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Metabolic and Mechanical Effects of Laddermill Graded Exercise Testing

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Abstract

Allerton, TD, Earnest, CP, and Johannsen, NM. Metabolic and mechanical effects of laddermill graded exercise testing. *J Strength Cond Res* 32(1): 195–200, 2018—The purpose of this study was to compare the metabolic responses and mechanical impact forces during a maximal graded exercise test (GXT) on a laddermill (LM) vs. a standard treadmill (TM). Twenty college-aged men ($n = 10$) and women completed a GXT on the TM and LM in random order. During the GXT, expired gases ($\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$), heart rate, accelerometer data, blood lactate (BLa), and rating of perceived exertion (RPE) were collected in the last minute of each stage. Data were analyzed by paired t -tests and presented herein as mean $\pm$ SD . Treadmill exercise resulted in a higher $\dot{V}_{O_2}$ peak than LM exercise (45.6 ± 7.5 vs. 41.2 ± 5.6 ml·kg⁻¹·min⁻¹, $p < 0.001$). Blood lactate threshold was similar ($p = 0.2$) between LM ($62 \pm 17\%$ $\dot{V}_{O_2}$ peak) and TM ($68 \pm 1\%$ $\dot{V}_{O_2}$ peak). The average activity level experienced during LM (0.14 ± 0.04 vector magnitude unit [VMU]) exercise was lower ($p < 0.0001$) vs. TM (0.67 ± 0.01 VMU). Additionally, impact forces were reduced ($p < 0.005$) from the vertical plane during LM ($-0.46 \pm 0.12g$) compared with TM ($-0.81 \pm 0.06g$) exercise. Our results suggest that the nature of LM exercise does not elicit the same $\dot{V}_{O_2}$ peak response observed during TM exercise. However, impact forces were reduced and energy expenditure remained higher during LM testing, whereas RPE was similar between modalities. LM exercise may provide an alternative to individuals seeking to incur a negative energy balance, but to whom higher impact forces are detrimental.

Keywords

$\dot{V}_{O_2}$ max; energy expenditure; impact

Introduction

Different exercise modalities place varying levels of physiological and mechanical stress on the human body; therefore, it is important to understand the modality at a fundamental level. For example, chronic overuse and high ground reaction forces, or impact forces, have been shown to cause excessive stress during running and contribute considerably to the risk of

injury (23). Techniques and equipment designed to reduce impact forces are thought to promote reduced risk of injury (14,22).

Combined upper- and lower-body exercise has been shown to increase the energy requirement of exercise (2,4,15). Additionally, arm exercise has been shown to alter normal ventilation, which could influence the perceived intensity of exercise and the dynamics of oxygen utilization and blood pressure during submaximal or maximal exercise (5–7). Previous work suggests that energy expenditure varies from different exercise equipment even at the same perceived level of exertion (rating of perceived exertion [RPE]) (17). Exercises that are higher in energy expenditure, for a given level of perceived exertion, are associated with many positive health outcomes including greater reductions in subcutaneous and visceral body fat and increases in insulin sensitivity, and may positively impact exercise adherence (8,9).

Few studies (3,16) have compared vertical climbing exercises to other modalities (i.e., treadmill [TM] or rowing ergometer); however, typical climbing exercise machines used in previous studies are considerably different in function when compared with the Jacob's Ladder laddermill (LM) (3,11,16). The Jacob's Ladder is a non-motorized, self-powered LM set at a constant 40° angle (Figure 1). The primary aim of our study was to investigate the metabolic and mechanical effects of LM exercise graded exercise testing (GXT) compared with traditional TM GXT. Based on previous research, we hypothesized that participants would achieve higher $\dot{V}_{O_2}$ peak value during LM than TM during the GXT (1,3). As a secondary aim, we assessed blood lactate (BLa), impact forces, and RPE to compare the biochemical response, mechanical stress, and perceived intensity, of LM exercise to TM walking and running.

Methods

Experimental Approach to the Problem

After the initial screening visit, eligible participants performed a familiarization session on the LM to become accustomed to the different voluntary speed levels that were required during the testing session. After that, participants were randomly allocated to the LM or TM test for the first GXT to be completed the same day or within 2 days of the screening visit. After trial 1 was completed, participants were crossed over into the opposite modality to complete the second GXT. The time between GXT protocols was at least 4 days.

Subjects

Twenty healthy, college-aged (Mean $\pm$ SD 25 ± 4 years, 18–34 years) men ($n = 10$) and women (body mass index [BMI] = 23.5 ± 2.4 kg·m⁻²) were recruited to participate in this study. Study participants were all considered recreationally active, but not specifically trained. All participants were naive to the LM. All participants underwent screening and were tested in the fall semester in the clinical exercise physiology testing laboratory at Louisiana State University. The Institutional Review Board of Louisiana State University approved this study, and each participant provided written informed consent before the collection of any study-related data.

$\dot{V}O_2$ max Assessment

Treadmill Protocol—The TM GXT was conducted on a Track-Master TMX425C (Carefusion, Newton, KS, USA). Participants walked at an initial speed of 3.0 mph at a level grade for the first 3 minutes. The TM speed and grade were then increased to 5.0 mph and 2.5% incline for 2 minutes with additional increases of 2.5% incline every 2 minutes thereafter until volitional exhaustion. Throughout the test, respiratory gas exchange was determined using an integrated oxygen/carbon dioxide analyzer calibrated with standard gas mixtures (TrueOne 2400; ParvoMedics, Inc., Sandy, UT, USA). Stoichiometric equations were used to determine fat and carbohydrate oxidation rates as well as caloric expenditure rates (10). During the $\dot{V}O_2$ max test, finger stick BLa concentrations (Lactate Plus, Waltham, MA, USA) were obtained, at the end of each interval for the determination of lactate threshold (4 mM lactate).

Laddermill Protocol—Participants were allowed an additional familiarization period (5 minutes) before testing on the Jacob's Ladder (Jacob's Ladder, LLC, Niagara Falls, NY, USA) (Figure 1). Participants then engaged the ladder by pushing with their legs and coordinately grabbing the ladder rungs with their hands. The participants were provided with an audible metronome to keep the work rate consistent within each stage. The metronome was set initially at 60 ft·min⁻¹ for 3 minutes. Every 2 minutes thereafter, the pace was increased by 10 ft·min⁻¹ until the (a) respiratory exchange ratio (RER) exceeds 1.14 or (b) $\dot{V}O_2$ or heart rate (HR) reached plateau with an increase in workload. In a similar fashion, we obtained earlobe blood samples at the end of each interval. Rating of perceived exertion and the total distance climbed were recorded at the end of each stage.

Measurement of Physiological and Mechanical Stress

To measure the physiological (HR) and mechanic stress (impact forces) of TM and LM exercise, each participant wore a BioHarness 3.0 (Zephyr; Performance Systems, Annapolis, MD, USA). The BioHarness 3.0 is a physiological monitoring telemetry device which consists of a chest strap and an electronics module that attaches to the strap. The device stores and transmits vital sign data including electrocardiogram, HR, respiration rate, body orientation, and activity. Accelerometer data were transmitted at 100 Hz over the range of $\pm 16g$ and reported as averaged g forces for each GXT stage. Total activity level was reported in vector magnitude units (VMUs) and expressed as units of (9.81 m·s⁻²) g forces. To analyze the effect of forces from different planes of motion, raw data were measured and reported at 50 Hz in the vertical, lateral, and sagittal planes. Mechanical intensity is defined according to range into which the peak acceleration g value fits into any 1-second epoch (1/60th minute). We defined the average mechanical intensity as the mechanical load divided by the exercise test duration (minutes).

Statistical Analyses

All statistics will be performed using JMP version 12.0.1 statistical software (SAS Institute, Inc., Cary, NC, USA). Baseline characteristics were compared factoring in gender using an independent t -test. To test the primary outcome of $\dot{V}O_{2peak}$, a paired t -test was used to assess the difference in response between TM and LM peak and threshold responses across

modalities. We employed a two-way analysis of variance with gender as a nested variable to determine the effect of gender on peak responses. We also tested for a treatment order effect. To compare the degree of bias, we performed Bland-Altman plots comparing LM $\dot{V}_{O_2}$ peak values with the $\dot{V}_{O_2}$ peak from TM GXT (2). All statistics will be performed using JMP version 12.0.1 statistical software (SAS Institute, Inc.). Data will be reported as mean + *SD* unless otherwise noted, and statistical significance was determined at $p = 0.05$.

Results

Baseline characteristics stratified by sex are located in Table 1. BMI and body fat percentage were significantly different between men and women ($p = 0.05$); however, all other parameters were similar by sex, and we did not observe a treatment order effect for $\dot{V}_{O_2}$ peak ($p > 0.05$).

$\dot{V}_{O_2}$ peak and Cardiovascular Responses

The $\dot{V}_{O_2}$ peak responses (Figure 2) for the LM ($41.2 \pm 5.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, CV = 14%) were significantly lower when compared with the TM ($45.6 \pm 7.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, CV = 16%, $p < 0.0001$). This phenomenon was consistent by sex, with men ($p < 0.0005$) and women ($p = 0.05$) having lower $\dot{V}_{O_2}$ peak after LM GXT compared with TM. Peak RER (1.14 ± 0.3 vs. 1.15 ± 0.1), HR (190.6 ± 11.6 vs. $188.5 \pm 9.6 \text{ b}\cdot\text{min}^{-1}$), and BLa (10.4 ± 4.3 vs. $9.1 \pm 2.4 \text{ mM}$) were not significantly different between TM and LM GXT, respectively ($P > 0.05$ for all comparisons). HR was different during the initial stage of the LM ($137 \pm 28 \text{ b}\cdot\text{min}^{-1}$) GXT compared with TM ($102 \pm 14 \text{ b}\cdot\text{min}^{-1}$; $p < 0.001$). The Bland-Altman plot for $\dot{V}_{O_2}$ peak (Figure 3) suggests a tendency for participants with lower $\dot{V}_{O_2}$ peak, as measured by the TM GXT, to attain relatively higher $\dot{V}_{O_2}$ peak values for the LM GXT. Accordingly, those participants who achieved greater $\dot{V}_{O_2}$ peak values on the TM experienced a more precipitous drop in $\dot{V}_{O_2}$ peak as a result of their LM GXT.

Lactate and Ventilatory Thresholds

No significant differences were detected when comparing the percentage of $\dot{V}_{O_2}$ peak (TM $68.0 \pm 14.0\%$ vs. LM $61.5 \pm 17.4\%$; $P = 0.22$) at the point of BLa threshold (4 mM) (Figure 4). The ventilatory threshold (% $\dot{V}_{O_2}$ peak) for the group was also similar between TM ($65.2 \pm 11.4\%$) and LM ($63.4 \pm 12.1\%$) in the entire sample. However, TM ventilatory threshold was significantly higher in men ($70.3\% \pm 8.4$) compared with women ($60.8\% \pm 11.9$; $P = 0.03$), but not significantly different between men ($62.5\% \pm 16.3$) and women ($64.0\% \pm 5.3$) during LM.

Impact Forces

The average activity level (VMU) and mechanical intensity (g) was significantly lower during LM GXT compared with TM (Table 2). When separating the planes of movement into the vertical, lateral, and sagittal planes, negative g forces experienced in the vertical and lateral planes ($p = 0.05$) were greater during the TM GXT versus the LM GXT.

Stage-Wise Comparison

The caloric cost of exercise during the initial stage of the LM GXT (60 ft·min⁻¹) was 44% (8.7 ± 0.9 vs. 3.8 ± 2.9 kcal·min⁻¹; $p < 0.0001$) higher than initial walking stage (3.0 mph 0% grade) of the TM GXT. During the next two stages, the energy expenditure for LM climbing (70 and 80 ft·min⁻¹; 10 ± 1.9 and 12.9 ± 3.0 kcal·min⁻¹, respectively) was approximately 30 and 20% higher ($p < 0.0001$) than corresponding TM stages (5.0 mph 0% grade and 5.0 mph 2.5% grade; 7.8 ± 1.7 and 10.0 ± 1.9 kcal·min⁻¹, respectively). Once the TM stage increased to 5.0 mph with 5.0% grade, the differences in energy expenditure were no longer significant.

HR was higher in LM compared with TM (102.1 ± 14.4 vs. 128 ± 28.1 ; $p < 0.0001$) during the first stage; however, HR was no significantly different throughout the remainder of stages. No significant differences existed for RPE reported at the end of each stage between TM and LM exercise. Importantly, the comparisons were made during stages, where HR and BLa were similar between treatments ($p > 0.05$). The average RPE for the totality of the TM and LM tests were 12.0 and 12.1, respectively, and were not significantly different ($p = 0.12$).

Discussion

The primary aim of our study was to examine the difference in $\dot{V}_{O_2\text{peak}}$ between TM and LM devices. Accordingly, we observed that participants could achieve a significantly higher $\dot{V}_{O_2\text{peak}}$ during TM testing. Our secondary aims were to examine the submaximal metabolic and mechanical effects of LM compared with TM exercise. During these assessments, we observed a similar BLa threshold between the TM and LM at similar HR and RPE. Based on our findings, we reject our research hypothesis stating that higher levels of peak oxygen consumption would be achieved during LM testing.

The results of our study agree with previous research demonstrating differential responses for $\dot{V}_{O_2\text{peak}}$, compared with TM running, using exercise modalities that require arm ergometer in addition to cycle ergometry or because of the nature of the sport (i.e., cross country skiing) (1,19,20). During steady-state (55% $\dot{V}_{O_2\text{max}}$) lower-body exercise, additional arm ergometry increases submaximal $\dot{V}_{O_2}$ by ~27% (12). The additional muscle mass required when arm work is added to steady-state lower-body exercise does not always predict greater peak oxygen consumption. In this study of the LM from Jacob's Ladder, we did not detect a significant increase in $\dot{V}_{O_2\text{peak}}$ above the value attained on the TM. Interestingly, we did observe greater energy expenditure rates with LM exercise at an equivalent HR, BLa, and RPE compared with TM exercise.

Prescribing an appropriate intensity of training for LM exercise based on HRmax may be appropriate during higher intensity. HR at BLa and ventilatory threshold on the LM occurred at a similar HR and % $\dot{V}_{O_2\text{peak}}$ to the TM GXT. However, at 60 ft·min⁻¹, HR is elevated ($137 \text{ b} \cdot \text{min}^{-1}$, ~73% HRmax) on LM, when compared with TM walking ($102 \text{ b} \cdot \text{min}^{-1}$, ~54% HRmax). This disparity in heart could be explained by the involvement of the upper body, which contributes to the novelty of the equipment. Therefore, it may be appropriate to initially prescribe exercise intensity based on RPE until specific adaptations are gained.

Many of the studies that demonstrate an increased $\dot{V}_{O_2\text{peak}}$ with whole-body exercise are conducted in individuals that are specifically trained for the activity. For example, competitive rowers demonstrate a higher $\dot{V}_{O_2\text{peak}}$ on the rowing ergometer than on a TM or cycle ergometer (21). However, in novice rowers, the $\dot{V}_{O_2\text{peak}}$ response is higher on the cycle ergometer and TM compared with the rower (21). Likewise, in those specifically trained in cycling, $\dot{V}_{O_2\text{peak}}$ responses are typically lower when measured on the TM (18). This is likely due to training adaptations acquired by the competitive rowers and cyclist and the effectiveness by which they produce power under the constraints of the sport.

In our study, none of the participants were specifically trained on the LM. Maximal oxygen uptake responses were significantly lower on the LM compared with the TM; however, peak HR, lactate, RER, or RPE were similar, suggesting that a similar maximal, or near maximal, state was achieved. These data contrast those of Reybrouck et al. (1975) who found that participants with $\dot{V}_{O_2\text{max}}$ lower than $45 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ were able to achieve 19% higher $\dot{V}_{O_2\text{max}}$ values when upper-body work was combined with lower-body cycle ergometry, whereas those with higher $\dot{V}_{O_2\text{max}}$ values ($>50 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) had similar maximal values with and without the addition of arm exercise (19). The participants in our study with lower $\dot{V}_{O_2\text{peak}}$ values on the TM had a tendency to reach similar values on the LM, but did not exceed (with the exception of 1 participant) their TM $\dot{V}_{O_2\text{peak}}$.

The mechanism to explain the lower $\dot{V}_{O_2\text{peak}}$ values during LM compared with TM would be speculative based on the available data. These results are consistent with other investigators comparing ladder climbing with other exercise modalities showing either lower (16) or similar (11) $\dot{V}_{O_2\text{peak}}$ responses when compared with TM running. However, unlike the previous studies, we used a commercially available LM and tested participants naive to the exercise modality. The novelty of the LM exercise possibly influenced our results. Further research is warranted to understand if training adaptations allow for greater peak oxygen consumption during LM GXT.

A novel finding of our study is that the activity measured in VMUs did not increase significantly throughout the LM GXT, whereas VMUs increased during the TM GXT. The mechanical impact of LM climbing never exceeded $0.7g$, whereas the impact forces progressively increased during the TM GXT (Table 2). Furthermore, analysis of impact forces demonstrated a tendency for the impact forces coming from the vertical plane of movement to increase with TM compared with LM exercise. These impact forces have been implicated with a greater risk of injury during running (23,24). Interestingly, although activity levels and impact levels were low during LM GXT, energy expenditure rate at a given amount of impact remained higher. The disparity in energy expenditure across the stages is likely due to the amount of external work performed at each stage. During pilot testing, we determined that the maximal rate of climbing that a participant could attain with good form was approximately $100 \text{ ft}\cdot\text{min}^{-1}$.

The strengths of this study include standard measurements of gas exchange and pulmonary ventilation on a previously untested, commercially available LM. Additionally, we incorporated unique sensors to detect changes in HR and impact during the course of our experiment. A major limitation of our study was the disparity in external work rates between

modalities. The lack of work matched stages, where mechanical works is equivalent, complicates the comparison between LM and TM. Also, generalizability is limited due to the data acquired from this homogeneous group and the lack of specific training.

Practical Applications

The combined effects of upper- and lower-body exercise has been studied extensively (1,3–5,7,13,21). Exercise equipment that requires the additional use of the arms elicits differential responses in terms of HR (4), blood pressure (5,7), and perceived exertion (7). Therefore, the method for prescribing training intensity on the LM should involve an individual assessment of HR response during increasing climbing rates. Reassessment should be conducted to determine the degree of training adaptation and adjust per specific training goals.

Laddermill exercise, in participants not specifically trained on the LM, does not elicit greater $\dot{V}_{O_2\text{peak}}$ than TM exercise. However, the average energy expenditure rate is greater and impact is lower during LM exercise at a similar HR and RPE. The application of equations to predict $\dot{V}_{O_2\text{max}}$ and caloric expenditure is likely not appropriate, at least in individuals naive to the device, when using the Jacob's Ladder because of the exponential nature of oxygen utilization and energy expenditure. These results are consistent with comparisons of other upper- and lower-body exercise modes compared with TM running (15). However, these data suggest that LM exercise may potentially provide an alternative to individuals seeking to incur a negative energy balance, but to whom higher impact forces are detrimental.

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Figure 1.
Picture of the laddermill.

Figure 2.

$\dot{V}O_2$ peak values ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) for treadmill (TM) (45.6 ± 7.5) and laddermill (LM) (41.25 ± 5.6) overall, men (TM 49.9 ± 6.9 , LM 44.7 ± 4.1), and women (TM 41.4 ± 6.9 , LM 37.6 ± 4.4). Data are mean $\pm$ SD. ** $p < 0.0001$, * $p < 0.0005$, # $p = 0.05$.

Figure 3.
Bland-Altman plot comparing the $\dot{V}O_{2\text{peak}}$ values achieved on the treadmill vs. laddermill.

Figure 4. Blood lactate (BLa) (mM) levels for laddermill (LM) (circles) and treadmill (TM) (squares). Dashed line represents the 4 mM threshold used to detect the onset of BLa threshold. Data are mean $\pm$ SD.

Table 1

Participant characteristics. *

	Men	Women	Total
<i>n</i>	10	10	20
Age	25.3 ± 4.4	22.3 ± 7.1	22.6 ± 3.4
Weight	75.4 ± 10.1	60.2 ± 7.9	67.8 ± 11.8
Body mass index	25.1 ± 1.9	22.0 ± 1.7	23.5 ± 2.4

*
Data are mean ± *SD*.

Table 2

Impact forces.

	Treadmill	Laddermill
Average activity (vector magnitude unit)	0.67 ± 0.01	$0.14 \pm 0.04^*$
Mechanical intensity (<i>g</i>)	3.9 ± 1.2	$0.7 \pm 0.4^*$
Vertical (<i>g</i>)	20.81 ± 0.06	$20.46 \pm 0.12^{\dagger}$
Lateral (<i>g</i>)	$20.17 \pm 0.01^*$	0.09 ± 0.16
Sagittal (<i>g</i>)	20.09 ± 0.03	$20.63 \pm 0.17^*$

^{*}
 $p < 0.0001$.

[†]
 $p < 0.005$.