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Submaximal cardiopulmonary thresholds on a robotics-assisted tilt table, a cycle and a treadmill: a comparative analysis

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Abstract

Background: The robotics-assisted tilt table (RATT), including actuators for tilting and cyclical leg movement, is used for rehabilitation of severely disabled neurological patients. Following further engineering development of the system, i.e. the addition of force sensors and visual bio-feedback, patients can actively participate in exercise testing and training on the device. Peak cardiopulmonary performance parameters were previously investigated, but it also important to compare submaximal parameters with standard devices. The aim of this study was to evaluate the feasibility of the RATT for estimation of submaximal exercise thresholds by comparison with a cycle ergometer and a treadmill.

Methods: 17 healthy subjects randomly performed six maximal individualized incremental exercise tests, with two tests on each of the three exercise modalities. The ventilatory anaerobic threshold (VAT) and respiratory compensation point (RCP) were determined from breath-by-breath data.

Results: VAT and RCP on the RATT were lower than the cycle ergometer and the treadmill: oxygen uptake ($V'O_2$) at VAT was [mean (SD)] 1.2 (0.3), 1.5 (0.4) and 1.6 (0.5) L/min, respectively ($p < 0.001$); $V'O_2$ at RCP was 1.7 (0.4), 2.3 (0.8) and 2.6 (0.9) L/min, respectively ($p = 0.001$). High correlations for VAT and RCP were found between the RATT vs the cycle ergometer and RATT vs the treadmill (R on the range 0.69–0.80). VAT and RCP demonstrated excellent test–retest reliability for all three devices (ICC from 0.81 to 0.98). Mean differences between the test and retest values on each device were close to zero. The ventilatory equivalent for O_2 at VAT for the RATT and cycle ergometer were similar and both were higher than the treadmill. The ventilatory equivalent for CO_2 at RCP was similar for all devices. Ventilatory equivalent parameters demonstrated fair-to-excellent reliability and repeatability.

Conclusions: It is feasible to use the RATT for estimation of submaximal exercise thresholds: VAT and RCP on the RATT were lower than the cycle ergometer and the treadmill, but there were high correlations between the RATT vs the cycle ergometer and vs the treadmill. Repeatability and test–retest reliability of all submaximal threshold parameters from the RATT were comparable to those of standard devices.

Keywords: Robotics-assisted tilt table, Treadmill, Cycle ergometer, Submaximal exercise, Anaerobic threshold, Respiratory compensation point, Cardiopulmonary exercise testing

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Background

A robotics-assisted tilt table (RATT) provides safe mobilization and intensive sensorimotor stimulation for early rehabilitation of neurological patients by tilting the patient upright and implementing cyclical leg stepping movement. The RATT has separate actuators for tilting the table and for continuously moving the legs during therapy.

The RATT device employed in the present work is a clinical product (Erigo, Hocoma AG, Switzerland), which as standard includes neither measurement of the patient's work rate, nor does it provide the patient with any form of biofeedback which could be used to guide their active participation. To extend the functionality of the standard RATT, specifically to make it possible to implement formal exercise testing protocols on the device, the RATT was augmented with force sensors and a visual bio-feedback system [1]. The force sensors were inserted under the leg cuffs which attach the patient's legs to the leg-drive systems. Using additional measurements of the moment arms and the joint angular velocities, the true work rate (in Watts) applied by the patient at the human–machine interface can be calculated in real time. The new visual biofeedback system which was added to the standard device shows the patient a target work rate and, in real time, the actual, measured work rate. The patient is instructed to adapt their volition leg effort, by producing forces into the leg cuffs in synchrony with the cyclical leg motion, in order to follow the work rate target as closely as possible. The target work rate can be chosen arbitrarily, but, for exercise testing purposes, it will be a standardized test protocol such as a constant work rate or incremental ramp. These engineering extensions have enabled severely disabled neurological patients to actively participate in exercise testing and training on the RATT [2, 3].

The augmented RATT device, with the engineering developments outlined above, makes possible for the first time the implementation of standardized exercise testing protocols on a robotics-assisted tilt table for determination of the key parameters of cardiopulmonary status (testing) and to allow optimized prescription of exercise regimes (training). An incremental exercise test, where the patient's work rate increases linearly over a short time period, delivers two types of parameters: (1) peak cardiopulmonary performance parameters (peak oxygen uptake and peak heart rate), which characterize aerobic capacity, and (2) submaximal exercise thresholds (primarily the ventilatory anaerobic threshold, VAT, and respiratory compensation point, RCP), which serve mainly to allow prescription of training intensity.

We previously reported on peak cardiopulmonary performance parameters (parameter group (1), above) obtained using the augmented RATT, and compared peak responses from the augmented RATT with standard modalities (treadmill and cycle ergometers) [4]. In the present work, we investigate the second major parameter group, (2) above, which can be obtained from incremental exercise testing, viz. the submaximal exercise thresholds VAT and RCP, together with several secondary submaximal parameters. The submaximal parameters from the RATT are directly compared with values obtained in the same subjects using treadmill and cycle ergometers. This investigation is considered clinically relevant because most neurological patients such as those with stroke or multiple sclerosis often terminate exercise testing before their maximal effort is reached. Non-cardiopulmonary factors, such as cognitive problems, muscle weakness or fatigue, are the causes linked to exercise termination in these patients [5, 6].

The submaximal exercise thresholds, i.e. the oxygen uptake at the ventilatory anaerobic threshold ($V'O_{2@VAT}$) and at the respiratory compensation point ($V'O_{2@RCP}$), are important because they can provide crucial information for the assessment of fitness status [7–9] or for exercise prescription [10–12]. They are independent of subjects' motivation [13] and the duration of the exercise testing protocol [14]. Furthermore, $V'O_{2@VAT}$ is reported to be useful for follow up after an intervention [15–17], for the prediction of all-cause postoperative mortality [18] and for the assessment of the severity of heart failure [19].

Other submaximal exercise parameters derived from ventilation (V′E), such as ventilatory equivalent of oxygen ($V'E/V'O_2$), ventilatory equivalent of carbon dioxide ($V'E/V'CO_2$) and the V′E-vs-$V'CO_2$ slope, provide additional information regarding the existence and severity of heart and lung diseases [20, 21]. Additionally, $V'E/V'CO_2$ and the V′E-vs-$V'CO_2$ slope are important predictors for mortality in some groups of patients, e.g. patients with heart failure [22, 23].

Numerous studies reported differences in submaximal exercise parameters on the cycle ergometer and the treadmill [14, 24–26], the arm ergometer and the cycle ergometer [27, 28], and the arm ergometer, the cycle ergometer and the treadmill [29]. It has been shown that the submaximal thresholds, e.g. $V'O_{2@VAT}$, from the arm ergometer were lower than the cycle ergometer, and $V'O_{2@VAT}$ from the cycle ergometer was lower than the treadmill [14, 24, 27, 28]. Regarding submaximal exercise parameters such as $V'E/V'CO_2$ and the V′E-vs-$V'CO_2$ slope, there are conflicting data. Sun et al. reported no mode-dependent difference in $V'E/V'CO_2$ and the V′E-vs-$V'CO_2$ slope [26]; however, Davis et al. found that $V'E/V'CO_2$ and the V′E-vs-$V'CO_2$ slope were higher on the treadmill than the cycle ergometer in women but not in men, and concluded that women demonstrated mode dependency in ventilatory efficiency indices [25].

Since there are no previous data regarding the comparative evaluation of submaximal exercise parameters from the RATT, the aim of this study was to evaluate the feasibility of the RATT for estimation of submaximal exercise thresholds and to compare these with the cycle ergometer and the treadmill.

Methods

Study design and selection criteria

This descriptive study was reviewed and approved by the Ethics Review Committee of the Swiss Canton of Bern, Switzerland (Reference No. 002/12). All research subjects gave their written informed consent before participating in the study.

Subjects were included in the study if they were 18–50 years and had no history of cardiovascular, pulmonary and musculoskeletal disease that might have interfered with the exercise testing.

Testing procedures

Subjects were randomly assigned to perform six maximal individualized incremental exercise tests, with two tests on each of the three exercise modalities: a treadmill (Venus, h/p/cosmos GmbH, Germany—2 tests), a cycle ergometer (LC7, Monark Exercise AB, Sweden—2 tests) and a robotics-assisted tilt table (RATT; Erigo, Hocoma AG, Switzerland—2 tests) [4]. Each test session was separated by at least 48 h but not more than

7 days and the time of day was controlled. Subjects were advised to avoid strenuous activity for at least 24 h and not to consume food for at least 3 h before the exercise testing [30].

The incremental exercise testing protocol on each device was the same: it started with 3 min of rest, 5 min of warm up, 3 min of rest, and 3 min of unloaded movement before the ramp phase (Fig. 1). Subjects' work rate increments during the ramp phase were estimated from their predicted maximal oxygen uptake [31] in order that the subjects would reach their maximal exercise performance in 8–12 min [14].

RATT: The subjects were first secured with a body harness, thigh cuffs and foot straps. Then the RATT was tilted to 70 degrees and the stepping movement was set at 80 steps/min, which is the maximal achievable step rate on this device. The RATT ramp rate was set in the range of 4 to 12 W/min. The subjects were instructed to actively push into the leg cuffs to produce force to follow the target work rate which they could see and compare to their actual work rate in real time (Fig. 2).

Cycle ergometer: The ramp rate ranged from 12 to 40 W/min. The settings for the seating and pedalling were adjusted for each subject and recorded to ensure the same position in subsequent tests.

Treadmill: During the ramp phase, the work rate increment ranged from 14 to 30 W/min. The work rate was increased linearly every 30 s using combined non-linear changes in speed and slope [32].

Cardiopulmonary data were recorded with a breath-by-breath cardiopulmonary testing system (MetaMax 3B, Cortex Biophysik GmbH, Germany). Before each test, full calibration was performed: pressure calibration; volume calibration with a 3-L syringe; and two-point gas calibration using ambient air and a precision gas mixture (15 % oxygen and 5 % carbon dioxide). Heart rate was recorded using a chest strap (model T34, Polar Electro Oy, Finland). The cardiopulmonary variables were analysed using a 15-breath average on the corresponding Metasoft software (version 2.7.29, Cortex Biophysik GmbH, Germany) [33].

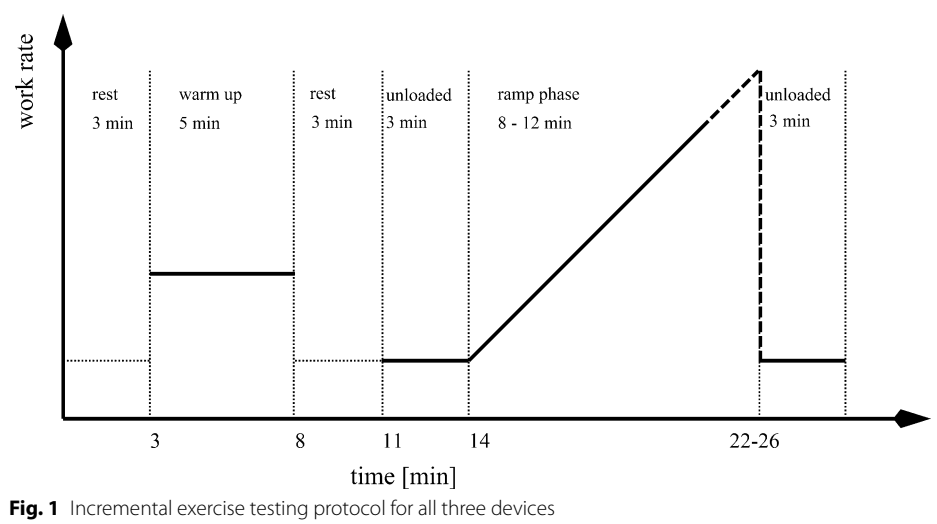

Fig. 1 Incremental exercise testing protocol for all three devices

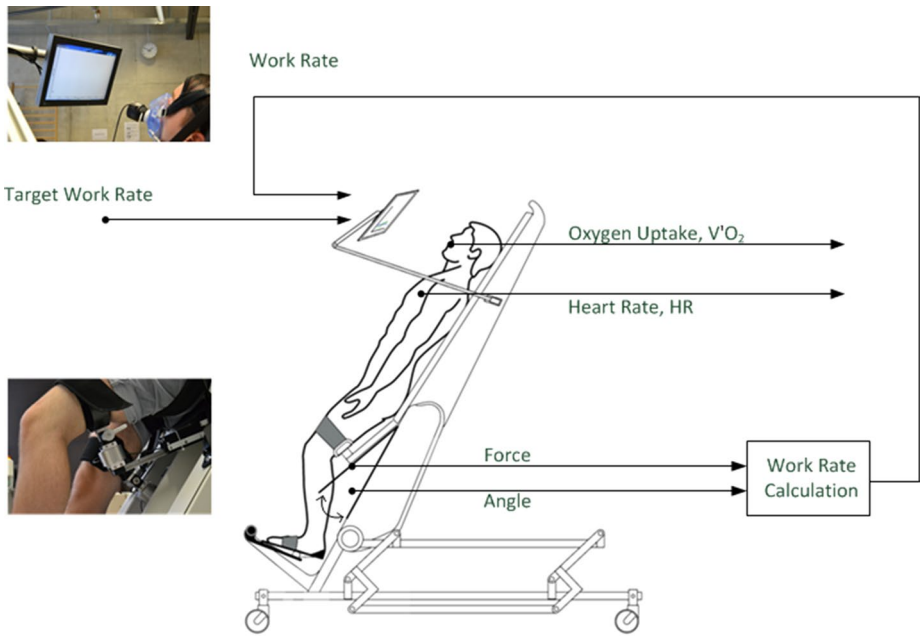

Fig. 2 Robotics-assisted tilt table (RATT) with visual feedback system. The visual feedback screen shows the target work rate and the subject's work rate. The subject's work rate was calculated from the forces in the thigh cuffs and the angular velocities

Outcome measures

The VAT and RCP were identified according to the criteria suggested by Binder et al. [11]. The VAT was visually determined using the combination of these approaches: (1) the point of deflection of $V'CO_2$ versus $V'O_2$ (V-slope method) [34]; (2) the point where $V'E/V'O_2$ reaches its minimum or starts to rise without a rise in $V'E/V'CO_2$; and, (3) the point at which partial pressure of end-tidal oxygen tension ($P_{ET}O_2$) reaches a minimum or starts to rise without a decline in the partial pressure of end-tidal carbon dioxide tension ($P_{ET}CO_2$).

The RCP was visually determined by: (1) the point of deflection of $V'E$ versus $V'CO_2$; (2) the minimal value or nonlinear rise of $V'E/V'CO_2$; and, (3) the point that $P_{ET}CO_2$ starts to decline.

The above approaches were used to determine the values of $V'O_2$ and $V'E/V'O_2$ at VAT ($V'O_{2@VAT}$ and $V'E/V'O_{2@VAT}$), and $V'O_2$ and $V'E/V'CO_2$ at RCP ($V'O_{2@RCP}$ and $V'E/V'CO_{2@RCP}$). The slope of $V'E$-vs-$V'CO_2$ from the start of the ramp phase to the RCP was also estimated.

Statistical analysis

Normality of the data was assessed by the Shapiro–Wilk test. Data from the second tests on each device were used for the comparative and correlation analyses. Repeated measures analysis of variance (ANOVA) was conducted to determine whether there were differences of $V'O_{2@VAT}$ and $V'O_{2@RCP}$ between the three devices. If a statistically significant difference was found, Bonferroni post hoc multiple comparison corrections were applied to examine differences between each paired data set.

Linear regression analysis was used to identify the correlation between the values of $V'O_{2@VAT}$ and $V'O_{2@RCP}$ on the RATT vs cycle ergometer and vs treadmill. The regression equation, correlation coefficient (R), coefficient of determination (R^2) and standard error of the estimate (SEE) were obtained.

Test–retest reliability of submaximal parameters on each device was analysed using a 2-way mixed single measures (absolute agreement) intraclass correlation coefficient ($ICC_{3,1}$) [35]. $0.40 \leq ICC < 0.75$ was considered as fair to good reliability and $ICC \geq 0.75$ was considered excellent reliability [36]. Repeatability was analysed using the Bland and Altman limits of agreement, incorporating mean difference and coefficient of repeatability [37]. The within-subject coefficients of variation were also calculated [38]. The test–retest reliability was based on only nine subjects because of a technical problem in the measurement device detected in the data from the first tests in eight subjects.

All analyses were performed using SPSS (Version 19.0, IBM Corp.).

Results

Seventeen subjects were included (9 male, 8 female). The subjects had the following characteristics [mean (SD))]: age 28.4 (6.4) years, height 171.8 (9.8) cm, body mass 68.1 (12.5) kg and body mass index 22.6 (2.2) kg/m^2.

VAT and RCP

The VAT was able to be identified in all subjects on all three devices. The RCP on the RATT was identified in 10 subjects (58.8 %), on the cycle ergometer in 17 subjects (100 %), and on the treadmill in 15 subjects (88.2 %); in 9 subjects, the RCP was identified for all three devices.

The $V'O_{2@VAT}$ and $V'O_{2@RCP}$ from the RATT were lower than the cycle ergometer and the treadmill: absolute $V'O_{2@VAT}$ from the RATT, the cycle ergometer and the treadmill was [mean (SD)] 1.2 (0.3), 1.5 (0.4) and 1.6 (0.5) L/min, respectively ($p < 0.001$); $V'O_{2@RCP}$ from the RATT, the cycle ergometer and the treadmill was 1.7 (0.4), 2.3 (0.8) and 2.6 (0.9) L/min, respectively ($p = 0.001$) (Table 1; Fig. 3). On average, the $V'O_{2@VAT}$ on the RATT was 21.4 % lower than the cycle ergometer $V'O_{2@VAT}$ and 26.1 % lower than the treadmill $V'O_{2@VAT}$ (mean individual differences). The $V'O_{2@RCP}$ on the RATT was 23.9 % lower than the cycle ergometer $V'O_{2@RCP}$ and 30.6 % lower than the treadmill $V'O_{2@RCP}$ (mean individual differences).

High correlations were found between the RATT vs the cycle ergometer $V'O_{2@VAT}$ ($R = 0.70$, $p < 0.01$) and $V'O_{2@RCP}$ ($R = 0.80$, $p < 0.01$). The RATT vs the treadmill $V'O_{2@VAT}$ ($R = 0.73$, $p < 0.01$) and $V'O_{2@RCP}$ ($R = 0.69$, $p < 0.05$) demonstrated similarly high correlations (Fig. 4). The $V'O_{2@VAT}$ and $V'O_{2@RCP}$ demonstrated excellent test–retest reliability for all three devices (ICC 0.81–0.98). The mean differences between the test and retest values on each device were close to zero (Table 2).

Other parameters

$V'E/V'O_{2@VAT}$ from the RATT and the cycle ergometer were comparable and both were higher than the treadmill. There were no significant differences in $V'E/V'CO_{2@RCP}$. The $V'E$-vs-$V'CO_2$ slope to RCP on the RATT was higher than the cycle ergometer and the treadmill (Table 1). $V'E/V'O_{2@VAT}$, $V'E/V'CO_{2@RCP}$ and $V'E$-vs-$V'CO_2$ slope to RCP had

Table 1 Submaximal performance parameters from the RATT, cycle and treadmill (VAT: n = 17; RCP: n = 9)

Variables	RATT	Cycle ergometer	Treadmill	*P* value
$V'O_{2peak}$ absolute (L/min)[a,b,c] (n = 17)	2.39 ± 0.6	2.82 ± 0.8	3.2 ± 0.9	<0.001
Absolute $V'O_{2@VAT}$ (L/min)[a,b] (n = 17)	1.16 ± 0.3	1.53 ± 0.4	1.64 ± 0.5	<0.001
Relative $V'O_{2@VAT}$ (mL/kg/min)[a,b]	17.2 ± 3.6	22.3 ± 4.0	23.8 ± 4.7	<0.001
$V'O_{2@VAT}$ as % of $V'O_{2peak}$	49.4 ± 8.8	54.5 ± 5.1	50.6 ± 5.9	0.047
HR at VAT (beats/min)[a]	114.3 ± 12.9	125.3 ± 10.6	121.7 ± 12.8	0.007
HR at VAT as percent predicted HR_{peak} (%)[a]	59.6 ± 6.3	65.4 ± 4.8	63.5 ± 5.9	0.007
Absolute $V'O_{2@RCP}$ (L/min)[a,b,c] (n = 9)	1.68 ± 0.4	2.26 ± 0.8	2.55 ± 0.9	0.001
Relative $V'O_{2@RCP}$ (mL/kg/min)[a,b]	24.9 ± 5.1	33.0 ± 7.5	37.3 ± 9.3	<0.001
$V'O_{2@RCP}$ as % of $V'O^{a}_{2peak}$	68.7 ± 10.2	78.5 ± 9.9	79.1 ± 15.6	0.022
HR at RCP (beats/min)[a]	141.3 ± 17.5	153.2 ± 18.1	158.7 ± 21.9	0.004
HR at RCP as percent predicted HR_{peak} (%)[a]	73.6 ± 7.1	79.8 ± 6.9	82.6 ± 9.0	0.003
$V'E/V'O^{b,c}_{2@VAT}$ (n = 17)	23.6 ± 2.9	23.8 ± 3.0	21.8 ± 2.2	0.002
$V'E/V'CO_{2@RCP}$ (n = 9)	28.9 ± 2.3	27.5 ± 2.8	26.7 ± 2.9	0.022
$V'E$-vs-$V'CO_2$ slope to RCP[a,b] (n = 9)	28.4 ± 2.8	26.4 ± 2.4	25.7 ± 2.7	0.002

Data are given as mean ± standard deviation

$V'O_{2peak}$ peak oxygen uptake, *$V'O_2$* oxygen uptake, *VAT* ventilatory anaerobic threshold, *$V'O_{2@VAT}$* $V'O_2$ at VAT, *HR* heart rate, *HR_{peak}* peak heart rate, *RCP* respiratory compensation point, *$V'O_{2@RCP}$* $V'O_2$ at RCP, *$V'E/V'O_{2@VAT}$* ventilatory equivalent of oxygen at VAT, *$V'E/V'CO_{2@RCP}$* ventilatory equivalent of carbon dioxide at RCP, *$V'E$-vs-$V'CO_2$ slope* ventilation versus carbon dioxide output slope

[a] $p < 0.05$ between the RATT and the cycle ergometer

[b] $p < 0.05$ between the RATT and the treadmill

[c] $p < 0.05$ between the cycle ergometer and the treadmill

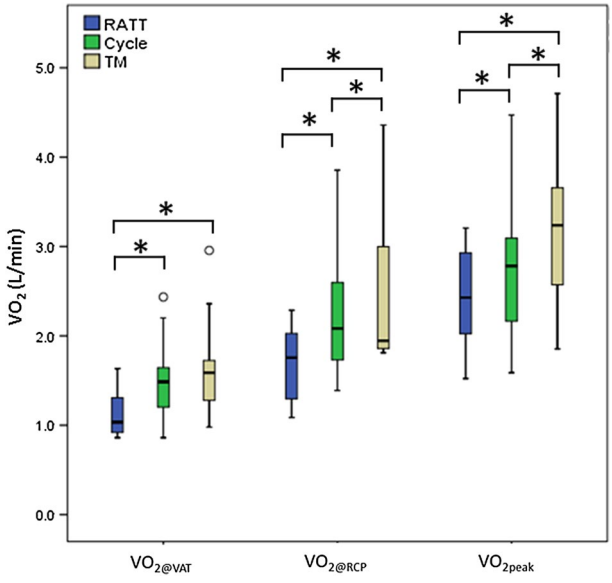

Fig. 3 Box plots for $VO_{2@VAT}$, $VO_{2@RCP}$ and VO_{2peak} among the 3 devices. *Asterisks* represent significant differences in each paired data set assessed by Bonferroni post hoc multiple comparison corrections

coefficients of variation less than 10 %, the ICC ranged from 0.53 to 0.92 and the repeatability of the parameters, demonstrated by the mean difference, on the RATT and the treadmill were lower than the cycle ergometer (Table 2).

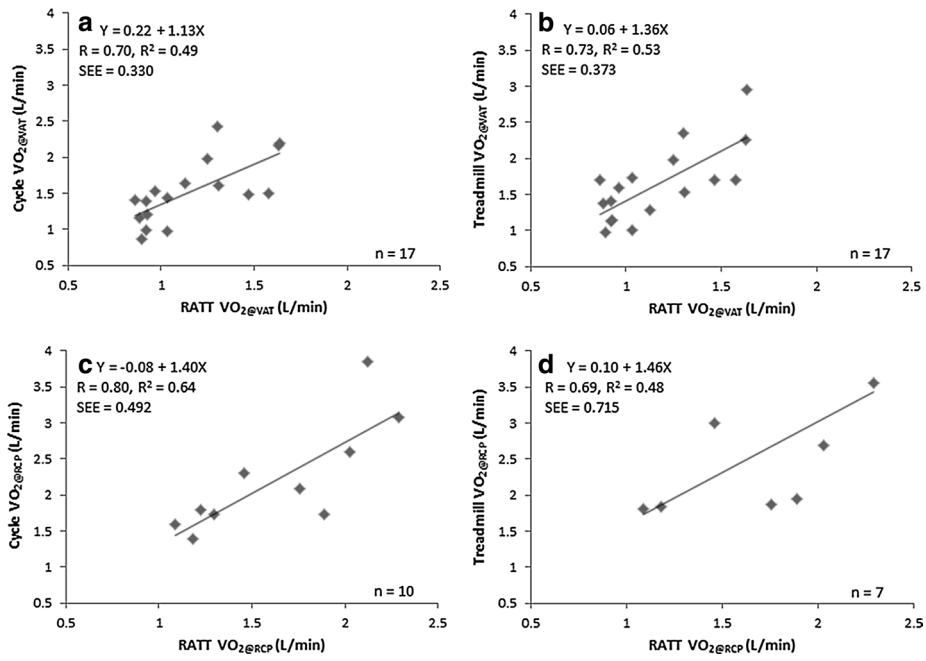

Fig. 4 Linear regression analysis of $V'O_{2@VAT}$ (**a**, **b**) and $V'O_{2@RCP}$ (**c**, **d**) on the RATT vs the cycle ergometer and the RATT vs the treadmill

Discussion

The aim of this study was to evaluate the feasibility of the RATT for estimation of submaximal exercise thresholds by comparison with a cycle ergometer and a treadmill.

Submaximal exercise thresholds

We found that $V'O_{2@VAT}$ and $V'O_{2@RCP}$ were lower on the RATT than on the cycle and the treadmill. These findings are in line with the differences in $V'O_{2peak}$ found between three devices: the $V'O_{2peak}$ from the RATT was approximately 20 % lower than the cycle $V'O_{2peak}$ and 30 % lower than the treadmill $V'O_{2peak}$ [4]. The lower $V'O_2$ may be explained by the lower muscle mass needed to exercise on the RATT. Additionally, the subjects may be less familiar with the stepping movement on the RATT compared with the movement on the standard devices [4].

High correlations were found between $V'O_{2@VAT}$ and $V'O_{2@RCP}$ on the RATT vs the treadmill and on the RATT vs the cycle ergometer; however, the correlation coefficients found were lower than those for the $V'O_{2peak}$ between devices (R = 0.94–0.95) [4]. The difference in the level of correlations found may be related to differences in muscle groups and muscle fibre types used during submaximal exercise on each device for each individual [7]. The correlations we found for $V'O_{2@VAT}$ are higher than in studies of arm ergometer vs cycle ergometer in normal subjects (0.60–0.64) [27, 28], which may reflect the closer pattern of movement on the RATT vs the cycle ergometer compared with different muscles used for exercise on the arm ergometer.

We found no pairwise differences in $V'O_{2@VAT}$ as a percentage of $V'O_{2peak}$ among the three devices. The $V'O_{2@VAT}$ (%$V'O_{2peak}$) found here, 49–55 %, is consistent with some studies on the treadmill or the cycle ergometer (range from 47 to 58 %) [14, 24, 27,

Table 2 Test-retest reliability of the submaximal performance parameters from the RATT, cycle and treadmill

	Overall mean (tests 1 and 2)	MD (95 % LoA)	CoV (%)	ICC (95 % CI)	SEM	%SEM
$V'O_{2@VAT}$ (L/min) (n = 9)						
RATT	1.129	−0.047 (−0.225, 0.131)	5.91	0.92 (0.60–0.98)	0.064	5.67
Cycle ergometer	1.411	0.082 (−0.459, 0.624)	14.10	0.81 (0.39–0.95)	0.195	13.82
Treadmill	1.561	−0.015 (−0.290, 0.259)	6.78	0.98 (0.90–1.0)	0.099	6.34
$V'O_{2@RCP}$ (L/min)						
RATT (n = 6)	1.649	0.094 (−0.208, 0.395)	6.52	0.92 (0.52–0.99)	0.109	6.61
Cycle ergometer (n = 8)	2.344	−0.014 (−0.706, 0.678)	8.66	0.87 (0.47–0.97)	0.245	10.45
Treadmill (n = 7)	2.609	−0.069 (−0.640, 0.502)	7.17	0.95 (0.74–0.99)	0.206	7.90
$V'E/V'O_{2@VAT}$ (n = 9)						
RATT	23.7	−0.01 (−3.5, 3.5)	5.02	0.70 (0.10–0.93)	1.26	5.31
Cycle ergometer	23.4	1.46 (−4.3, 7.2)	9.78	0.62 (0.05–0.90)	2.07	8.87
Treadmill	21.7	0.20 (−2.5, 2.9)	4.33	0.74 (0.19–0.94)	0.97	4.47
$VE/V'CO_{2@RCP}$						
RATT (n = 6)	28.8	0.70 (−1.0, 2.4)	2.48	0.77 (0.03–0.97)	0.62	2.16
Cycle ergometer (n = 8)	27.7	1.24 (−1.2, 3.6)	4.80	0.90 (0.33–0.98)	0.86	3.10
Treadmill (n = 7)	26.4	−0.97 (−4.6, 2.6)	5.23	0.71 (0.09–0.94)	1.30	4.92
$V'E$-vs-$V'CO_2$ slope to RCP						
RATT (n = 6)	28.0	0.73 (−4.0, 5.5)	6.00	0.53 (−0.38–0.92)	1.71	6.11
Cycle ergometer (n = 8)	26.4	2.19 (−2.0, 6.4)	8.26	0.75 (0.04–0.95)	1.52	5.77
Treadmill (n = 7)	25.4	−1.14 (−4.3, 2.1)	5.13	0.74 (0.12–0.95)	1.15	4.54

MD mean difference, *LoA* limits of agreement, *CoV* coefficient of variation, *ICC* intraclass correlation coefficient, *CI* confidence interval, *SEM* standard error of the measurement

39–41], and consistent with the observation that $V'O_{2@VAT}$ ($\%V'O_{2peak}$) rarely exceeds 60 % of $V'O_{2peak}$ [12]. However, other studies reported higher $V'O_{2@VAT}$ ($\%V'O_{2peak}$) (range from 60.4 to 77 %) in normal subjects [19, 42, 43]. The difference between $V'O_{2@VAT}$ ($\%V'O_{2peak}$) among studies may be caused by the difference in methods of identifying $V'O_{2@VAT}$, the gender, the fitness level and the age distribution of the subjects studied. It was found that $V'O_{2@VAT}$ occurs at a higher percentage of $V'O_{2peak}$ in older subjects, in women and in well-trained subjects [12, 20, 44, 45].

The $V'O_{2@RCP}$ as a percentage of $V'O_{2peak}$ on the RATT was approximately 10 % lower than on the treadmill. In general, data regarding $V'O_{2@RCP}$ ($\%V'O_{2peak}$) are less well established compared to $V'O_{2@VAT}$ ($\%V'O_{2peak}$). The $V'O_{2@RCP}$ ($\%V'O_{2peak}$) identified is in accordance with previous reports [42, 46, 47]. The lower proportion of subjects whose RCP could be identified on the RATT than the cycle or the treadmill may reflect that the RATT is less consistent in provoking cardiorespiratory loads high enough to reach RCP.

We found excellent test–retest reliability in submaximal exercise thresholds (ICC 0.81–0.98). The test–retest reliability of submaximal exercise thresholds obtained from the RATT was comparable to the treadmill and the cycle ergometer. The test–retest reliability for submaximal exercise thresholds found here were slightly lower than for peak oxygen uptake (ICC 0.97–0.99) [4]. The lower test–retest reliability in submaximal

exercise thresholds than in peak oxygen uptake has been demonstrated both in normal subjects, and cardiac and pulmonary patients [48–50]. One possible explanation is that the submaximal exercise thresholds may be more sensitive to day-to-day biological variability [51, 52].

Other parameters

Although there was a trend toward higher $V'E/V'CO_{2@RCP}$ on the RATT, the pairwise comparison did not reach statistical significance. $V'E/V'O_{2@VAT}$ and V′E-vs-$V'CO_2$ slope to RCP on the RATT were higher than on the cycle and the treadmill. A study on the arm ergometer found significant differences in $V'E/V'O_{2@VAT}$ (27.7 and 22.1) and $V'E/V'CO_{2@VAT}$ (29.7 and 25.7) between the arm ergometer and the cycle ergometer, respectively [27]. The lower ventilatory efficiency of the RATT and arm ergometer confirms that mode dependency in ventilatory efficiency indices exists. Therefore, the device used for exercise testing should be considered in the analysis of the ventilatory efficiency data. Apart from the arm ergometer, there are no data regarding the ventilatory efficiency in alternative exercise devices for a comparison of results. Most studies on alternative devices focused more on the peak cardiopulmonary values [53, 54] or submaximal values of $V'O_2$ or heart rate [55–57]. Since ventilatory efficiency data could provide additional information regarding the severity and prognosis of some heart or lung diseases [20–23], more study of these parameters on the alternative exercise testing devices should be done.

The test–retest reliability of the ventilatory efficiency was fair to excellent. The coefficient of variation was less than 10 %. This is consistent with Davis et al. who found that the test–retest reliability of the $V'E/V'CO_2$ and V′E-vs-$V'CO_2$ slope to RCP were high [58].

Our study has some limitations. Firstly, the RCP on the RATT could be identified in only 10/17 subjects. This may be because of the limitation that the RATT can elicit lower cardiopulmonary responses compared to the cycle ergometer and the treadmill in healthy subjects. Since this device is mainly intended to be used in patients with severe disability, this may not be a problem in the target population. Secondly, it cannot be verified whether the differences in submaximal exercise thresholds on each device would be the same for severely disabled neurological patients because it is not possible to implement the exercise tests on standard devices (e.g. treadmill) in severely disabled patients. Finally, the sample size was small, but the results provide preliminary estimates to support further study in target patient populations.

Conclusion

The results suggest that it is feasible to use the RATT for estimation of submaximal exercise thresholds: although $V'O_{2@VAT}$ and $V'O_{2@RCP}$ from the RATT were lower than the cycle ergometer and the treadmill, there were high correlations demonstrated between the RATT vs the cycle ergometer and vs the treadmill; furthermore, the repeatability and test–retest reliability of all submaximal threshold parameters from the RATT were comparable to those of standard devices. There was evidence of mode-dependent differences in $V'E/V'O_{2@VAT}$ and V′E-vs-$V'CO_2$ slope to RCP.

Abbreviations

CI: confidence interval; CoV: coefficient of variation; HR: heart rate; HR_{peak}: peak heart rate; ICC: intraclass correlation coefficient; LoA: limits of agreement; MD: mean difference; $P_{ET}CO_2$: partial pressure of end-tidal carbon dioxide tension; $P_{ET}O_2$: partial pressure of end-tidal oxygen tension; R: correlation coefficient; R^2: coefficient of determination; RATT: robotics-assisted tilt table; RCP: respiratory compensation point; SEE: standard error of the estimate; SEM: standard error of measurement; VAT: ventilatory anaerobic threshold; $V'CO_2$: carbon dioxide output; V′E: minute ventilation; $V'E/V'CO_2$: ventilatory equivalent of carbon dioxide; $V'E/V'O_2$: ventilatory equivalent of oxygen; $V'O_2$: oxygen uptake; $V'O_{2peak}$: peak oxygen uptake.

Authors' contributions

All authors made substantial contributions to the study and to manuscript preparation. JS, KH, TN and ML contributed to the design of the study. JS and KH carried out the assessments and performed the data analysis. JS, TN, ML and KH participated in drafting and critical review of the manuscript. All authors read and approved the final manuscript.

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Lukas Bichsel and Matthias Schindelholz developed and implemented the force sensors, work-rate estimation algorithm and the visual feedback system for the RATT.

Competing interests

The authors declare that they have no competing interests.

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