predicted maximum work rates for the treadmill and the cycle ergometer were calculated based on estimation of VO_{2max} [14] and the VO_2-WR relationship [4]. For the RATT, individual maximum work rates were estimated using pilot data for healthy subjects [10]. The rate of increase in work rate was then calculated for each subject to achieve the predicted peak work rate in 10 minutes. Subjects then exercised until they reached their maximal performance and could not maintain the target work rate. Subjects were verbally encouraged to exercise to their limit of functional capacity.

RATT. The subjects were first placed in a horizontal position on the tilt table and secured in accordance with the provisions of the support system. The thighs and the feet were fixed to the thigh cuffs and foot straps. The tilt table then was tilted to 70 degrees and the stepping movement was set at 80 steps/minute. Warm up involved active participation of the subject at a constant work rate of 15 W. Unloaded movement was achieved by subjects remaining passive while the RATT moved their legs, which was associated with a work rate of 0 W. The RATT ramp rate was individually set in the range 4 to 12 W/min to meet the target ramp duration. During the ramp phase, subjects were instructed to actively produce force by pushing into the leg cuffs. The target work rate and measured work rate were visually fed back to the subjects in real time on a computer screen (Fig 1).

Cycle ergometer. The ramp phase was implemented by linearly increasing the work rate on the electromechanical brake. The warm up phase was set at a constant work rate of 50 W. Unloaded movement was achieved by subjects cycling at 0 W. The cycle ramp rate ranged from 12 to 40 W/min. The cycle cadence throughout the test was freely selected but always above 60 rpm. The settings for the seat height, handlebar height and the seat to handlebar distance were adjusted to accommodate each subject. Each individual set up was recorded to ensure the same position in subsequent tests.
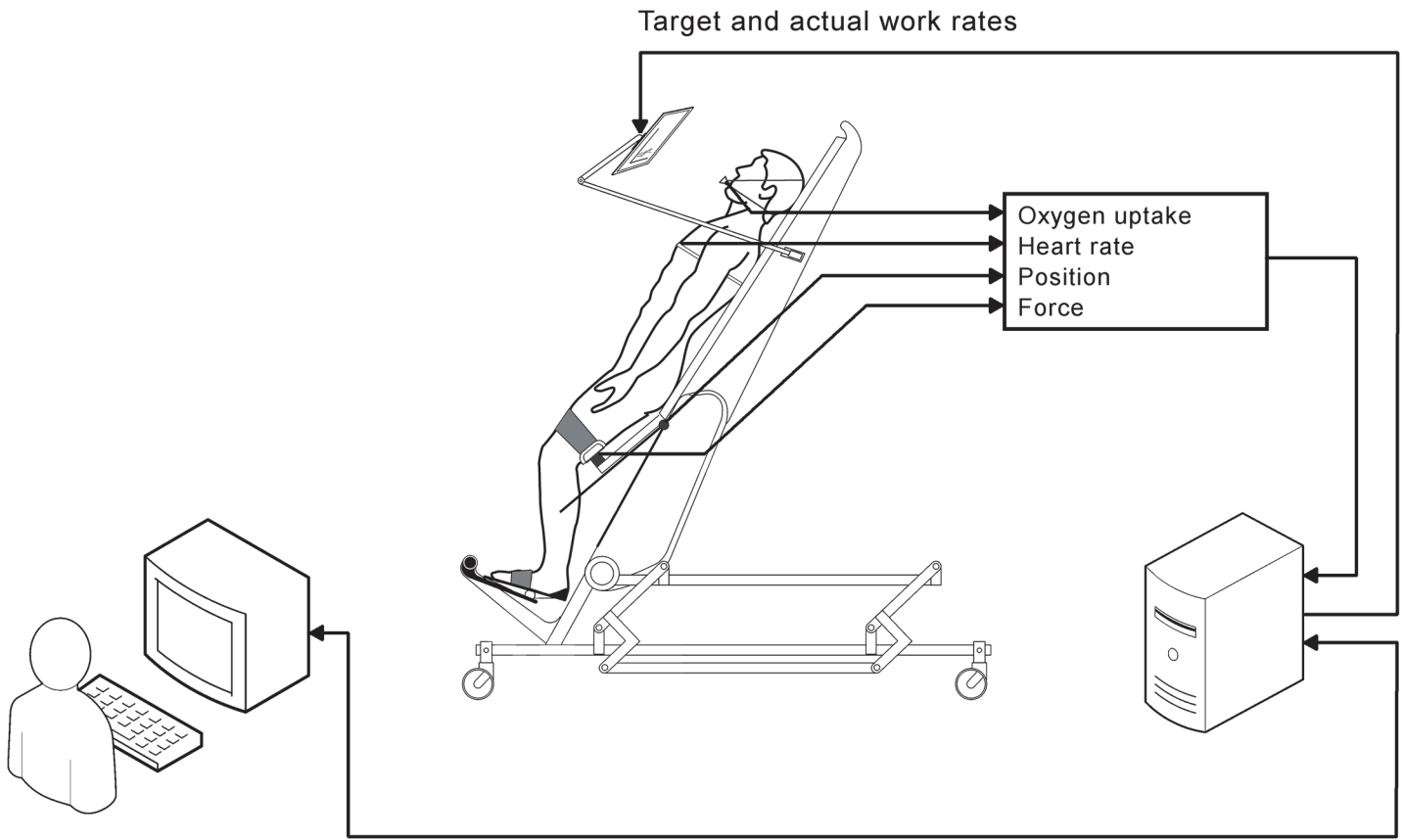
Fig 1. Work rate estimation and visual feedback. The subject's work rate is estimated continuously from forces in the thigh cuffs and joint angular velocities. A target work rate profile is displayed with the estimated work rate and the subject must adapt volitional muscular work to maintain the target. Physiological variables are monitored continuously.

doi:10.1371/journal.pone.0122767.g001

Treadmill. Unloaded work was implemented using a low treadmill speed (0.9 km/h) and zero slope. The warm up phase was set at a speed of 5 km/h and zero slope. During the ramp phase, work rate was increased linearly every 30 seconds using combined non-linear changes in speed and slope [15].

Measurements

Cardiopulmonary response variables were monitored using a breath-by-breath system (Meta-Max 3B, Cortex Biophysik GmbH, Germany). The device was calibrated prior to each test for volume and gas concentration using a 3-L syringe and a precision gas calibration mixture (15% O_2 and 5% CO_2). Heart rate was continuously measured using a chest belt (T31, Polar Electro, Finland) and recorded directly on the MetaMax system. Additionally, on the RATT, the heart rate was recorded using a receiver board (HRMI, Sparkfun, Boulder, USA). Subjects rated perceived exertion and leg fatigue every 3 minutes during the incremental exercise test using the Borg CR10 scale for dyspnea and leg fatigue [16, 17].

Outcome measures

Cardiopulmonary performance parameters were evaluated as follows: VO_{2peak} was obtained from a 30-second moving average of VO_2. Peak respiratory exchange ratio (RER_{peak}) was the average value of RER during the same period. Peak heart rate (HR_{peak}) was the maximal heart

rate value reached during the incremental phase. VE_{peak} was a 30-second average of the peak minute ventilation. Peak work rate (WR_{peak}) was calculated from a 10-second average of the recorded work rate. The peak Borg CR10 scale for both dyspnea and leg fatigue were those recorded at the time that subjects reached their maximal performance. Time to VO_{2peak} and the reasons for test termination were also recorded.

Statistical analysis

Data from the second test from each device were used for the comparative analysis among the three modalities. Normality of the data was assessed by the Kolmogorov-Smirnov test. Repeated measures analysis of variance (ANOVA) was conducted to determine whether there were significant differences between the peak cardiopulmonary performance parameters. If Mauchly's test of sphericity was significant ($p<0.05$), Greenhouse-Geiser corrections were used. Bonferroni post-hoc multiple comparison corrections were applied to examine the differences between each paired data set, if a significant F ratio was found.

For correlation analysis, linear regression of the VO_{2peak} and HR_{peak} values for the RATT vs cycle ergometer and the RATT vs treadmill was performed. The regression equation, the correlation coefficient (R), the coefficient of determination (R^2) and the standard error of estimate (SEE) were computed.

Test-retest reliability of VO_{2peak} and HR_{peak} on each device was analyzed using a 2-way, random intraclass correlation coefficient ($ICC_{2,1}$) and a 95% confidence interval (CI). The within-subject variation of VO_{2peak} and HR_{peak} was calculated using the coefficient of variation [18]. The Bland and Altman limits of agreement were used to investigate the repeatability of VO_{2peak} and the HR_{peak} on each device. All analyses were performed using SPSS (Version 19.0, IBM Corp.).

During the first series of tests with each device, technical problems with the VO_2 measurement device were detected in 9 subjects. Thus the comparative analysis was carried out using only data from the second series (all 18 subjects), and test-retest analysis was based on only 9 subjects.

Results

Comparison of peak values

Overall, statistically significant differences in all peak performance parameters, except in the Borg CR10 scale for leg effort, were seen between the RATT, the cycle ergometer and the treadmill (Table 2).

Absolute VO_{2peak} from the RATT, the cycle ergometer and the treadmill was (mean (SD)) 2.2 (0.56), 2.8 (0.80) and 3.2 (0.87) L/min, respectively ($p < 0.001$). Absolute VO_{2peak} obtained from the RATT was on average 19.0% lower than the cycle ergometer and 29.2% lower than on the treadmill.

HR_{peak} from the RATT, the cycle ergometer and the treadmill was 168 (9.5), 179 (7.9) and 184 (6.9) beats/min, respectively ($p < 0.001$). HR_{peak} obtained on the RATT was on average 6.0% lower than the cycle ergometer and 8.6% lower than on the treadmill.

The three most common reasons given by the subjects for stopping the RATT test were leg fatigue (66.7%), generalized fatigue (11.1%) and leg discomfort at high work rate (11.1%). Two subjects reported foot pain due to tight foot strap fixation, which immediately resolved after the straps were released following the test. The main reasons for stopping the test on the treadmill were breathing effort (44.4%), generalized fatigue (33.3%), and leg fatigue (16.6%). The main reasons for stopping the cycle test were leg fatigue (66.7%), generalized fatigue (16.7%)

Table 2. Peak performance values from the RATT, cycle and treadmill (n = 18).

Variables	RATT	Cycle ergometer	Treadmill	P value
VO_{2peak} absolute (L/min)[a, b, c]	2.24 ± 0.13	2.81 ± 0.19	3.19 ± 0.20	<0.001
VO_{2peak} relative (mL/kg/min) [a, b, c]	32.3 ± 4.9	40.2 ± 7.0	45.9 ± 7.6	<0.001
HR_{peak} (beats/min)[a, b, c]	168.0 ± 9.5	178.8 ± 7.9	183.8 ± 6.9	<0.001
Percent predicted HR_{peak} (%)[a, b, c]	87.8 ± 5.3	93.5 ± 4.8	96.1 ± 4.2	<0.001
RER_{peak} [a, b]	1.03 ± 0.1	1.13 ± 0.1	1.11 ± 0.1	<0.001
VE_{peak} (L/min) [a, b, d] (n = 17)	72.2 ± 21.1	101.4 ± 31.0	106.1 ± 32.0	<0.001
Borg CR10 scale dyspnea [b, d]	6.6 ± 2.0	7.6 ± 1.7	9.1 ± 0.6	<0.001
Borg CR10 scale leg effort	8.8 ± 1.4	9.0 ± 1.6	9.1 ± 1.0	0. 65
WR_{peak} (W) [a, b, c]	65.9 ± 18.0	233.5 ± 72.7	205.9 ± 70.1	<0.001
Time to VO_{2peak} (min)	9.9 ± 1.0	9.7 ± 1.2	9.0 ± 1.1	0.063

Data are given as mean ± standard deviation. VO_2 = oxygen uptake, VO_{2peak} = peak oxygen uptake, HR_{peak} = peak heart rate, Percent predicted HR_{peak} = the peak heart rate expressed as a percentage of the predicted peak heart rate, RER_{peak} = peak respiratory exchange ratio, VE_{peak} = peak minute ventilation, WR_{peak} = peak work rate.

[a] $p < 0.001$ between the RATT and the cycle ergometer
[b] $p < 0.001$ between the RATT and the treadmill
[c] $p < 0.001$ between the cycle ergometer and the treadmill
[d] $p < 0.05$ between the cycle ergometer and the treadmill.

doi:10.1371/journal.pone.0122767.t002

and breathing effort (11.1%). No other complaints or immediate complications after the exercise testing were observed.

Correlation analysis

Linear regression analysis revealed very strong positive correlations between the RATT vs the cycle ergometer VO_{2peak} (r = 0.95. p<0.001) and the RATT vs the treadmill VO_{2peak} (r = 0.94. p<0.001) (Fig 2). There were strong positive correlation between the RATT HR_{peak} vs the cycle ergometer HR_{peak} (r = 0.64, p<0.005) and the RATT HR_{peak} vs the treadmill HR_{peak} (r = 0.62, p<0.05) (Fig 3).
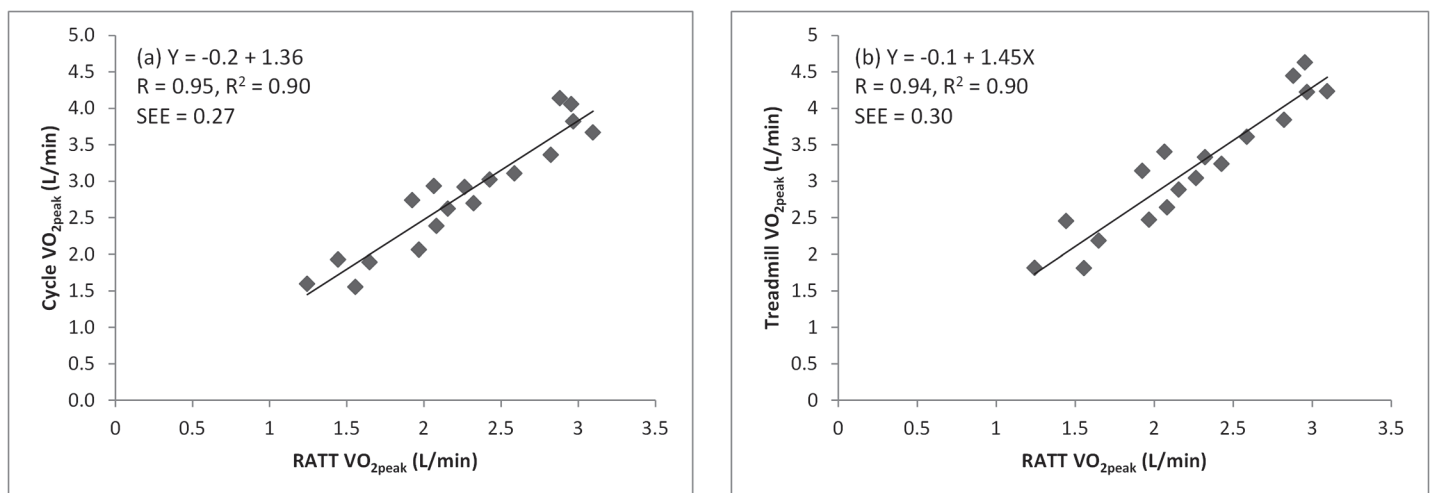

Fig 2. Linear regression analysis of VO_{2peak} (peak oxygen uptake): (a) RATT vs cycle, and (b) RATT vs treadmill. The equation, the correlation coefficient (R), the coefficient of determination (R^2) and the standard error of estimation (SEE) are shown. The regression line is shown in each graph.

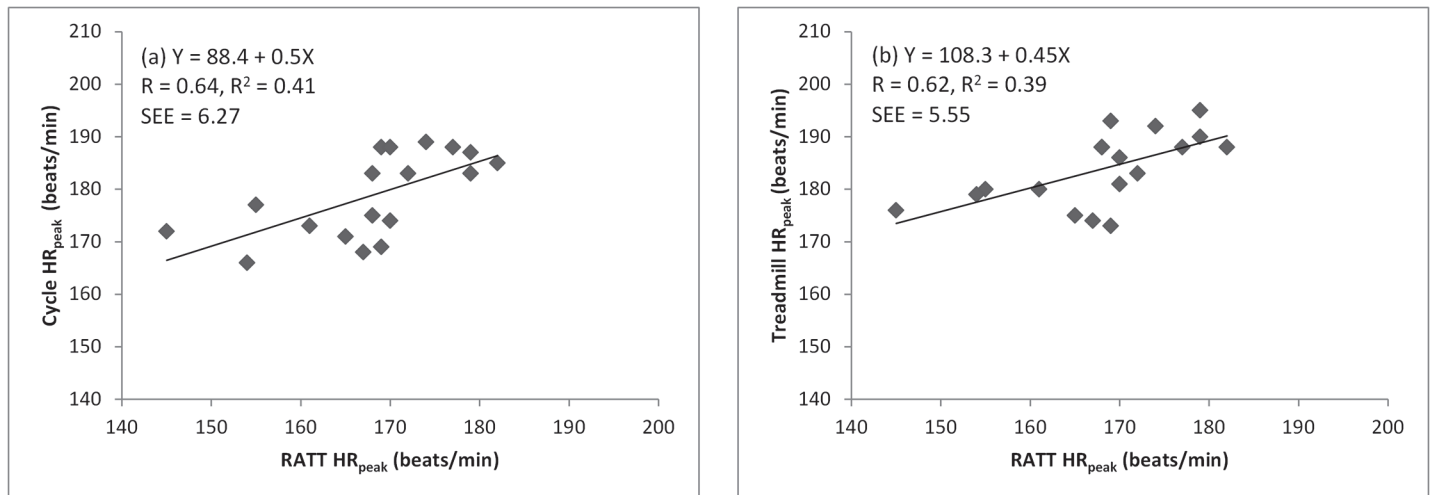doi:10.1371/journal.pone.0122767.g002

Fig 3. Linear regression analysis of HR$_{peak}$: (a) RATT vs cycle, and (b) RATT vs treadmill. The equation, the correlation coefficient (R), the coefficient of determination (R^2) and the standard error of estimation (SEE) are shown. The regression line is shown in each graph.

doi:10.1371/journal.pone.0122767.g003

Test-retest reliability and repeatability

VO$_{2peak}$ and HR$_{peak}$ measured with all 3 devices had very high test-retest reliability with ICC$_{2,1}$ $\geq$ 0.85 (Table 3). The coefficient of variation of the VO$_{2peak}$ and HR$_{peak}$ was less than 5% in all devices. The Bland and Altman analysis showed similar limits of agreement among the devices (Table 3).

Discussion

The aim in the present study was to compare the magnitude of peak cardiopulmonary performance parameters including peak oxygen uptake (VO$_{2peak}$) and peak heart rate (HR$_{peak}$) obtained from the RATT, a treadmill and a cycle ergometer. It was also an aim to assess the strength of correlations between the devices, test-retest reliability and repeatability.

The results demonstrate that VO$_{2peak}$ on the treadmill and the cycle ergometer is higher than on the RATT. On average, the VO$_{2peak}$ values obtained from the RATT were 81.0% of the cycle ergometer VO$_{2peak}$ and 70.8% of the treadmill VO$_{2peak}$.

Table 3. Test-retest reliability and repeatability of each device (n = 9).

	Overall mean (tests 1 and 2)	MD (95% LoA)	CoV (%)	ICC (95% CI)
VO$_{2peak}$ (L/min)				
RATT	2.152	0.026 (-0.268, 0.320)	4.1	0.97 (0.89–0.99)
cycle ergometer	2.622	0.056 (-0.238, 0.342)	3.3	0.98 (0.94–1.00)
treadmill	2.924	0.013 (-0.271, 0.305)	2.4	0.99 (0.95–1.00)
HR$_{peak}$ (beats/min)				
RATT	169.0	0.67 (12.57, -11.23)	1.8	0.89 (0.58–0.97)
cycle ergometer	180.3	2.56 (-5.77, 10.89)	1.6	0.86 (0.48–0.97)
treadmill	185.3	2.38 (-2.67, 7.33)	0.9	0.89 (0.40–0.98)

MD, mean difference; LoA, limits of agreement; CoV, coefficient of variation; ICC, intraclass correlation coefficient; CI, confidence interval; VO$_{2peak}$, peak oxygen uptake; HR$_{peak}$, peak heart rate.

doi:10.1371/journal.pone.0122767.t003

There were strong correlations between the RATT vs the cycle ergometer and the RATT vs the treadmill VO_{2peak}. These results are comparable to the correlation of treadmill vs total body recumbent stepper VO_{2peak} (r = 0.92) [19] and the correlation of arm ergometer vs treadmill VO_{2peak} (r = 0.85) [20]. Both the cycle ergometer and treadmill have been validated as standard devices for estimation of peak cardiopulmonary performance parameters. The high correlation coefficients of VO_{2peak} between the devices investigated here suggests that the RATT, similarly, is a valid device for peak exercise testing within and between subjects. There is potential for the RATT to serve as an alternative to the cycle ergometer and treadmill for the estimation of VO_{2peak} in severely impaired subjects who cannot use the standard modalities.

An alternative device for investigation of cardiopulmonary performance in impaired subjects is the supine cycle ergometer [21]. Comparing the VO_{2peak} obtained from the RATT and the published data for the supine cycle ergometer, the RATT value is lower than the supine cycle ergometer: the supine cycle ergometer was approximately 22% lower than the treadmill VO_{2peak} in normal subjects [21]. The difference in the movement pattern on the RATT may account for the lower VO_{2peak} on the RATT. However, neurological patients who have severe weakness or spasticity may have difficulty pedaling on the supine cycle ergometer because there is no leg support.

The RATT appears to be able to provoke higher VO_{2peak} compared to arm ergometry. VO_{2peak} obtained from arm ergometry in healthy subjects was 42–43% lower than the treadmill VO_{2peak} [20] and 30–34% lower than the cycle ergometry VO_{2peak} [22–24]. Although the peak cardiopulmonary stress for the RATT is higher than for an arm ergometer, it is still lower than for a treadmill or cycle ergometer (VO_{2peak}, HR_{peak} or RER_{peak}). The lower cardiopulmonary stress may be explained by the lower level of muscle recruitment as a result of the body support and the differences in muscle mass used during the exercise, when compared to more physiological movement such as running or cycling [10].

Regarding test-retest reliability, the ICC for VO_{2peak} from each device is high. The lower limit of the 95% CI of the ICC for each device was more than 0.75, which is considered good reliability [25, 26]. Furthermore, the VO_{2peak} obtained from each device has high repeatability as determined by the Bland-Altman limits of agreement. The repeatability data were more precise than in a study of the repeatability of VO_{2peak} from the arm-leg ergometer as tested in healthy subjects (bias ± 1.96 SD = 0.016 ± 0.74 L/min) [27]. The within-subject coefficients of variation for VO_{2peak} and HR_{peak} were comparable to previous studies using cycle ergometry and treadmill exercise [28, 29].

HR_{peak} obtained from the RATT was lower than HR_{peak} from the treadmill and the cycle ergometer. Although strong correlations between the RATT vs cycle HR_{peak} and the RATT vs treadmill HR_{peak} were found, the correlation coefficient (R) and the coefficient of determination (R^2) are lower compared to those for VO_{2peak}. The R^2 values found in this study (0.41 for the cycle, 0.39 for the treadmill) are slightly higher than in a study of Shrieks et al., who compared a treadmill with an arm crank ergometer and found that a linear regression for HR_{peak} for treadmill vs arm crank ergometer had $R^2 = 0.33$ [20], which reflects that there are some factors which influence HR_{peak} other than the effect of the device itself. Previous work showed that age explained the majority of the variance [30, 31]. Other factors such as sex are controversial: Tanaka et al. stated that age predicted maximal heart rate to a large extent is independent of gender or physical activity status [30]; however, Faff et al. found a significant sex-dependent difference in the regression formula obtained after exercise on the treadmill and the cycle ergometer in athletes [32].

Repeatability of HR_{peak} from the RATT is comparable to the cycle ergometer. It was more precise compared to the study of Simmerlink et al., in which HR_{peak} repeatability from an arm-leg ergometer was 2.83 ± 19.85 beats/min [27]. Although the point estimates of ICC of the

HR_{peak} from all devices studied here were high and comparable, the 95% CI were wide. Overall, the HRpeak parameter was seen to be less reliable than VO_{2peak}.

A limitation of the present study is that, since a direct comparison between the devices in moderately or severely disabled neurological patients is not possible, it remains unknown whether the relative peak cardiopulmonary performance parameters can be extrapolated to the target patient population.

The data presented here, in particular the high correlation with standard devices and the high test-retest reliability and repeatability, support the validity and reliability of the RATT as a means of estimating peak cardiopulmonary performance parameters. The results demonstrate that the RATT has potential to be used for exercise testing in patients who have limitations for use of standard exercise testing modalities. The visual feedback system may be beneficial for the motivation of patients in both exercise testing and prescriptive exercise training. Future work should focus on the feasibility of peak cardiopulmonary performance testing using the RATT in populations with severe neurological impairments.

Conclusions

The present study demonstrated that VO_{2peak} from the RATT was $\sim 20\%$ lower than the cycle ergometer and $\sim 30\%$ lower than the treadmill. The magnitude of difference is less than the arm ergometer [20, 23] but more than the supine cycle ergometer [21]. The high correlation coefficients, the high test-retest reliability and the high repeatability of the VO_{2peak} suggest that the RATT is a valid and reliable device for exercise testing. There is potential for the RATT to be used in severely impaired subjects who cannot use the standard modalities.

Acknowledgments

Author Contributions

Conceived and designed the experiments: JS ML KH TN. Performed the experiments: JS ML KH. Analyzed the data: JS ML KH TN. Contributed reagents/materials/analysis tools: JS ML KH TN. Wrote the paper: JS ML KH TN.

References

1. Myers J, Nieman D, eds. ACSM's resources for clinical exercise physiology: musculoskeletal, neuro-muscular, neoplastic, immunologic, and hematologic conditions. 2nd ed. Philadelphia: Wolters Kluwer Health/Lippincott Williams & Wilkins; 2010.

2. Pescatello LS, Arena R, Riebe D, Thompson PD, eds. ACSM's guidelines for exercise testing and pre-scription. 9th ed. Philadelphia: Wolters Kluwer Health/Lippincott Williams & Wilkins; 2014.

3. Marzolini S, Oh P, McIlroy W, Brooks D. The Feasibility of cardiopulmonary exercise testing for pre-scribing exercise to people after stroke. Stroke. 2012; 43: 1075–1081. doi: 10.1161/STROKEAHA.111.635128 PMID: 22328554

4. Porszasz J, Casaburi R, Somfay A, Woodhouse LJ, Whipp BJ. A treadmill ramp protocol using simulta-neous changes in speed and grade. Med Sci Sports Exerc. 2003; 35: 1596–1603. PMID: 12972882

5. Buchfuhrer MJ, Hansen JE, Robinson TE, Sue DY, Wasserman K, Whipp BJ. Optimizing the exercise protocol for cardiopulmonary assessment. J Appl Physiol Respir Environ Exerc Physiol. 1983; 55: 1558–1564. PMID: 6643191

6. Carter H, Jones AM, Barstow TJ, Burnley M, Williams CA, Doust JH. Oxygen uptake kinetics in tread-mill running and cycle ergometry: a comparison. J Appl Physiol. 2000; 89: 899–907. PMID: 10956332

7. Smith AC, Saunders DH, Mead G. Cardiorespiratory fitness after stroke: a systematic review. Int J Stroke. 2012; 7: 499–510. doi: 10.1111/j.1747-4949.2012.00791.x PMID: 22568786

8. Jacobs PL, Nash MS. Exercise recommendations for individuals with spinal cord injury. Sports Med. 2004; 34: 727–751. PMID: 15456347

9. Bichsel L, Sommer M, Hunt KJ. Development of a biofeedback system for controlling the patients work rate, heart rate and oxygen uptake during robot-assisted tilt table therapy. Automatisierungstechnik. 2011; 59: 622–628.

10. Saengsuwan J, Laubacher M, Nef T, Hunt KJ. Cardiopulmonary performance testing using a robotics-assisted tilt table: feasibility assessment in able-bodied subjects. Technol Health Care. 2014; 22: 179–187. doi: 10.3233/THC-140783 PMID: 24576813

11. Laubacher M, Perret C, Hunt KJ. Work-rate-guided exercise testing in patients with incomplete spinal cord injury using a robotics-assisted tilt-table. Disabil Rehabil Assist Technol. 2014 Apr 8. doi: 10.3109/17483107.2014.908246

12. Pina IL, Balady GJ, Hanson P, Labovitz AJ, Madonna DW, Myers J. Guidelines for clinical exercise testing laboratories. A statement for healthcare professionals from the Committee on Exercise and Cardiac Rehabilitation, American Heart Association. Circulation. 1995; 91: 912–921.

13. Myers J, Buchanan N, Walsh D, Kraemer M, McAuley P, Hamilton-Wessler M, et al. Comparison of the ramp versus standard exercise protocols. J Am Coll Cardiol. 1991; 17: 1334–1342. PMID: 2016451

14. Jurca R, Jackson AS, LaMonte MJ, Morrow JR Jr, Blair SN, Wareham NJ, et al. Assessing cardiorespiratory fitness without performing exercise testing. Am J Prev Med. 2005; 29: 185–193. PMID: 16376715

15. Hunt KJ. Treadmill control protocols for arbitrary work rate profiles combining simultaneous nonlinear changes in speed and angle. Biomed Signal Process Control. 2008; 3: 278–282.

16. Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc. 1982; 14: 377–381. PMID: 7154893

17. Borg G. Psychophysical scaling with applications in physical work and the perception of exertion. Scand J Work Environ Health. 1990; 16: 55–58. PMID: 2345867

18. Bland JM, Altman DG. Statistics notes: Measurement error proportional to the mean. BMJ. 1996; 313: 106. PMID: 8688716

19. Billinger SA, Loudon JK, Gajewski BJ. Validity of a total body recumbent stepper exercise test to assess cardiorespiratory fitness. J Strength Cond Res. 2008; 22: 1556–1562. doi: 10.1519/JSC.0b013e3181739dd7 PMID: 18714232

20. Schrieks IC, Barnes MJ, Hodges LD. Comparison study of treadmill versus arm ergometry. Clin Physiol Funct Imaging. 2011; 31: 326–331. doi: 10.1111/j.1475-097X.2011.01014.x PMID: 21672142

21. Simonson SR, Wyatt FB. The rate pressure product is greater during supine cycle ergometry than during treadmill running. Biol Sport. 2003; 20: 3–14.

22. Reybrouck T, Heigenhauser GF, Faulkner JA. Limitations to maximum oxygen uptake in arms, leg, and combined arm-leg ergometry. J Appl Physiol. 1975; 38: 774–779. PMID: 1126885

23. Astrand PO, Saltin B. Maximal oxygen uptake and heart rate in various types of muscular activity. J Appl Physiol. 1961; 16: 977–981. PMID: 13863012

24. Orr JL, Williamson P, Anderson W, Ross R, McCafferty S, Fettes P. Cardiopulmonary exercise testing: arm crank vs cycle ergometry. Anaesthesia. 2013; 68: 497–501. doi: 10.1111/anae.12195 PMID: 23573845

25. Tammemagi MC, Frank JW, Leblanc M, Artsob H, Streiner DL. Methodological issues in assessing reproducibility—a comparative study of various indices of reproducibility applied to repeat ELISA serologic tests for Lyme disease. J Clin Epidemiol. 1995; 48: 1123–1132. PMID: 7636514

26. Lee J, Koh D, Ong CN. Statistical evaluation of agreement between two methods for measuring a quantitative variable. Comput Biol Med. 1989; 19: 61–70. PMID: 2917462

27. Simmelink EK, Wempe JB, Geertzen JHB, Dekker R. Repeatability and validity of the combined arm-leg (Cruiser) ergometer. Int J Rehabil Res. 2009; 32: 324–330. doi: 10.1097/MRR.0b013e328325a8a8 PMID: 19252438

28. Nordrehaug JE, Danielsen R, Stangeland L, Rosland GA, Vik-Mo H. Respiratory gas exchange during treadmill exercise testing: reproducibility and comparison of different exercise protocols. Scand J Clin Lab Invest. 1991; 51: 655–658. PMID: 1810026

29. Garrard CS, Emmons C. The reproducibility of the respiratory responses to maximum exercise. Respiration. 1986; 49: 94–100. PMID: 3081979

30. Tanaka H, Monahan KD, Seals DR. Age-predicted maximal heart rate revisited. J Am Coll Cardiol. 2001; 37: 153–156. PMID: 11153730

31. Fairbarn MS, Blackie SP, McElvaney NG, Wiggs BR, Paré PD, Pardy RL. Prediction of heart rate and oxygen uptake during incremental and maximal exercise in healthy adults. Chest. 1994; 105: 1365–1369. PMID: 8181321

32. Faff J, Sitkowski D, Ladyga M, Klusiewicz A, Borkowski L, Starczewska-Czapowska J. Maximal heart rate in athletes. Biol Sport. 2007; 24: 129–142.