An experiment to compare the physiological effects of 3 intensities of stepping exercise

Introduction

There are many well established measures to be taken in order to indicate the level of exertion of people from at rest to undergoing strenuous exercise. A brief explanation of those used in this experiment follows.

Heart rate (HR) - the number of times the heart completes a full cardiac cycle per minute. Along with stroke volume, this controls the volume of blood that passes by the muscles per unit time. (Becque *et al.* 1993)

Borg rating of perceived exertion scale (RPE) - a number scale from 6 to 20 with qualitative description of exertion, on which the participant indicates how hard they feel they are working. This tends to correlate highly with HR when multiplied by 10, but is also affected by psychological factors (Borg, 1982).

The volume of O_2 (VO_2) consumed by cells is a "reliable and consistent" indicator of exertion (Becque *et al.* 1993).

The respiratory exchange ratio (RER) is the ratio between carbon dioxide produced to oxygen consumed. It is used interchangeably with the respiratory quotient, but by comparison is the far less invasive of the 2, calculated by comparing the expired CO_2 and O_2 with the content in atmospheric air. As cells require different quantities of O_2 to metabolise different substrates, also producing differing CO_2 levels, RER provides an estimate of the proportions of carbohydrate(:protein):fat used (McArdle, Katch and Katch, 2015), and is also indicative of "the muscle's oxidative capacity to get energy" (Ramos-Jiménez *et al.*, 2008)

The metabolic rate of the cells provides a directly comparable figure of the energy used at different levels of intensity, and which here will be estimated by Weir's formula (Weir, 1949).

In this study, the aim was to compare changes in a number of measures of the physiological response of an athlete performing different levels of exercise.
It is expected that as the intensity of exercise increases, heart rate (HR), Borg rating of perceived exertion scale (RPE), respiration rate (RR) and volume of O_2 (VO_2) consumed will also increase. The respiratory exchange ratio will increase as well, as the participant's body increases its carbohydrate metabolism.

Method

Participant

The procedure was carried out by 2 participants, however the data for the second was unusable due to a number of factors, and so only the results of the first will be presented and analyzed. The participant whose data will be presented is 18, male, and a triathlete who trains most days of the week. He weighed 62.1kg immediately before the test began.

Apparatus

- Servomex 1440 gas analyzer
- Heart Rate Monitor Watch + chest strap
- 3 Douglas bags + tubing + mouthpiece + 3-way valve + nose clip
- Timer
- Electronic metronome
- Stepping box
- Borg scale chart
- Thermometer
- Barometer

Procedure

The procedure was decided such that the 3 variations of the activity performed would remain as similar as possible, differing only with respect to their intensity.
The exercise decided on was stepping, as the intensity can be varied consistently and linearly, by altering the frequency of steps. The conditions decided upon were standing (0 steps/minute), slow (80 steps/minute), and fast (160 steps/minute), where a step was counted each time either foot is placed on the box or the floor. The pace was set by the metronome

The stepping method used starts with the participant standing with the box in front of them, they place either foot onto the box, and then bring the other foot up as well, making sure they stand fully on the box.

They then reverse this action, stepping backwards and down to the floor with one foot and then the other, such that they finish in the starting position.
This repeats until the allotted time is finished.

Each condition lasted for 5 minutes, with no break between conditions. The conditions were performed in ascending order of step frequency.

A small pilot trial by the experimenters suggested that these rates with this stepping method would be feasible.

The participant wore the HR chest strap, the BP cuff at the radial artery and the mouthpiece for the Douglas bags for the duration of the study to minimise any effect that changing the apparatus might have on the other measures. Multiple experimenters were needed to operate the apparatus and measure and record all the different variables; four were present for the duration of this trial.

The HR was recorded every 30 seconds, using the value on the HR watch. The respiration rate was counted for 30 seconds of each minute looking at the movement of the ‘in’ valve on the Douglas bag mouthpiece and then doubled to find the approximate breaths per minute. Borg’s rate of perceived exertion (RPE) was determined by the participant pointing to a number on the chart next to the qualitative description (see *Appendix A*) every 30 seconds, immediately following the HR measurement. BP was measured as the experiment began and in the last 30 seconds of each condition (allowing for the time elapsed in taking a reading). Taking the air samples began 120 seconds after the start of each condition (to allow time for the participant to acclimatise to the level of activity) and finished either as the condition ended or as the Douglas bag began to look full, whichever came first. Once all 3 conditions had been done, the Douglas bags sequentially had the 1L of the gas they contained analysed for O_2 and CO_2 levels, and their volumes and air temperatures measured, using the Servomex gas analyser. Along with the other relevant variables - ambient temperature and pressure, participant's body mass - these measurements were used to calculate the RER and VO_2 consumed.

Results

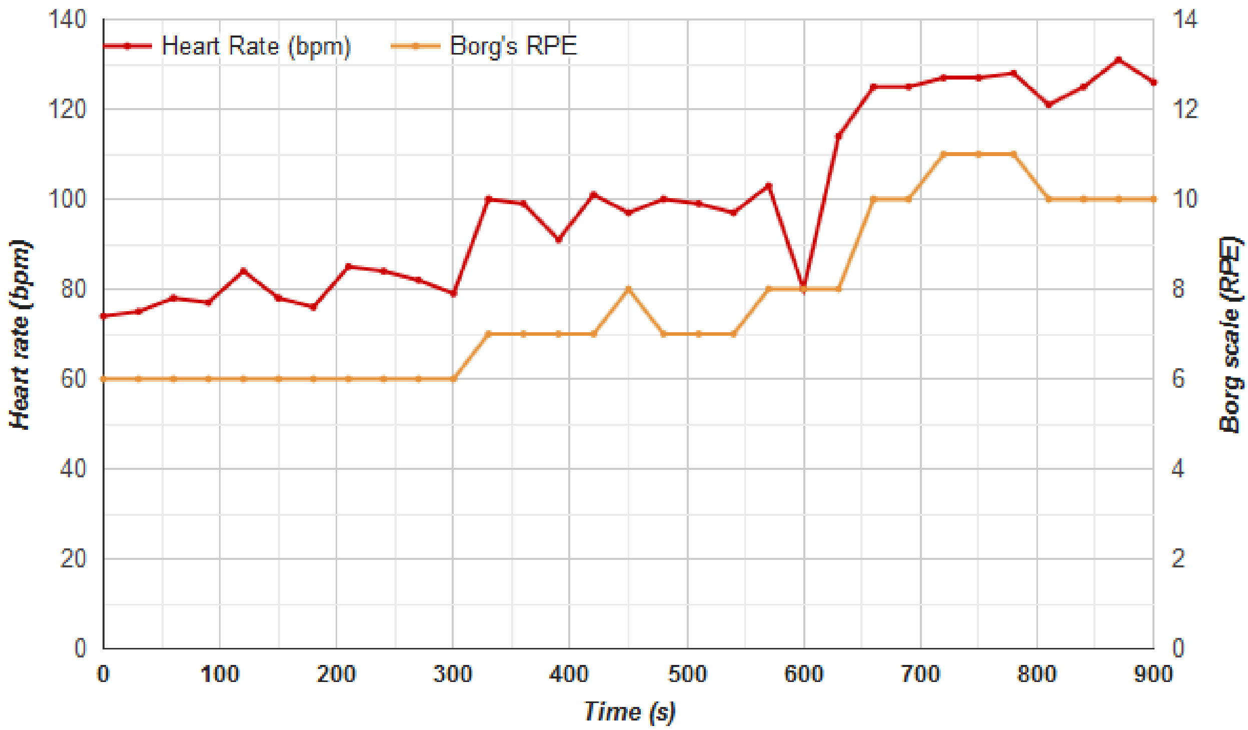

Figure 1: Graph showing heart rate and RPE changes over time at different stepping frequencies

The heart rate (HR) and Borg rating of perceived exertion scale (RPE) both noticeably increase as the participant steps at a faster rate. Most of the increase occurs within the first 30 seconds after the stepping rate changes and the measurement is taken.

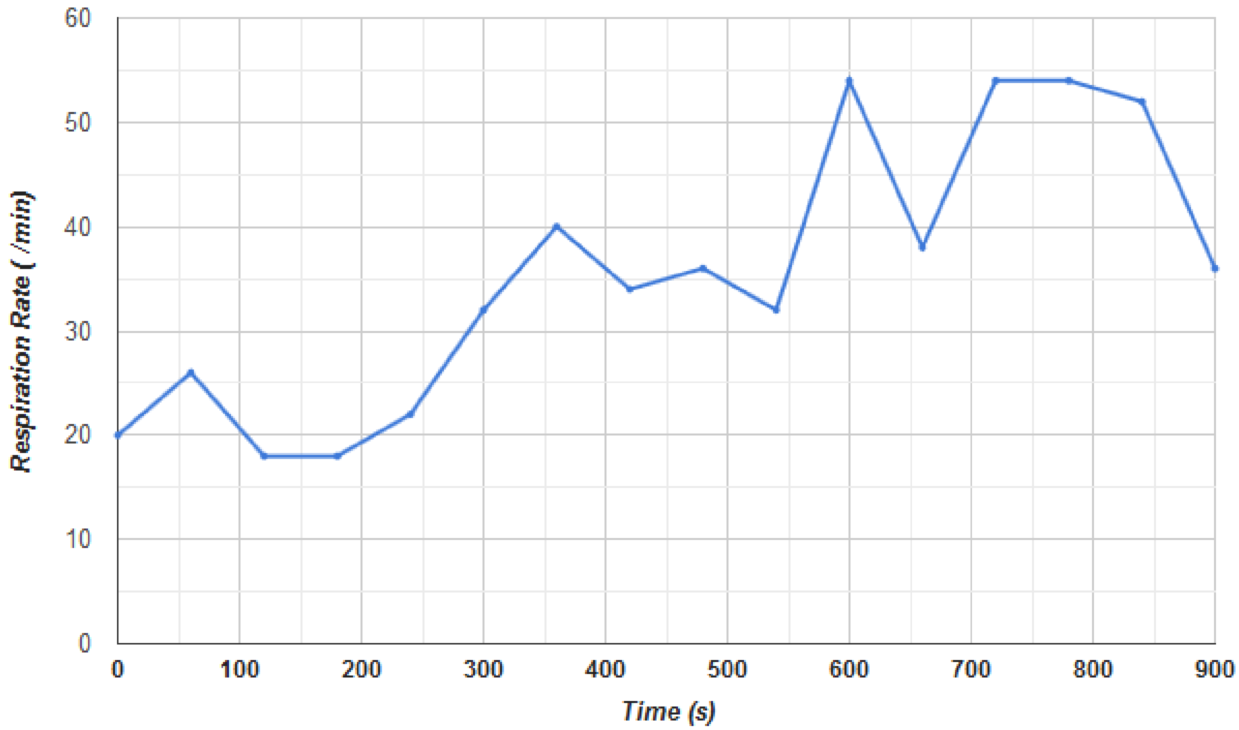

Figure 2: Graph showing respiration rate over time at different stepping frequencies

Figure 2 shows that the respiration rate is higher as the stepping exercise becomes more difficult, with rough plateaus for each condition, but there is some variability greater than the expected error range of the data collection method (+/- 6 due to missed/added breaths at each end, plus 1 to allow for a mistake in the middle, all doubled). The RR increases before the start of the following condition and drops before the end of the experiment.

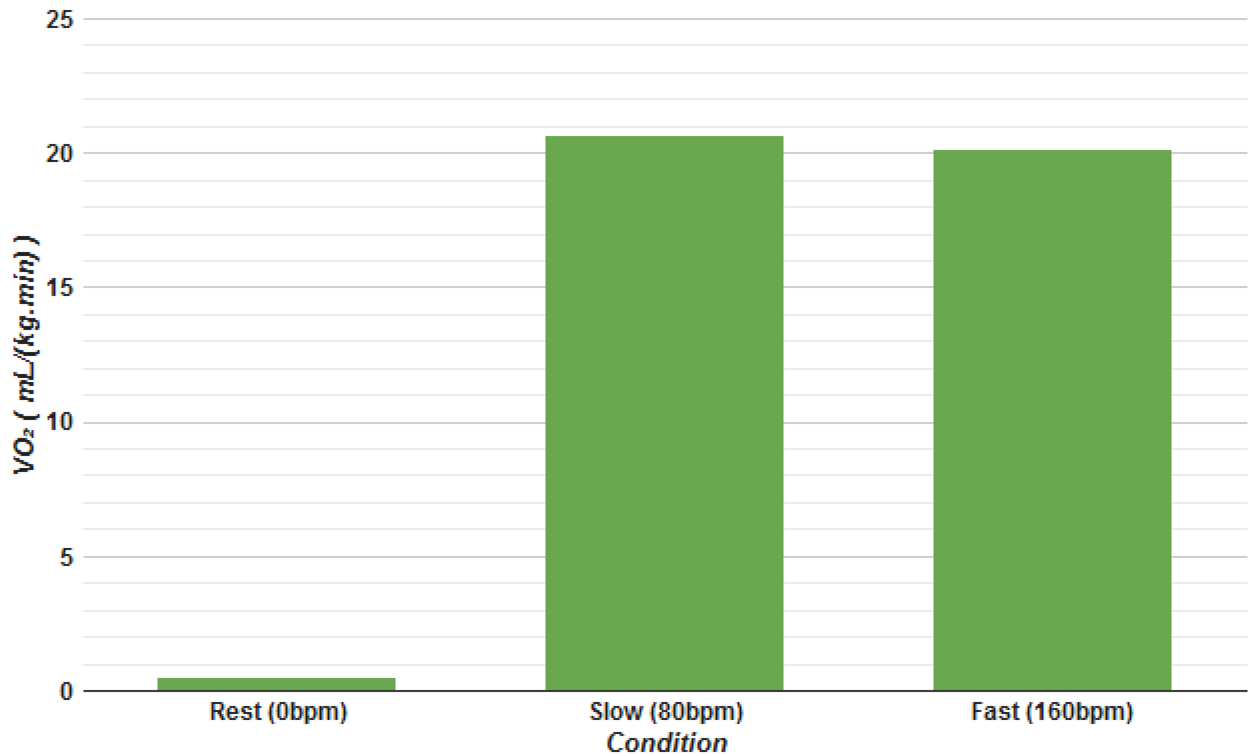

Figure 3: graph comparing the VO_2 consumed at different stepping speeds

As shown in *Figure 3*, the VO_2 in both stepping conditions was >4000% that of the standing condition, however the difference between the two was minimal, with the VO_2 slightly lower in the fast condition than the slow one.

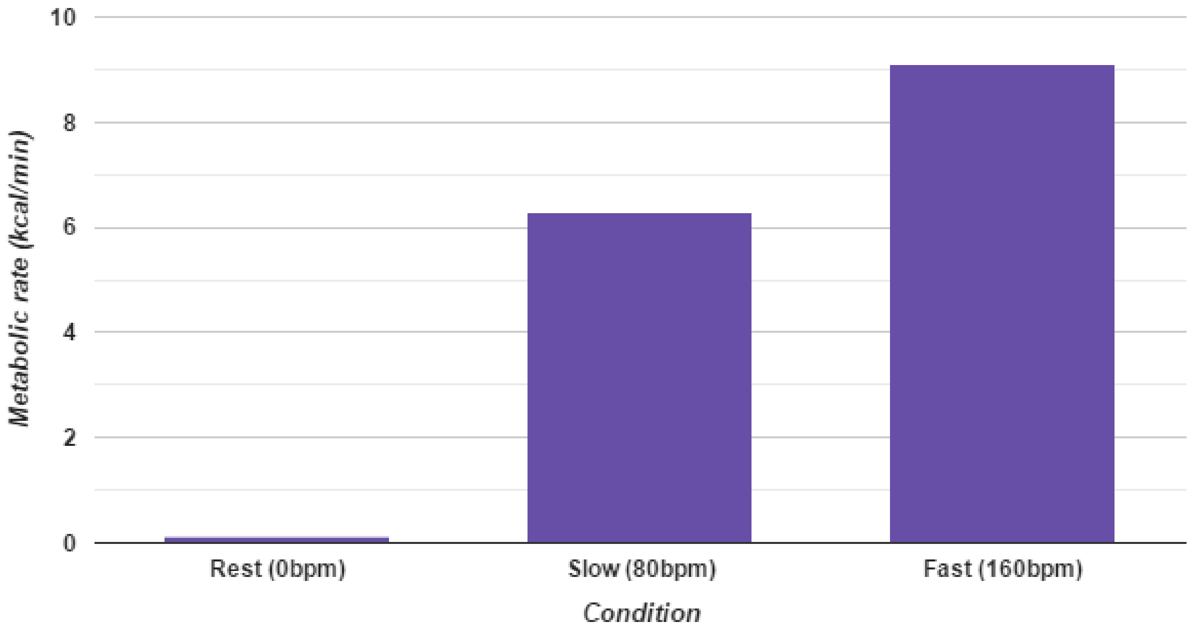

Figure 4 - graph showing metabolic rate at different stepping rates

As shown in *Figure 4*, for the conditions tested, the faster the step rate, the higher the metabolic rate. The increase is not linear, however: slow stepping produced a metabolic rate 4846% of standing, while double the step rate in the fast condition had a metabolic rate of 144% of the slow condition. See *Appendix B* for calculation method.

Table 1: Respiratory exchange rate at different stepping rates

Condition	RER	%Carbohydrate	%Fat
Standing (0bpm)	0.67	0	100
Slow (80bpm)	0.86	54.1	45.9
Fast (160bpm)	0.82	40.3	59.7

Table 1 shows that while standing, the participant had an RER of 0.67, an RER of 0.86 during slow stepping and an RER of 0.82 during fast stepping. The

carbohydrate **:** fat ratios worked out from this show that while standing, fat was the sole substrate, which then increased and decreased in the slow and fast conditions respectively, similar to the pattern of VO_2 in *Figure 3.*

Discussion

Despite the pilot study attempted at the before the experiment started, the participant could not always keep up with the fast stepping rate (160 steps/min) with the intended strategy. This led to some missed steps and an easier stepping strategy, resulting in a fast condition neither quite twice the speed of the slow condition nor as difficult per step. Nonetheless, a number of inferences can be drawn from the data obtained.

Cardiac and Borg

As expected, the heart rate (HR) and Borg rating of perceived exertion scale (RPE) both noticeably increase as the participant steps at a faster rate. Most of the increase occurs within the first 30 seconds after the stepping rate changes and the first measurement for the condition is taken. The increased oxygen demand from the muscles requires more blood to be circulated to carry oxygen toward the muscle and carry the waste product of carbon dioxide away.

The autonomic nervous system (ANS) plays a large role in the control of heart rate: Up to ~100 bpm, the change in HR is primarily mediated by the reduced activation of the parasympathetic nervous system (PN), above this crossover point the increase is mainly controlled by increased activation of the sympathetic nervous system (SNS) (Nakamura, Yamamoto and Muraoka, 1993; Robinson *et al.*, 1966). The PN reduces the inhibition of HR by reducing the quantity of the neurotransmitter acetylcholine (ACh) secreted by vagal nerves at the SA and AV nodes and atria (Sakmann, Noma and Trautwein, 1983). The fibres of the SNS innervate the heart at the atrial and ventricular myocardia as well as the SA and AV nodes. The sympathetic stimulation is effected (*sic*) by the secretion of the catecholamines adrenaline and noradrenaline, which along with increasing heart rate, also increases myocardial contractility, thereby increasing stroke volume (McArdle, Katch and Katch, 2015: 326-331).

The control over the ANS appear to be primarily the domain of the cardiovascular centre of the medulla oblongata, although SNS stimulation is supported by dorsal anterior cingulate cortex activation (Critchley *et al.*, 2003). These respond to a number of peripheral inputs, of which the primary for increasing heart rate due to exercise are the mechanoreceptors and metabolite-sensing chemoreceptors in the active muscles. This exercise pressor reflex is progressively activated as the muscle use/exercise intensity increases. (McArdle, Katch and Katch, 2015)

As the HRs in the first 2 conditions were all below or very close to 100bpm (max: 103bpm in slow condition), the increase in HR from standing to slow stepping was most likely modulated by the decrease in parasympathetic activation, while the increase to the fast condition was mediated by an increase in sympathetic activation.

The RPE follows the pattern of the HR closely, also as expected, however it is consistently around 2 points lower than predicted. This may be an issue with the scaling of the RPE, the understanding of the descriptors of effort level or, most likely, this resulted from the participant underestimating their effort (probably subconsciously) in order to seem more impressive to himself and/or the experimenters.

Respiration

As predicted, the respiration rate increases along with the stepping frequency. This is caused by a greater demand for oxygen for the muscles. To meet this demand, the respiratory system changes in 2 main ways: more air (and therefore more oxygen) is inspired, and the efficiency of oxygen metabolism increases. Similar to the heart rate, the ventilatory control is mostly modulated by the respiratory centre of the medulla oblongata, which stimulates the ventilatory muscles - the diaphragm, the intercostals and the scalene muscles - controlling both the respiration rate (RR) and the tidal volume (TV). The muscles involved in a heavy inspiration flatten the normally upward dome-shaped diaphragm and raise the rib cage, increasing the volume of the thoracic cavity, which creates an area of low pressure that air from the atmosphere moves into the lungs to fill (Martini and Bartholomew, 2013).

There are a number of triggers for an increase in RR and TV. The primary respiratory stimulus is an increase in the pressure of carbon dioxide (Pco_2) that is measured by peripheral chemoreceptors in the carotid artery and arch of aorta, where a small change in Pco_2 has a large effect on RR. This is largely due to the CO_2 dissolved in the blood plasma, which lowers the pH. These chemoreceptors are also triggered by lactate in the blood, which makes it more acidic. It is unlikely that this caused the increase in RR for our participant as the exercise did not seem to be strenuous enough to make him work anaerobically. A decrease in arterial Po_2, measured by carotid and aortic bodies in the same location as for Pco_2 also increases RR, although this is less common during exercise and the system primarily exists to prevent hypoxia in low O_2 environments. The ‘higher brain’ plays a significant role in controlling the breath by sending signals to the medulla. This would explain the anticipatory increase in RR that the participant demonstrates; he knew when the condition was about to become more difficult and so, consciously or not, increased RR in preparation. The other neurogenic factors involved are the mechanoreceptors and chemoreceptors in muscles, joints and tendons. The increased RR and TV remove unwanted carbonic acid and increase arterial oxygen levels. (McArdle, Katch and Katch 2015: 286-291)

The increased gas exchange efficiency mostly occurs due to changes in partial pressures around the alveoli and in the interstitial fluid around muscles. As muscles are used more, the cells within respire more. This leads to a high Pco_2 and low Po_2 around them. The heightened difference compared to the surrounding blood supply means that more O_2 will diffuse toward the muscle and more CO_2 will diffuse away. High Pco_2 also causes nearby smooth muscle to relax. As a result, local arterioles dilate and blood flow increases to that area. Similarly in the lungs, high Pco_2 causes bronchioles to dilate, increasing air flow. (Martini and Bartholomew, 2013)

The VO_2 results were partially as expected, in that a much higher VO_2 was consumed in the active stepping conditions than the standing condition, but that fast stepping produced a (minimally) lower VO_2 than slow stepping. There are a number of possible explanations for this. The participant is a highly trained athlete, and so he may have acclimatised to the level of exercise after around 10 minutes through an unmeasured mechanism. The change in stepping tactic may have contributed by making the strain for each step considerably lower (potentially not even holding his weight up while on the box). It is also possible that there was simply some error in the measurement and collection process, such as losing some air, or noting down the wrong measurement time period. Nordrehaug *et al.* (1991) found that oxygen consumption could be quite variable particularly when the participant is not working at maximum capacity, so this may have been an abnormal fluctuation. Replicating the experiment with the same participant would give an indication of the test-retest reliability for this and other measures.

Metabolism

As expected initially, in the more strenuous conditions, the metabolic rate increased. The non-linear increase may be in part due to the fast condition's rate (160 steps/min) being too fast for the participant to keep up for all of the steps, and so some were missed out. This is not a complete explanation, however, as stepped at the intended rate for most of the condition. It is possible that the tactic used in the fast condition was different from that in the slow condition - he may have not fully stood tall on the box before stepping down, which would have significantly reduced the demand of the task.

For the RER data, the 0.67 value of the standing condition suggests that the participant was solely using fat as their source of energy. At 0.86 in the slow condition he was using carbohydrate **:** fat at a ratio of around 54.1 **:** 45.9. At 0.82 in the fast condition, the carbohydrate **:** fat ratio dropped to 40.3 **:** 59.7. The variation occurs here based on the energy needs of the cell. As mentioned in the introduction, metabolising carbohydrate and fat requires different quantities of oxygen, and produces different quantities of carbon dioxide. Specifically, for one molecule of glucose or palmitic acid (typical carbohydrates/fats), the numbers of oxygen molecules needed to metabolise it are 6 and 23, and the numbers of CO_2 molecules produced are 6 and 16, respectively. This will vary slightly depending on the type of molecule in particular. From these, the ratios of CO_2 produced **:** O_2 consumed can be determined:

For carbohydrates (glucose): $6 \div 6 = 1.00$

For fats: $16 \div 23 = 0.69565217391 \approx 0.70$

These are then interpolated to find tables such as the one used for this experiment. (McArdle, Katch and Katch, 2015: 186-188). The RER is particular useful because it is “well correlated with other established fitness indicators” (Ramos-Jiménez *et al.*, 2008), and so may be used alone (or with other parameters) as an estimate of participants’ level of fitness.

General evaluation

The participant knew what was being tested and when, which may have affected the results. To prevent this, and increase the experiment’s internal validity, participants could be given noise cancelling headphones playing the metronome beat, and be faced away from any stimulation, i.e. facing a blank wall, with none of the experimenters in sight. This would also minimise the issue of distraction from other people in the lab, which resulted in our participant being brought to laughter during the first condition. As the difficulty of each individual step was very low, and the frequency too high, if using a similar protocol for another experiment, a higher box and a slower rate might be a better way to put strain on the participant, however a different protocol may well be an improvement. In order to maintain a consistent technique, an exercise such as using a cycling ergometer is suggested for future experiments. More participants would be preferable, as it would give a more generalizable result, as well as give an indication of the level of variation within a particular population.

To conclude, it appears that stepping, which should generalise to walking, even slowly, has a dramatic effect on a person’s physiology, making them breathe faster, increase their heart rate and their metabolism while still finding the activity “extremely light”. This likely has implications for those looking to lose/maintain weight in that activity does not have to be difficult in order to use a lot more energy than they would while resting, even in a standing state.

Word Count: 2998

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Appendix A: Borg Rating of Perceived Exertion Scale

Value	Description
6	NO EXERTION
7	EXTREMELY LIGHT
8	
9	VERY LIGHT
10	
11	LIGHT
12	
13	SOMEWHAT HARD
14	
15	HARD
16	
17	VERY HARD
18	
19	EXTREMELY HARD
20	MAXIMAL EXERTION

Appendix B: Determining metabolic rate with Weir's formula

1) $metabolic\ rate\ := \ mr$
2) $mr = V_{E(STPD)} \times (1.044 - 0.0499 \times \%O_{2E})$
3) $V_{E(STPD)} = V_{E(ATPS)} \times conversion\ factor$
4) $conversion\ factor = 0.90$ (found using nomogram from Weir (1949) with temperature of 24℃ and barometric pressure of 765 mmHg)
5) $V_{E(ATPS)} = \frac{V_{Total}}{t_{mins}}$
6) substituting ***5*** and ***4*** into ***3***: $V_{E(STPD)} = \frac{V_{Total}}{t_{mins}} \times 0.90$
7) substituting ***6*** into ***2***: $mr = \frac{V_{Total}}{t_{mins}} \times 0.90 \times (1.044 - 0.0499 \times \%O_{2E})$

Appendix C: Raw data

Time (s)	Heart Rate (bpm	Borg's RPE	Respiration Rate (/min)	BP	Collection time (s)	FEO2 (%)	FECO2 (%)	Temp air ('C)	Vol sample (L)	Vol in D.B. (L)	VE atps
0	74	6	20	128/68							
30	75	6									
60	78	6	26								
90	77	6									
120	84	6	18								
150	78	6									
180	76	6	18								
210	85	6									
240	84	6	22								
270	82	6									
300	79	6	32	130/74	180	20.5	0.28	21.3	1	19.2	20.2
330	100	7									
360	99	7	40								
390	91	7									
420	101	7	34								
450	97	8									
480	100	7	36								
510	99	7									
540	97	7	32								
570	103	8									
600	80	8	54	72/36	120	15.8	4.6	21.4	1	53	54
630	114	8									
660	125	10	38								
690	125	10									
720	127	11	54								
750	127	11									
780	128	11	54								
810	121	10									
840	125	10	52								
870	131	10									
900	126	10	36	119/81	90	16.2	4.07	21.7	1	41.5	42.5