Correlation analysis of oxygen consumptions between stepper and treadmill movements and implication for rehabilitation

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Abstract

Background: Stepper movement is popular as a home-based exercise. However, it has not been fully investigated how much energy is consumed during movement. This study aimed to investigate oxygen consumption for stepper movements at different cadence levels and to look into whether there are correlations between stepper movement and treadmill walking.

Methods: Twenty two healthy volunteers (10 males, 12 females, aged between 18 and 40 years) participated in the study. The participants randomly performed stepper movements and treadmill walking at three different cadences, a self-determined comfortable cadence, a 20% higher and a 20% lower ones than the comfortable one. Their oxygen consumption was measured using Oxycon mobile® system. A set of parameters, e.g. VO_2, Metabolic unit, Energy expenditure, etc were obtained. Statistical analysis was carried out to investigate correlations between stepper and treadmill movements in terms of oxygen consumptions.

Results: Strong correlations were found between two types of movements, most of metabolic parameters had correlation coefficients ranged proximately between 0.5 to 0.8, $p<0.001$, e.g. 0.789 for VO_2, 0.790 for energy consumption, 0.826 for ventilation, all $p<0.001$. In the conformable cadence level, VO_2 for stepper movements was 826.49±56.02 (ml/min) while VO_2 for treadmill walking was 787.16±56.02. Usually, stepper movements have oxygen consumption similar to or slightly higher than that in treadmill walking.

Conclusions: This study indicates that stepper movement has similar oxygen consumption level to treadmill at a comfortable cadence level and at a 20% higher than the comfortable one, but stepper movement consumes more energy than treadmill walking by approximately 10% at lower cadence (i.e. 20% lower than the comfortable one). The study shows that the stepper movements is highly correlated with treadmill walking in terms of oxygen consumption, and thus stepper movement data provided can be used as a reference for the healthy to estimate their energy consumption in rehabilitation at home.

Background

In rehabilitation, through different people select different exercise [1, 3, 8], both stepper and treadmill machines are popular [5, 6]. Stepper machine is easy to use, much less expensive, occupies less area, and no guidance is needed for its use as compared to the treadmill. As the home exercising machine, a stepper seems to be better than treadmill.

Stepper machine has various functions. It helps rehabilitation by stimulating the movement of ascending steps [21]. Steppers have a very strong impact on gluteal muscles, legs and lower back. It is an apparatus found to be very useful for rehabilitation by many researchers [2, 4, 11, 15, 16]. There have been a number of studies done on stepper to assess the feasibility for rehabilitation, however, most of them were limited to using electromyography (EMG) which has been considered as the most useful method to measure the muscle activity [15]. However, a few researchers stated that the EMG assessment is limited to the location of the muscles selected. In the situation with deeper muscles containing high threshold motor units the assessment through EMG gets limited in comparison to the fine low threshold motor units. This suggests that there is a need for other ways to find the muscle activity which is the starting point for rehabilitation [15].

The measurement of oxygen consumption is very useful for the assessment of physiological considerations, especially during rehabilitation of patients [9, 10, 14, 19, 20, 22]. There are numerous rehabilitation strategies that can be used, however, the better approach being an individualised approach [18], where each and every individual is assessed separately and the rehabilitation programme is specifically developed according to personal circumstance.

Test using the stepper machines has been used traditionally for submaximal testing due to their lower oxygen values in comparison to treadmill [13]. Balance issues, fatigue and higher rate of stepping are also some of the disadvantages which could be related to the use of stepper [13]. However, despite the fact that stepper machines are an important tool in rehabilitation, there has not been any significant research done to analyse their usefulness in terms of energy consumption [19].

Treadmill, on the other hand, is a common used equipment in rehabilitation [5, 7, 12]. Its research has been done for many years and has a reasonably completed database. It provides more collective form of physiological stress, as walking required by the participant results in higher uptake of oxygen and increased heart rate [1].

Today, it is popular for users to use treadmills in gymnasiums [23]. However, for those who cannot go to gymnasiums for some reasons, stepper exercise is an option [24, 25, 26]. Therefore, the research question is if the stepper movements could replace treadmill movements and whether correlations exist between stepper movement and treadmill walking. It is hypothesized that there are some kinds of correlations between two movements.

The aim of this study was to investigate oxygen consumption during stepper movement and to analyse whether stepper movement and treadmill walking are correlated or not. Hopefully, this research would provide clinicians with a useful database and allow them to guide patients in rehabilitation.

Methods

Data inclusion and exclusion

This was a single centre, observational study of a cohort of the healthy. The inclusion criteria was that the healthy, age 20-50, male or female and the exclusion was without any physical and medical disabilities or injuries. They were required to sign a consent form before they took part in the study. This project was approved by the university research ethics committee.

Equipment

Stepper

Reebok® mini side stepper (REM-7580) was used in this experiment. It consists of foot plates (Figure 1a), a knob to adjust the resistance and console (Figure 1b) that displays count, total count, time, calories and scan side to side action. Dimensions: H22, W51, D45 cm.

Treadmill

Vision fitness ^{TM} T 8500 treadmill was used for the experiment. Three different speeds with no inclination were used for the entire data collection. The treadmill picture is ignored.

Mobile Oxycon® System

The mobile Oxycon system consists of the following components (Figure 2):

- Calibration chamber
- Face mask
- Measuring sensors (Triple V)
- Receiver and interface to PC (Power calibration unit - PCa).
- Transmitter (Data exchange unit - DEx with transmitter antenna attached).
- Measuring unit (sensor box SBx/CPx).
- Laptop with the USB interface cable.

A vest for carrying the DEx and the sensor box SBx/ CPx

Protocol

Proper calibration was done before every data collection to get the accurate data.

Taking Cadence

To identify a reasonable cadence for each participant, a method was designed as below. The participants were asked to walk at their self-determined conformable walking speed for 1 min and their steps were counted for 15 seconds during walking. The procedure was repeated three times and the average cadence was taken as baseline, then 20% higher and 20% lower cadences were calculated from the baseline cadence. Three cadence values were then input into the Tempo Perfect Metronome Software (free from the internet) [17] that produces the beat sound accordingly for taking the corresponding data collection. This protocol was designed according to walking which is a commonly used movement daily and everybody has their own comfortable cadence. We asked each participant to do so that the cadence was calculated reliably.

Data Collection

The first data collection was done for the resting data by asking the subject to sit on a chair.

After five minutes the oxygen mask was removed and the subjects were allowed to relax for five minutes. The stepper or the treadmill machines were then chosen randomly to avoid any advantage of the machine being used first. The data for three different cadences were collected on each machine. A total of seven sets of data (one resting, three different cadences each on stepper and treadmill machines respectively) were collected. All the subjects were instructed to use the stepper or treadmill machine in tandem with the beat produced by the Tempo Perfect Metronome Software, and made sure they did so accordingly (Figures 3).

The data collection on stepper was done by setting the machine to the least resistance. On treadmill no inclination was used. The data collection for each cadence was done for five minutes on stepper or treadmill with five minutes rest in between data collections, and thus each data collection was done as a fresh one. The participants were reminded that they had the freedom to discontinue from the study any time during the experiment, if they developed any distress or difficulties. All the data collected were stored in the database of Oxycon Mobile® Software. The data were converted to .txt format and were stored on a flash drive for the analysis.

The Oxycon Mobile® can give different variables as below.

- VO_2 – Oxygen uptake in millilitres per minute (ml/min)
- VCO_2 – Carbon dioxide output in millilitres per minute (ml/min)
- VE–Ventilation (the movement of air between the atmosphere and the lungs via inhalation and exhalation)
- RER – Respiratory Exchange Ratio, which is Carbon dioxide output and the Oxygen uptake ($RER=VCO_2/VO_2$)
- EqO_2 – Breathing equivalent for Oxygen, which is the minute volume and the Oxygen uptake ($EqO_2= VE/VO_2$)
- $EqCO_2$– Breathing equivalent for Carbondioxide, which is the minute volume and carbon dioxide output ($EqCO_2= VE/VCO_2$)
- EE–Energy expenditure, which is the total energy consumed and is calculated as kilo calories per day.
- MET – Metabolic unit, in Oxycon Mobile® system, 1 MET=3.5 ml/min/kg

- Qtc – It is derived from the “Indirect Fick” Equation (Fick principle for CO_2). According to the equation the cardiac output (pumping of blood from heart/min) equals CO_2 production (VCO_2) divided by the difference of content of CO_2 in venous blood and the arterial blood ($CvC0_2$-$CaCO_2$). So Qtc= $VCO_2/CvCO_2$-$CaCO_2$ and it is calculated in Litres per minute (L/min).

Data Analysis

All the data collected were checked for any errors and any participant with inappropriate data was requested to repeat the data collection. All the data were analysed using SPSS® (version 21). The general linear model for repeated measurement was used to compare differences between various groups of data. When some variables were not normal distributed, non-parametric methods were used to double check p values. Pearson’s correlation coefficient and linear regression were used to analyse whether two variables are linearly correlated or not, and if correlated a regression function will be constructed. The significant level was set at $p<0.05$.

Results

Participants

Twenty two participants took part in the study, and they have ages mean 29.27 standard deviation (S.D.) 6.97 ranged 21-49 years old, heights mean 168.45 SD 10.14 ranged 155-191 cm, weights mean 71.69 SD 10.12 ranged 51-120 kg, body mass index (BMI) mean 25.01 SD 4.92 ranged 20.4-40.7, and 10 male and 12 female.

Variables given by Oxycon Mobile ® system

The results on the major parameters, e.g. VO_2 are shown in Table 1, and each parameter is analysed and plotted, one by one, as below.

VO_2 mean ml/min

The level of oxygen consumption (VO_2 mean, ml/min) in the S1, S2, S3 showed strong correlation with T1, T2, T3, where S1 and T1 are baseline cadence in stepper and treadmill movements, S2 and T2 represents 20% higher cadence than the baseline one, and S3 and T3 20% lower cadence than the baseline one. Mean values showed that S3 consumed more energy than T3 by approximately 14% (Table 1). The correlation coefficient between stepper and treadmill movements in VO_2 is very strong (0.789, $p< 0.001$) and a linear regression was constructed as seen in Figure 4.

Table 1. VO_2 oxygen consumption and other parameters using stepper and treadmill

Measure		Mean	Std. Error	95% Confidence Interval		p	note
				Lower Bound	Upper Bound		
VO_2 Mean ml/min	R	255.6	18.3	217.4	293.9	<0.001	vs all
	S1	834.5	63.9	700.7	968.3	0.285	vs T1
	S2	919.5	71.4	770.1	1068.9	0.478	vs T2
	S3	772.2	63.7	638.8	905.6	<0.016	vs T3
	T1	796.8	62.6	665.8	927.8		
	T2	959.6	73.7	805.3	1113.9		
	T3	677.7	58.4	555.6	799.9		
EqO_2 Mean	R	33.6	1.1	31.2	35.9	<0.001	vs all
	S1	29	0.7	27.6	30.4	0.455	vs T1
	S2	29	0.7	27.5	30.5	0.56	vs T2
	S3	28.2	0.6	26.9	29.4	<0.001	vs T3
	T1	28.3	0.8	26.6	30.1		
	T2	28.6	0.7	27.1	30.1		
	T3	29.9	0.5	28.8	31		
VCO_2 Mean ml/min	R	234	16.9	198.5	269.4	<0.001	vs all
	S1	799.9	69.8	653.8	945.9	<0.008	vs T1
	S2	859.8	71.8	709.6	1010.1	0.905	vs T2
	S3	670.8	54.1	557.6	784	<0.031	vs T3
	T1	690.8	52.6	580.7	800.9		
	T2	853	63.7	719.8	986.2		
	T3	598.8	55.3	483	714.7		
VO_2 Max ml/min/kg	R	4.44	0.3	3.81	5.07	p<0.001	vs all
	S1	12.35	0.66	10.97	13.73	0.291	vs T1
	S2	13.79	0.72	12.29	15.28	0.751	vs T2
	S3	11.37	0.57	10.17	12.56	0.003	vs T3
	T1	11.75	0.54	10.63	12.87		
	T2	14.03	0.78	12.39	15.66		

	T3	10.03	0.47	9.03	11.02		
$EqCO_2$ Mean	R	36.5	1.1	34.2	38.8	<0.001	vs all
	S1	30.6	0.6	29.3	31.8	<0.022	vs T1
	S2	31.3	0.7	29.7	32.8	0.3	vs T2
	S3	32.5	0.7	30.9	34	<0.001	vs T3
	T1	32.5	0.8	30.8	34.2		
	T2	32.1	0.8	30.3	33.9		
	T3	34.1	0.8	32.4	35.7		

Note: R- rest, S1–stepper movement with a normal cadence, S2-stepper cadence 20% higher than normal one, S3- stepper cadence 20% lower than the normal, T1-treadmill walking with a normal cadence, T2-treadmill 20% higher, T3-treadmill 20% lower

Breathing equivalent for oxygen (EqO_2)

EqO_2 mean in S1 (28.992) was very close to T1 mean value (28.33). It was found that the difference between S3 and T3 was significant, and T3 was higher than S3 by approximately 6% (Table 1). The correlation coefficient was also strong (0.489, $p < 0.001$) and linear regression as seen in Figure 5. The mean at Rest was observed at 33.560, which was significantly higher than the other situations, because EqO_2 is reversely proportional to VO_2.

Volume of CO_2 expired

VCO_2, which is the production of carbon dioxide per minute, was recorded. It is found that S1 and S3 were higher than T1 and T3 by approximately 16% and 11% respectively (Table 1). The correlation coefficient between two types of movements is 0.778 ($p<0.001$) as seen in Figure 6.

Respiratory exchange ratio (RER)

RER mean values showed a correlation between stepper and treadmill as in Figure 8, and S1 and S2 higher than T1 and T2 by approximately 8% and 6% respectively (Table 2). The correlation coefficient is 0.507 with $p< 0.001$, again confirming the correlation between the stepper and treadmill movements.

Table 2 Respiratory exchange ratio and parameters in stepper and treadmill measurements

Measure		Mean	Std. Error	95% Confidence Interval		p	note
				Lower Bound	Upper Bound		
Qtc Mean L/min	R	1.9	0.1	1.6	2.1	<0.001	vs all
	S1	5.5	0.4	4.6	6.4	0.323	vs T1
	S2	6.1	0.5	5.1	7.1	0.682	vs T2
	S3	5	0.4	4.2	5.9	<0.033	vs T3
	T1	5.3	0.4	4.4	6.1		
	T2	6.3	0.5	5.3	7.2		
	T3	4.5	0.4	3.8	5.3		
MET Mean	R	1	0.1	0.9	1.1	<0.001	vs all
	S1	3.2	0.2	2.8	3.6	0.221	vs T1
	S2	3.5	0.2	3.2	3.9	0.513	vs T2
	S3	3	0.2	2.7	3.3	<0.002	vs T3
	T1	3	0.1	2.7	3.3		
	T2	3.7	0.2	3.2	4.2		
	T3	2.6	0.1	2.3	2.8		
VE Mean L/min	R	9.6	0.7	8.2	11.1	<0.001	vs all
	S1	26.2	2.2	21.5	30.8	<0.042	vs T1
	S2	28.9	2.7	23.3	34.6	0.916	vs T2
	S3	23.5	1.8	19.8	27.1	0.115	vs T3
	T1	24	1.7	20.4	27.6		
	T2	29.1	2.2	24.5	33.7		
	T3	21.8	1.7	18.2	25.5		
EE mean Kcal/min	R	1791.7	130.1	1519.4	2064.1	<0.001	vs all
	S1	5979.2	472.1	4991.1	6967.3	0.129	vs T1
	S2	6557.5	518.3	5472.7	7642.3	0.597	vs T2
	S3	5420	447	4484.4	6355.7	<0.018	vs T3
	T1	5592	437.4	4676.5	6507.5		
	T2	6774.3	519.1	5687.9	7860.7		

	T3	4769.2	418.6	3893.1	5645.3		
RER Mean	R	0.92	0.018	0.882	0.959	<0.05	vs S3/T1
	S1	0.95	0.017	0.915	0.985	<0.001	vs T1
	S2	0.929	0.014	0.9	0.958	<0.009	vs T2
	S3	0.871	0.011	0.848	0.893	0.332	vs T3
	T1	0.873	0.015	0.84	0.905		
	T2	0.893	0.012	0.867	0.919		
	T3	0.881	0.013	0.854	0.908		

Note: R- rest, S1–stepper movement with a normal cadence, S2-stepper cadence 20% higher than normal one, S3- stepper cadence 20% lower than the normal, T1-treadmill walking with a normal cadence, T2-treadmill 20% higher, T3-treadmill 20% lower

Energy consumption using stepper and treadmill (EE)

At Rest, the lowest mean of energy consumption (EE) was recorded as 1791.723. It was found that S3 was significantly higher than T3 by approximately 14% as shown in Table 2. The correlation coefficient was 0.790 with p<0.001 as in Figure 9, showing strong correlation between two types of movements.

Ventilation (VE)

VE mean value showed that S1 was higher than T1 by approximately 9% in Table 1. The correlation coefficient between stepper and treadmill is 0.826 with p<0.001 as Figure 10.

MET using stepper and treadmill

Mean value for MET showed that S3 is higher than T3 by approximately 15% in Table 2. The correlation coefficient for MET was 0.598 with p<0.001 as Figure 11, so two type of movements were correlated.

Qtc

Qtc results showed correlation between stepper and treadmill as well, with the coefficient as 0.806 with p<0.001 as in Figure 12. It is also found that S3 is higher than T3 by approximately 11% as in Table 2.

Discussion

Analysis of objective data

As whole, stepper movement has a higher oxygen consumption than that in treadmill walking. This could be partly attributed to that most users are not familiar with stepper movements while they are familiar to treadmill walking as they horizontally walk every day. This point indicates that stepper movement is not an exercise as simple as treadmill, and in fact stepper movement requires the body to consume more energy than treadmill walking in order to maintain balance, especially in lower cadence (i.e. 20% lower than a comfortable one). From the results, it is estimated that in lower cadence, stepper movements consumes roughly 10% more energy than treadmill walking.

The reasons for differences or similarities could be that treadmill walking is similar to our daily movements and thus saves some energy while stepper movement is related to balance control and thus spends slightly more energy. The detailed mechanisms are to be explored in the future.

The results of the present study showed significant correlation of oxygen consumptions between using the stepper and treadmill. Also, almost all parameters analysed showed that there are linear correlations between two types of movements, and nearly half of the correlation coefficients reached or close to 0.8. Therefore, some of the regression functions provided are useful and would be used to describe the relationships between stepper movements and treadmill walking. In other words, users can use stepper movement data at home to estimate how much energy they could have consumed in treadmill walking in gymnasiums. The database produced from this study allows clinicians and physiotherapists to prescribe an exercise plan for the patients who 1) physically cannot go to gymnasium and have to stay at home, and 2) cannot horizontally walk in rehabilitation. To our best knowledge, there is little previous research done on this topic [4, 7, 11].

Sample size and power

As this study is brand new and there was no previous data available, we did a power analysis after data collection. Given the standard deviation as 280 in VO_2, clinical difference as 170 and power as 80%, the estimated sample size should be 22. Therefore, the power with the sample size in this study is reasonable.

Limitation of the study

Lack of ability of a few participants to work accurately on the stepper initially as they were not trained how to work with beep produced by the Tempo Perfect Metronome software. Sometimes it was getting difficult for them to keep balance on the stepper also. Regarding to BMI, there were two participants with extremity values 30 and 40 respectively, and hopefully their data may have not largely affected the general outcomes. General subject population (10 men and 12 women with age ranged between 18-40 years and with unknown habitual physical activity level were measured in this study, and, therefore, it is difficult to associate the results to gender and functional level. In this study, the gender has not been considered as a factor as we did consider general population and compared the data within-subject.

future study

In the future, the studies may focus on muscle force, muscle activities and kinematics and kinetics in the lower limbs in stepper movements. Further research should be done for patients, who may give practical feedbacks to different machine and movement types. If patients were not like stepper due to its stability, a handle or support could be designed for them. Also, a future study would consider for male and female separately and for different physical active levels.

Conclusion

This study indicates that stepper movement has similar oxygen consumption to treadmill at a comfortable cadence level and higher one (i.e. 20% higher than the comfortable one) but stepper movement consumes more energy than treadmill walking by approximately 10% at a lower cadence (i.e. 20% lower than the comfortable one). The study shows that stepper movement is highly correlated with treadmill walking in terms of oxygen consumption, and thus the stepper data provided can be used as reference for the healthy at home. In the future, the experiment could be done for the patients and similar analysis could be applied in rehabilitation.

Declarations

- Ethics approval and consent to participate: The study was approved by the University of Dundee Research Ethics Committee (UREC 14175). The participants were informed about the purpose and course of tests and signed a consent to participate in the tests.

- Consent to publish: Not Applicable.

- Availability of data and materials: The raw data will be available if it is required.

- Competing interests: The authors declare that they have no competing interests.

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- Authors' Contributions: AM, recruitment of participants and data collection. AM, GA, RA, WW for data analysis. WW, statistical analysis. AM, WW, writing of paper. WW, conception and supervision of the study. All authors made substantial contribution to the manuscript.

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Abbreviations

- VO_2 – Oxygen uptake in millilitres per minute (ml/min)
- VCO_2 – Carbon dioxide output in millilitres per minute (ml/min)

- VE–Ventilation (the movement of air between the atmosphere and the lungs via inhalation and exhalation)
- RER – Respiratory Exchange Ratio, which is Carbon dioxide output and the Oxygen uptake ($RER=VCO_2/VO_2$)
- EqO_2 – Breathing equivalent for Oxygen, which is the minute volume and the Oxygen uptake ($EqO_2= VE/VO_2$)
- $EqCO_2$– Breathing equivalent for Carbondioxide, which is the minute volume and carbon dioxide output ($EqCO_2= VE/VCO_2$)
- EE–Energy expenditure, which is the total energy consumed and is calculated as kilo calories per day.
- MET – Metabolic unit, in Oxycon Mobile® system, 1 MET=3.5 ml/min/kg
- Qtc – It is derived from the "Indirect Fick" Equation (Fick principle for CO_2). According to the equation the cardiac output (pumping of blood from heart/min) equals CO_2 production (VCO_2) divided by the difference of content of CO_2 in venous blood and the arterial blood ($CvC0_2$-$CaCO_2$). So Qtc= $VCO_2/CvCO_2-CaCO_2$ and it is calculated in Litres per minute (L/min).

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Figures

Figure 1a Stepper footplate

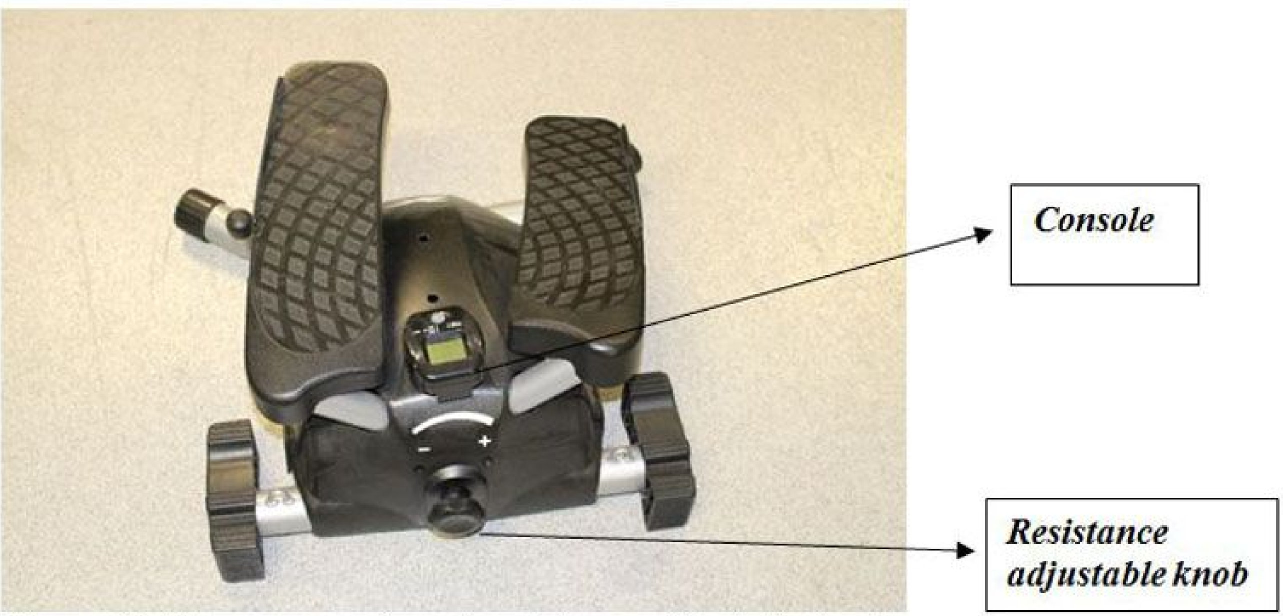

Figure 1b Stepper console and resistance adjustable knob

Figure 1

a Stepper footplate b Stepper console and resistance adjustable knob

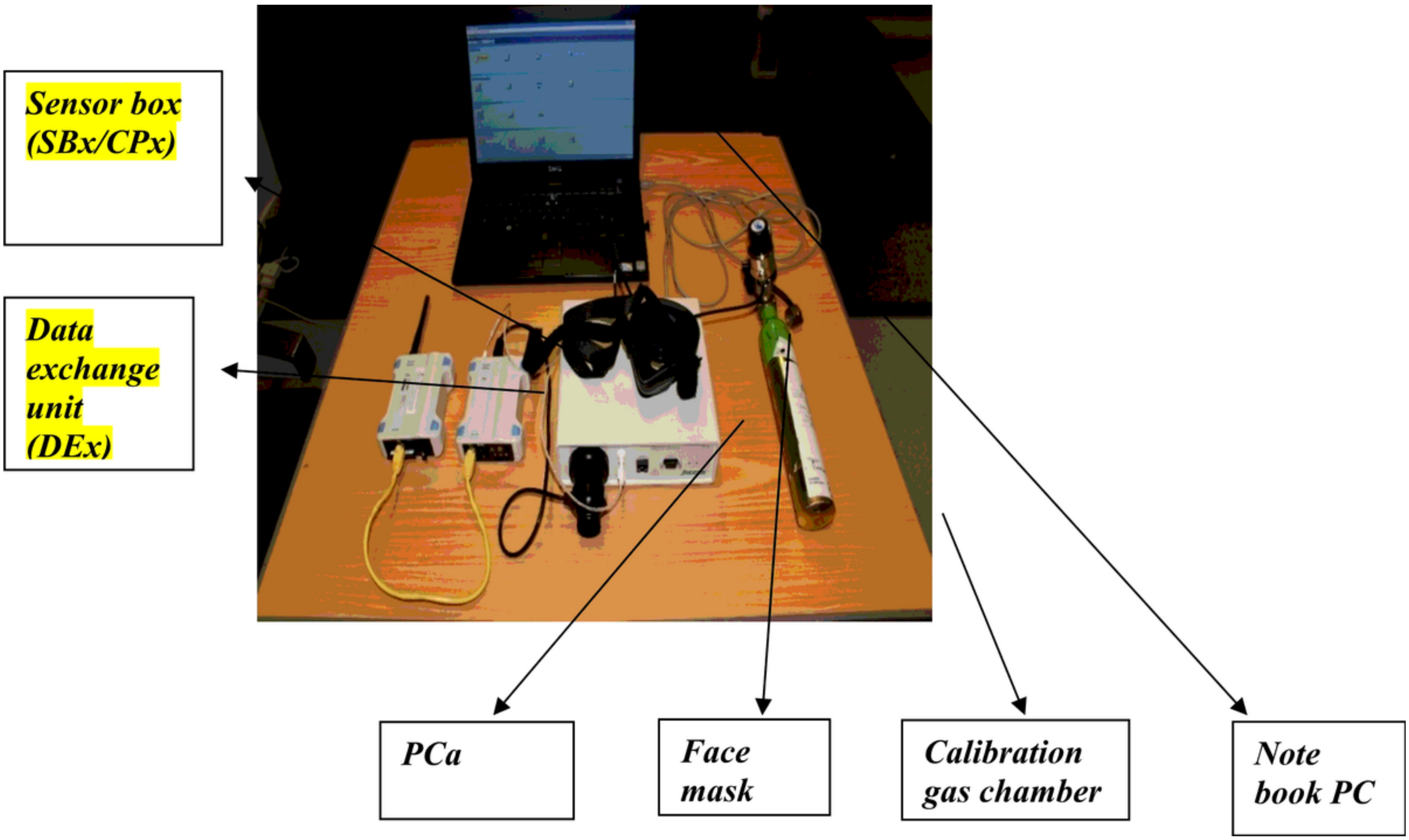

Figure 2

Oxycon Mobile® System

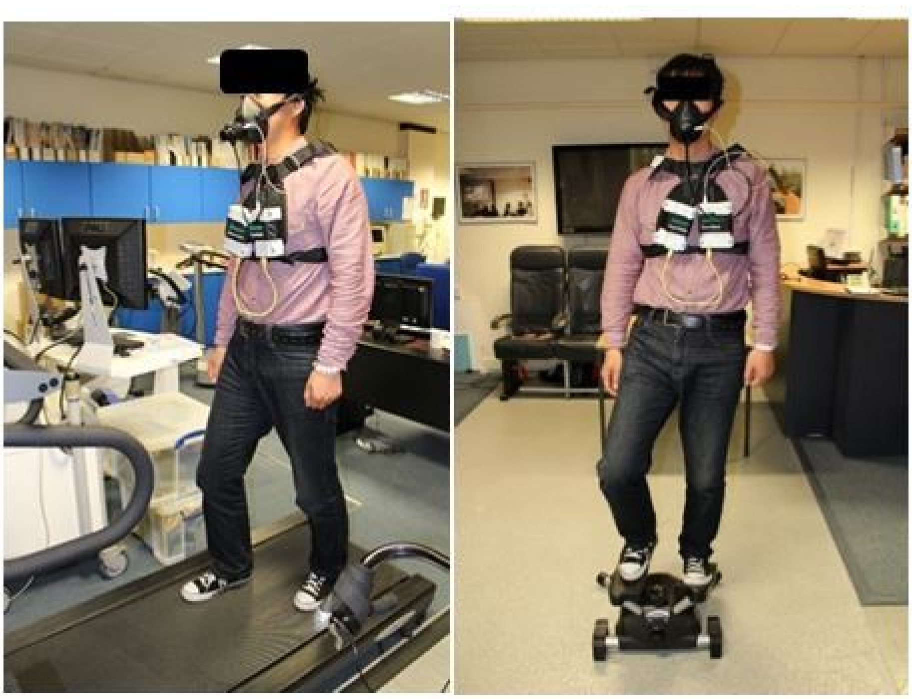

Figure 3

Data collection on stepper and treadmill

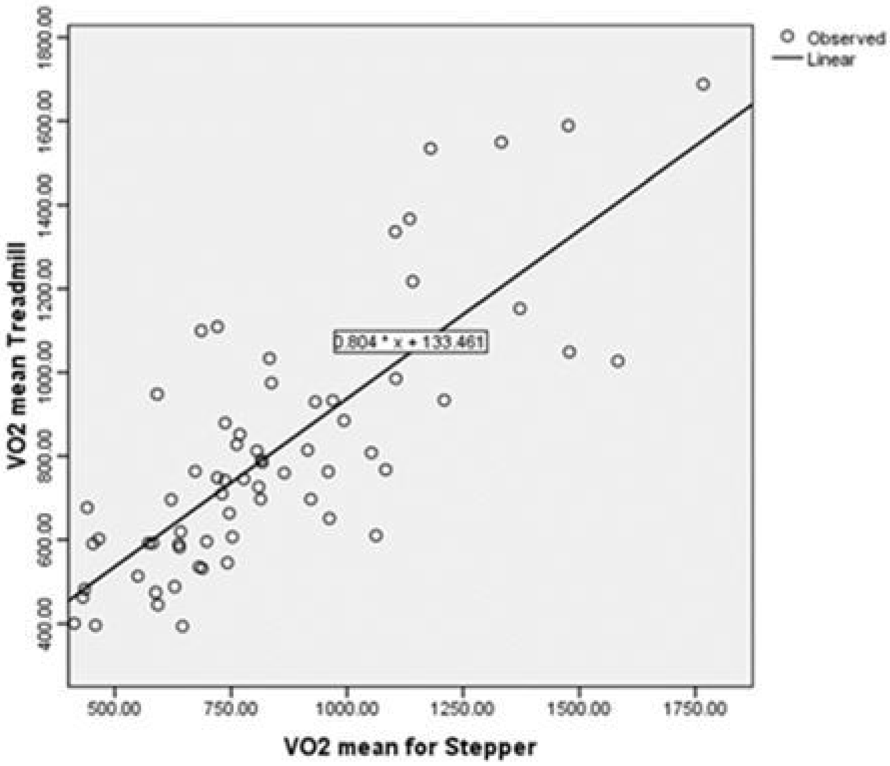

Figure 4

Linear regression of VO2 means between stepper and treadmill.

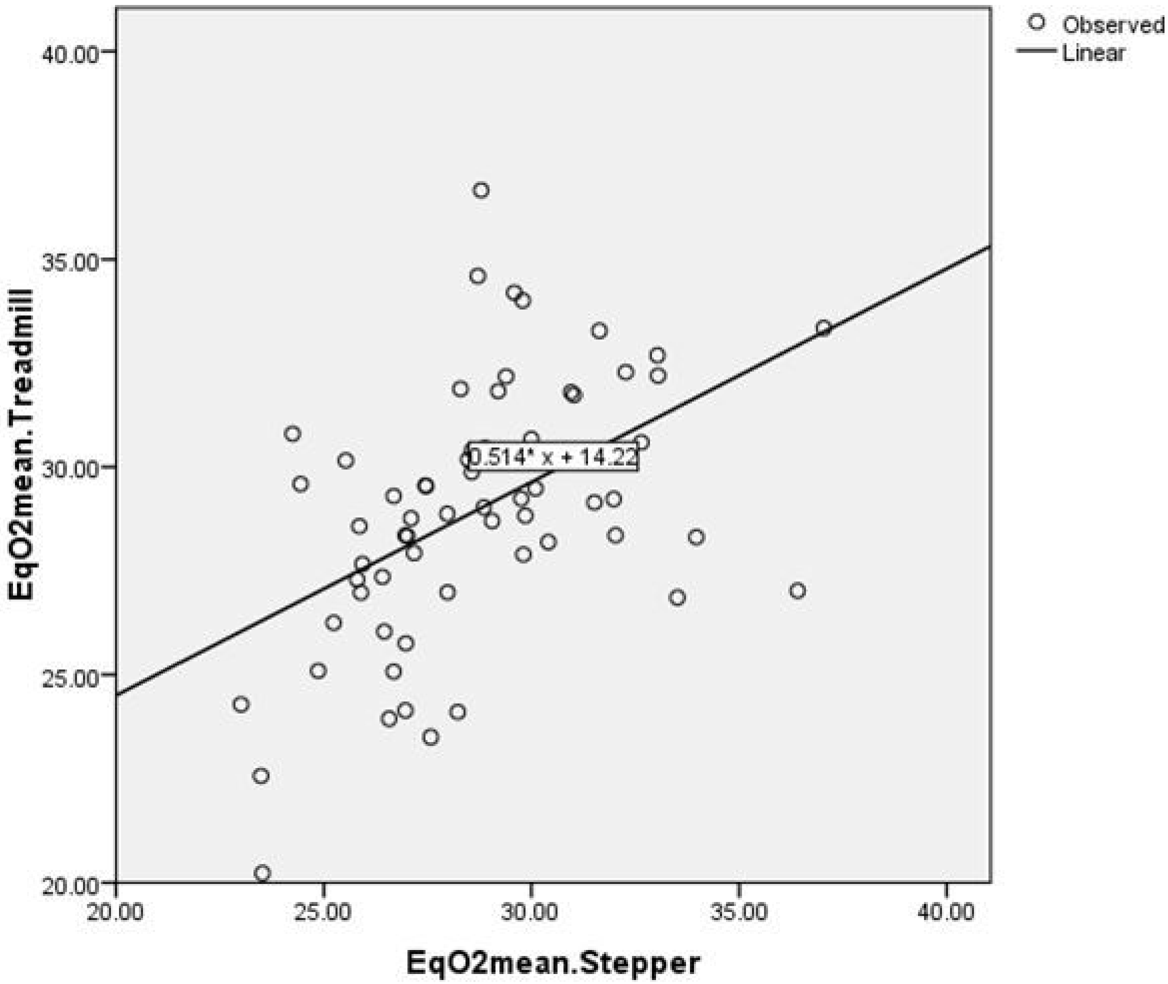

Figure 5

Figure 5 Linear regression of EqO2 using stepper and treadmill

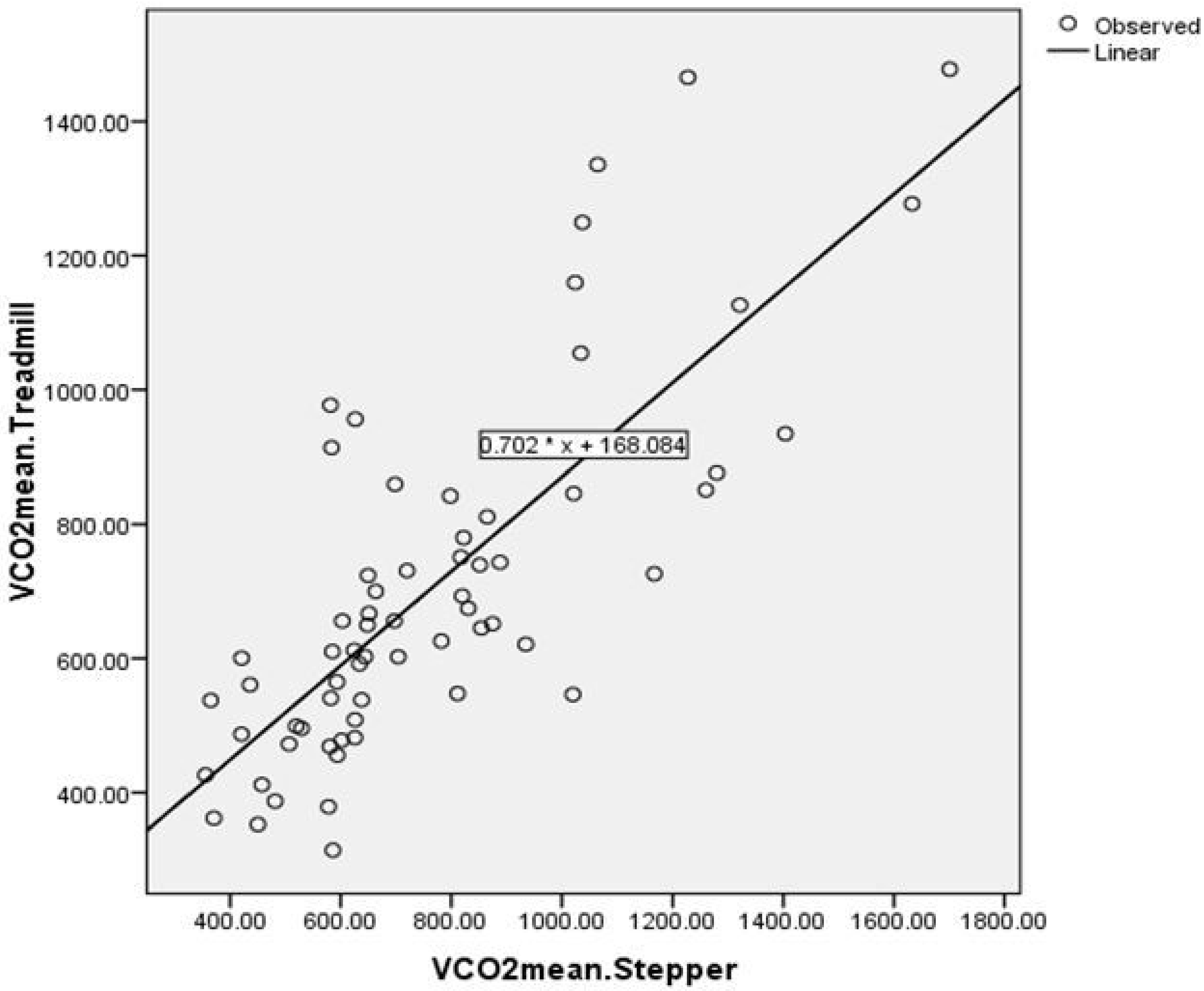

Figure 6

Linear correlation and regression for VCO2 using stepper and treadmill

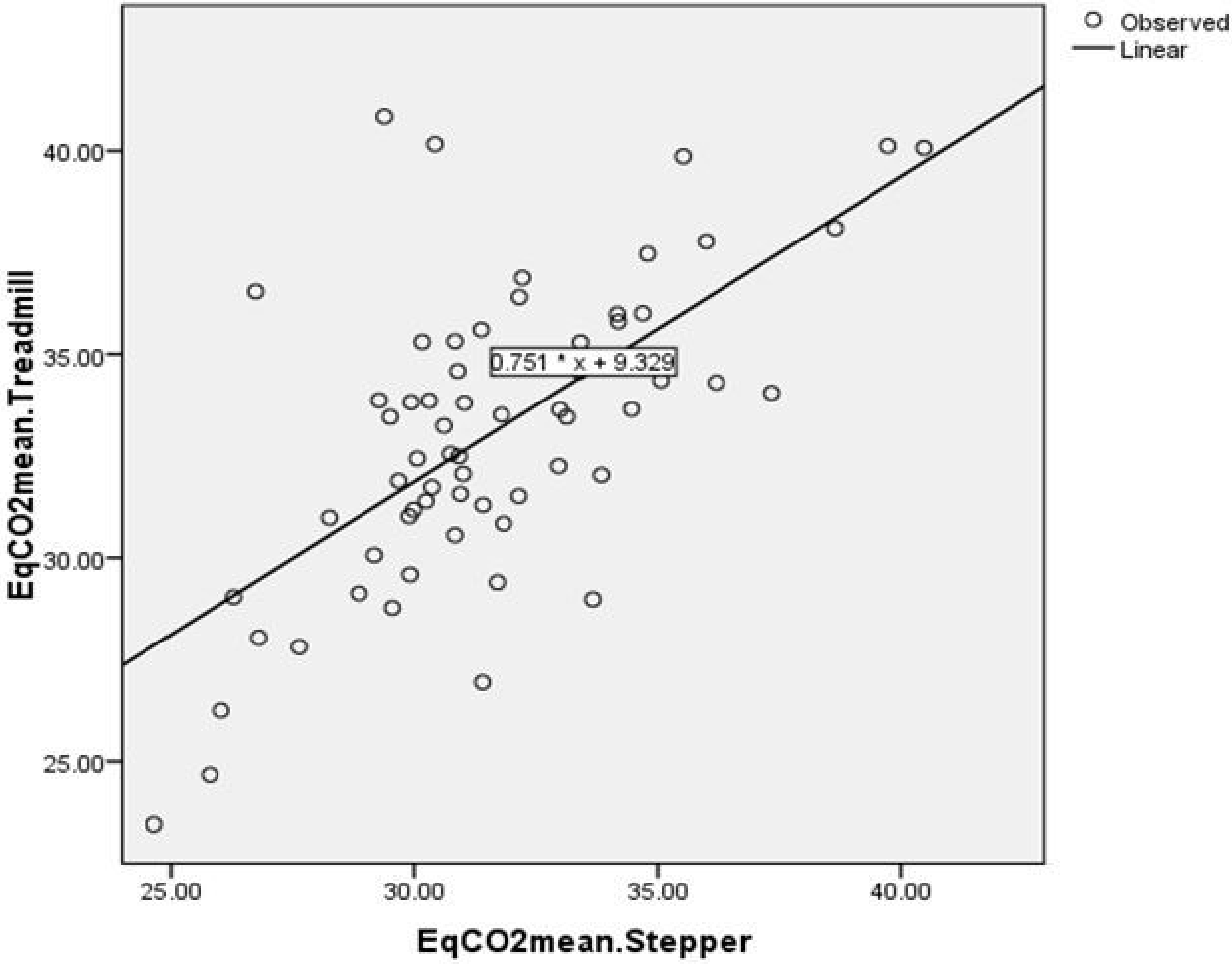

Figure 7

Linear correlation and regression for EQCO2 using stepper and treadmill

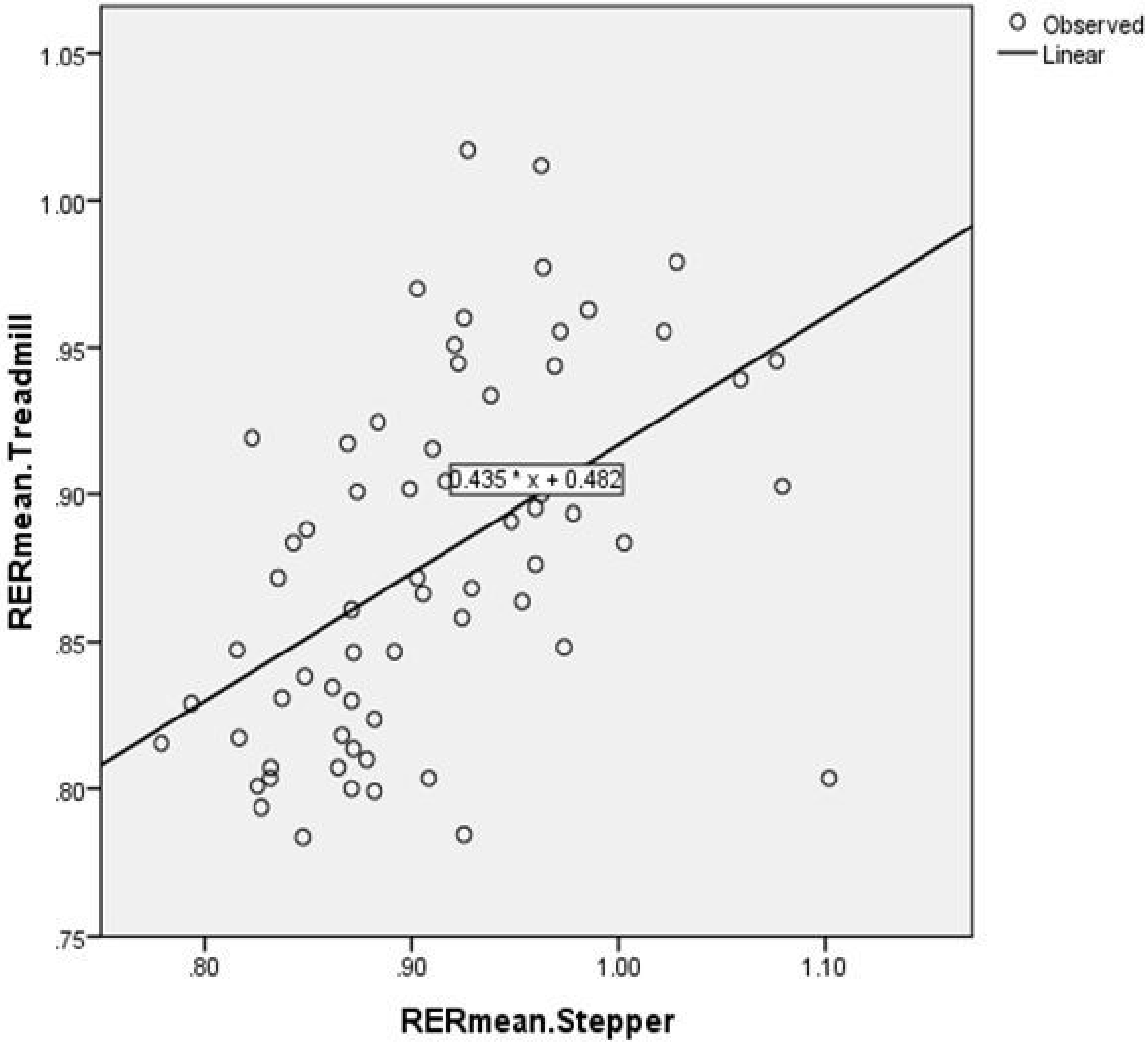

Figure 8

Linear correlation and regression for RER using stepper and treadmill

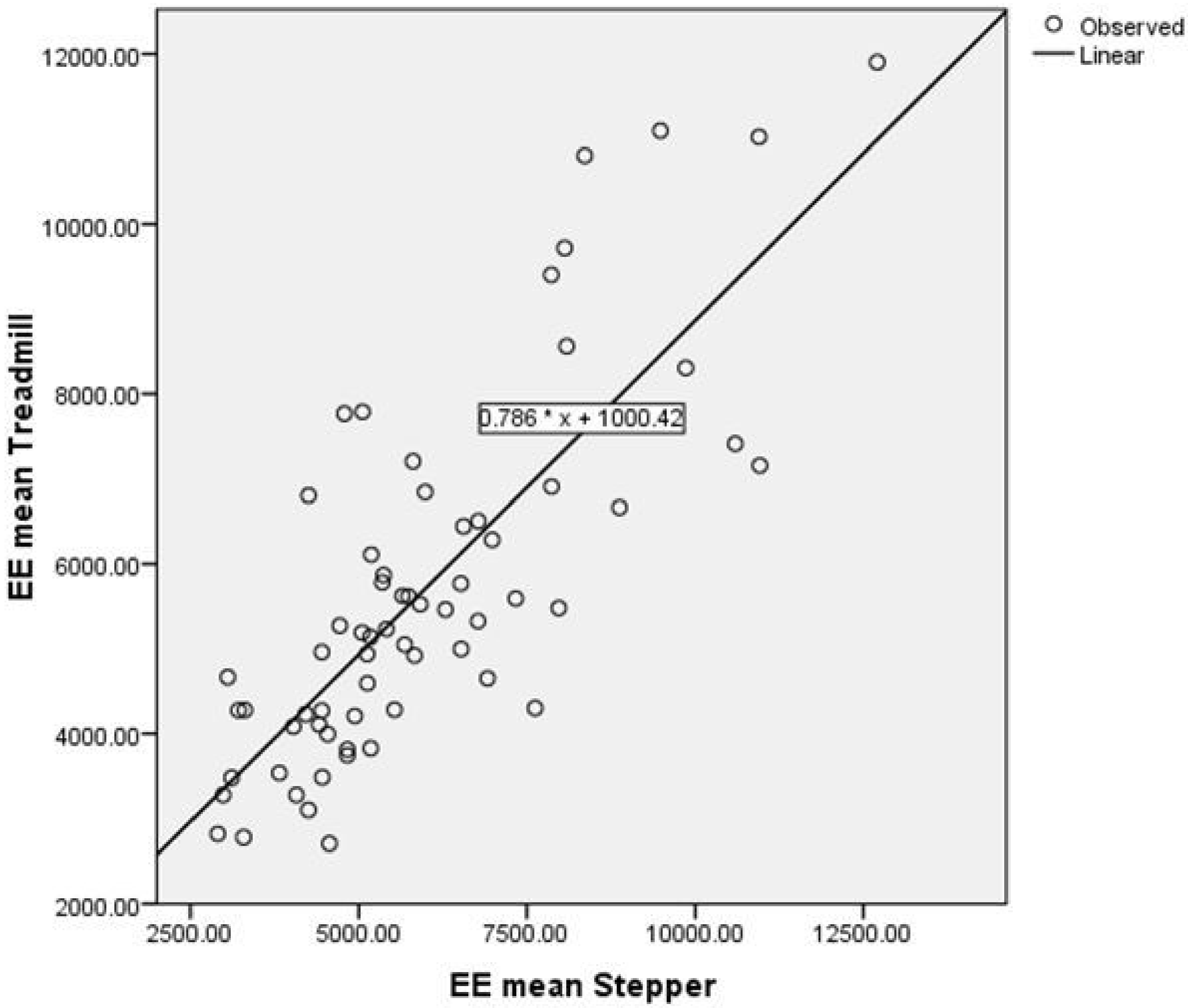

Figure 9

Linear correlation and regression on EE using stepper and treadmill.

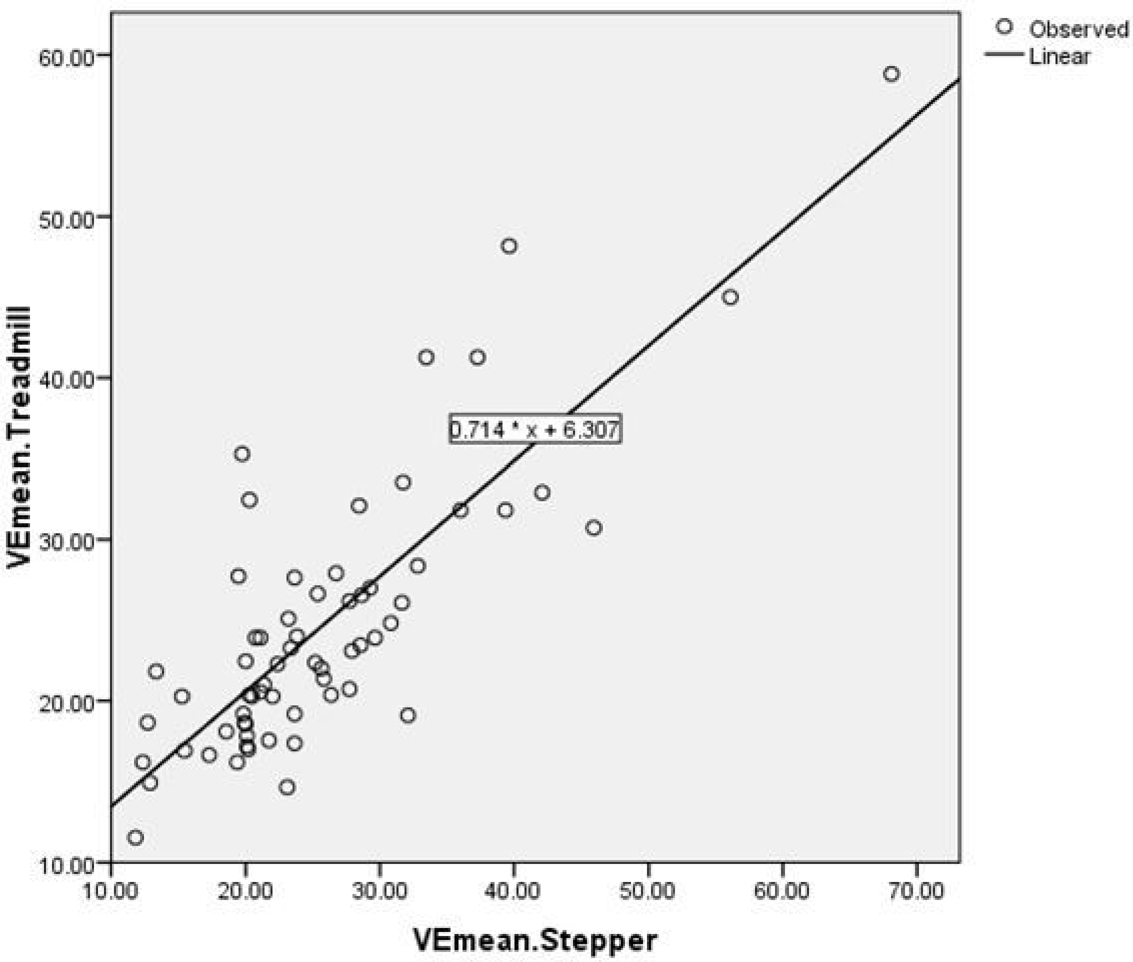

Figure 10

Linear correlation and regression on VE stepper and treadmill

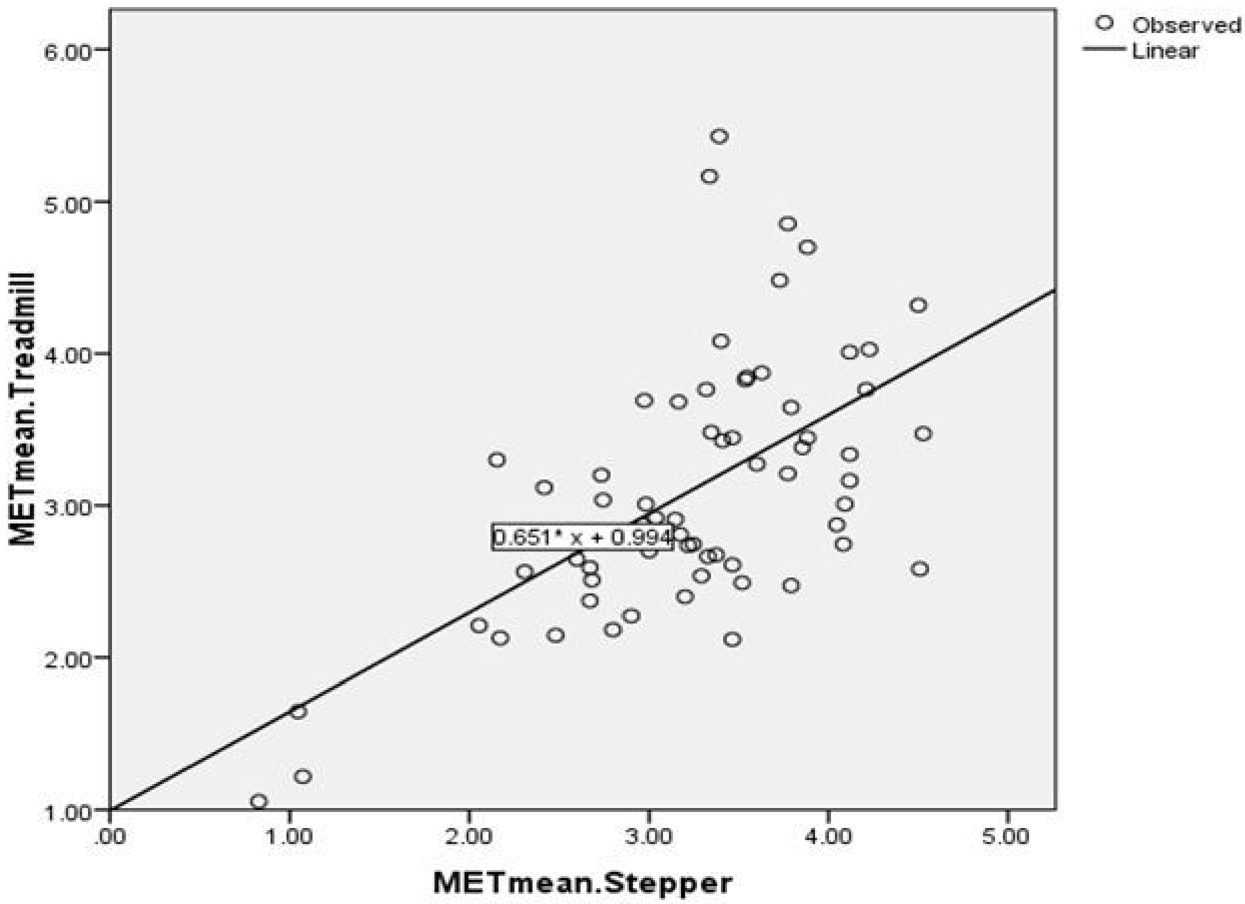

Figure 11

Linear correlation and regression on MET for stepper and treadmill

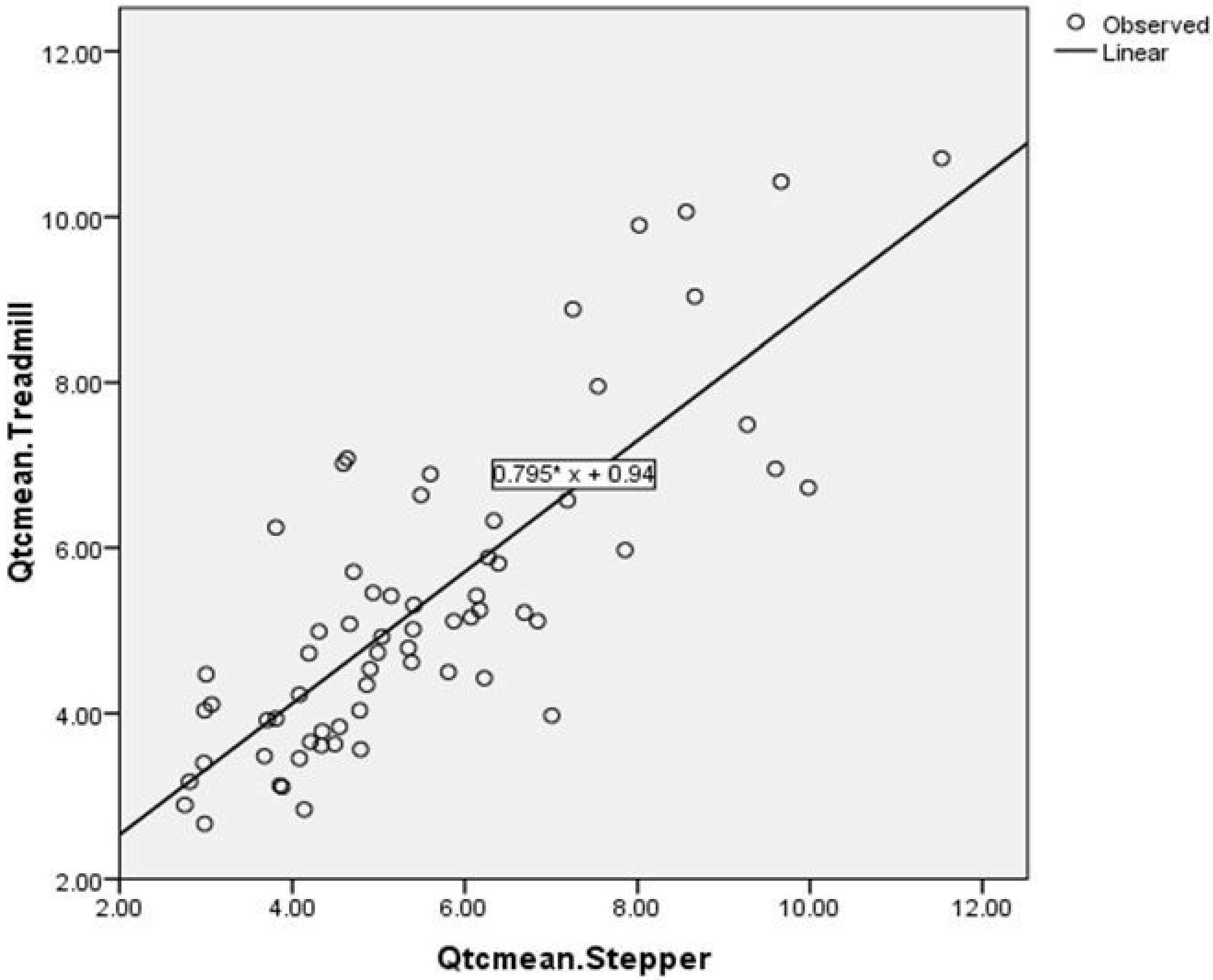

Figure 12

Linear correlation and regression on Qtc using stepper and treadmill