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Published in:
Ergonomics

DOI:
[10.1080/00140139.2018.1473644](https://doi.org/10.1080/00140139.2018.1473644)

2018

[Link to publication](#)

Citation for published version (APA):

Halder, A., Gao, C., Miller, M., & Kuklane, K. (2018). Oxygen uptake and muscle activity limitations during stepping on a stair machine at three different climbing speeds. *Ergonomics*, 61(10), 1382-1394. <https://doi.org/10.1080/00140139.2018.1473644>

Total number of authors:
4

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PO Box 117
221 00 Lund
+46 46-222 00 00



Oxygen uptake and muscle activity limitations during ascending on a stair machine

Journal:	<i>Ergonomics</i>
Manuscript ID	TERG-2017-0320.R3
Manuscript Type:	Original Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Halder, Amitava; Lund University, Department of Design Sciences Gao, Chuansi; Lund University, Faculty of Engineering (LTH), Department of Design Sciences Miller, Michael; Lund University, Health Sciences Kuklane, Kalev; Lund University, Design Sciences
Keywords:	Stair climbing, Ascending capacity, Oxygen consumption, Electromyography, Muscle fatigue

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Oxygen uptake and muscle activity limitations during ascending on a stair machine

Amitava Halder^{1*}, Chuansi Gao¹, Michael Miller² & Kalev Kuklane¹

¹ Chuansi Gao, Associate Professor, Division of Ergonomics and Aerosol Technology, Department of Design Sciences, Lund University, Box 118, 221 00 Lund, Sweden. E-mail: Chuansi.Gao@design.lth.se. Phone: +46 46222 3206.

² Michael Miller, Department of Health Sciences, Faculty of Medicine, Lund University, Box 117, 221 00 Lund, Sweden. E-mail: Michael.Miller@med.lu.se. Phone: +46 70 910 1191.

¹ Kalev Kuklane, Associate Professor, Division of Ergonomics and Aerosol Technology, Department of Design Sciences, Lund University, Box 118, 221 00 Lund, Sweden. E-mail: Kalev.Kuklane@design.lth.se. Phone: +46 46222 7833.

*Corresponding author:

Amitava Halder

Division of Ergonomics and Aerosol Technology, Department of Design Sciences, Lund University, Box 118, 221 00 Lund, Sweden. E-mail: Amitava.Halder@design.lth.se. Phone: +46 46 2228005.

Running Head: Stair climbing physiological limiting factors

Disclosure statement: The authors declare that no competing interests exist.

Funding Source: Swedish Fire Research Board (Brandforsk) and Swedish Transport Administration (Trafikverket).

Acknowledgments: The work was sponsored by the Swedish Fire Research Board (Brandforsk) and the Swedish Transport Administration (Trafikverket). The sponsors had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. The authors appreciate the useful contributions made by the project leaders, Karl Fridolf and Enrico Ronchi, from the Division of Fire Safety Engineering, and the cooperation partners, Mattias Delin from DeBrand Sverige AB and Johan Norén from Brand & Riskingenjörerna AB. Finally, we acknowledge Eileen Deaner for editing the language.

Oxygen uptake and muscle activity limitations during ascending on a stair machine

ABSTRACT

This laboratory study examined human stair ascending capacity and constraining factors including legs' local muscle fatigue (LMF) and cardiorespiratory capacity. Twenty-five healthy volunteers, mean age 35.3 years, with maximal oxygen uptake (VO_{2max}) of $46.7 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, and maximal heart rate of 190 bpm, ascended on a stair machine at 60% and 75% (3 min each), and 90% of VO_{2max} (5 min or until exhaustion). The VO_2 , HR and electromyography (EMG) of the leg muscles were measured. The average $VO_{2highest}$ reached $43.9 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, and $HR_{highest}$ peaked at 185 bpm at 90% of VO_{2max} step rate (SR). EMG amplitudes significantly increased at all three levels, $p < 0.05$, and median frequencies decreased mostly at 90% of VO_{2max} SR evidencing leg LMF. Muscle activity interpretation squares were developed and effectively used to observe changes over time, confirming LMF. The combined effects of LMF and cardiorespiratory constraints reduced ascending tolerance and constrained the duration to 4.32 minutes.

Practitioner Summary

To expedite ascending evacuation from high-rise buildings and deep underground structures, it is necessary to consider human physical load. This study investigated the limiting physiological factors and muscle activity rate changes (MARC) used in the muscle activity interpretation squares (MAIS) to evaluate leg local muscle fatigue (LMF). LMF and cardiorespiratory capacity significantly constrain human stair ascending capacities at high, constant step rates.

Keywords: Stair climbing, Ascending capacity, Oxygen consumption, Electromyography, Muscle fatigue

Abbreviations

HR_{max}	Maximum heart rate reached during maximal aerobic capacity test (bpm)
$HR_{last\ 30\ s}$	Average heart rate during the last 30 seconds of each ascending exercise (bpm)

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3	HR _{highest}	Maximum heart rate reached during ascending test (bpm)
4	MAIS	Muscle activity interpretation squares
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6	MARC	Muscle activity rate changes
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8	M _{highest}	Maximum metabolic rate reached during ascending test ($W \cdot m^{-2}$)
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10	M _{last 30 s}	Average metabolic rate during the last 30 seconds of each ascending exercise
11		($W \cdot m^{-2}$)
12		
13	V _{disp}	Vertical displacement ($m \cdot min^{-1}$)
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15	V _{height reached}	Vertical height reached (m)
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17	VO _{2max}	Maximum oxygen uptake reached during maximal aerobic capacity test
18		($L \cdot min^{-1}$, $mL \cdot min^{-1} \cdot kg^{-1}$)
19		
20	VO _{2highest}	Maximum oxygen uptake reached during stair ascending test
21		
22	VO _{2last 30 s}	Average oxygen uptake during the last 30 seconds of each ascending exercise
23		
24	%VO _{2max}	The average VO _{2highest} during the stair ascending test that reached the
25		percentage of VO _{2max}
26		
27	%HR _{max}	The average HR _{highest} during the stair ascending test that reached the
28		percentage of HR _{max}
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1. Introduction

Stair ascension is a physically challenging activity requiring both cardiorespiratory endurance and leg muscle power (Macdonald et al. 2007). Serious concerns in evacuation research include the physiological limitations, maximum capacities and durations in climbing stairs. Non-stop prolonged ascending can be required in an emergency evacuation to reach a safe refuge level from deep underground structures, such as subways and in high-rise buildings (Lam et al. 2014; Ronchi et al. 2015; Delin et al. 2016). From both the performance and evacuation perspectives, it is impossible for a person to continue ascending with the same maximum speed for a long duration. Emergency stair ascent requires strong repetitive leg muscle activity to carry the entire body weight. Generally, cardiorespiratory constraints limit human physiological performance. However, the effects of local muscle fatigue (LMF) due to a repetitive activity can further reduce the ascending capacity before the cardiorespiratory capacity limits are reached (Cheng and Rice 2013).

Several field and laboratory studies have assessed ascending capacity by measuring heart rate (HR), blood pressure and oxygen uptake (VO₂), and have estimated energy costs in

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3 preferred and prescribed speeds on different stair machines (Bassett et al. 1997; Butts,
4 Dodge, and McAlpine 1993; O'Connell et al. 1986; Teh and Aziz 2002; Lam et al. 2014). On a
5 step mill, the relative VO_2 values observed were 26, 32, 38 and 46 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ during
6 ascending for 5 minutes at 60, 77, 95, and 112 $\text{steps}\cdot\text{min}^{-1}$, respectively (Butts, Dodge, and
7 McAlpine 1993). Another study used gradual increments of step rates (SRs) every two
8 minutes on a step ergometer and obtained a lower $\text{VO}_{2\text{max}}$ than when running on a treadmill,
9 suggesting a contribution of leg LMF (Ben-Ezra and Verstraete 1988). The onset of fatigue
10 may have constrained the capacity and kept the VO_2 lower than the subjects' maximal levels,
11 indicating another possible performance constraining factor.
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18 Electromyography (EMG) studies have reported that muscle activity while ascending was
19 significantly higher than descending as the calf muscles worked proportionately at a higher
20 level than the shin muscles during ascension on regular stairs. (Eteraf Oskouei et al. 2014).
21 One study on an inclined treadmill demonstrated that greater ankle and knee extensor
22 activity was required for propulsion during a double-step stance phase compared to a single-
23 step (Gottschall, Aghazarian, and Rohrbach 2010). Scheuermann, Tripse McConnell, and
24 Barstow (2002) showed that both EMG and VO_2 measurements were used to observe
25 physiological responses during cycling where the EMG median frequency (MDF) decreased
26 during fast ramp cycling ($64 \text{ W}\cdot\text{min}^{-1}$), while it remained relatively constant at slow ramp
27 cycling ($8 \text{ W}\cdot\text{min}^{-1}$) at the same pedaling cadence of 70 cycles per minute. The increase of
28 amplitude (AMP) was related to the work rate increase. Another study showed the level of
29 muscle fatigue using the ratio of muscle maximum voluntary contraction (MVC) to AMP at
30 the beginning and end of repetitive work (Oksa, Ducharme, and Rintamaki 2002). However,
31 the observation of muscle activity, including the development of fatigue over time during
32 stair ascending evacuation at high intensity exercise, was not studied.
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45 Therefore, the laboratory study presented in this paper aimed to observe changes in both
46 the AMP and MDF over time in order to evaluate the development of muscle fatigue during
47 constant pace ascents on a stair machine. This was accomplished based on the muscle
48 activity rate changes (MARC) presented in the muscle activity interpretation squares (MAIS)
49 (Halder et al. 2018), which in turn are based on Cifrek et al.'s (2009) four possible
50 assumptions of muscle activity during any kind of work. Running and cycling physiological
51 responses have been examined using both EMG and VO_2 , but there is a lack of research on
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3 leg muscle fatigue in prolonged stair ascension. The measurements of leg muscle EMG and
4 VO_2 presented here are a complementary and novel approach to better observe and assess
5 fatigue that can constrain human ascending capacity during an evacuation. Thus, the overall
6 aim of the laboratory study was to explore stair ascending physiological limitations and
7 capacity by measuring VO_2 , HR and leg muscle EMG during ascending on a stair machine.
8 Specifically, the study investigated the extent to which the effects of LMF and VO_2 constrain
9 human ascending endurance during simulated urgent evacuation at 90% of VO_{2max} SR.
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16 **2. Methods**

17 **2.1. Subjects**

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19 The non-invasive methods and procedures used in this study comply with the Declaration of
20 Helsinki. The study was approved by the Regional Ethics Board in Lund, Sweden (Dnr.
21 2014/54). The subjects, representing a varied population with regards to age, gender and
22 body build, were recruited through announcements in the social media. To determine their
23 eligibility, the subjects completed a questionnaire that covered basic information including
24 history of disease and disabilities and medications. Twenty-five healthy subjects without any
25 musculoskeletal problems were selected for the study. They received both verbal and
26 written information about the test procedures during the recruiting period and before the
27 tests. Table 1 presents the subjects' anthropometrics, gender and VO_{2max} data with means
28 and standard deviations (SD).
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Table 1. Anthropometric, gender and maximum aerobic capacity (VO_{2max}) data of the total number of subjects (N=25), and for the males (N=13) and females (N=12) separately with

Parameters	Total subjects		Male		Female	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Age (years)	35.3 (12.3)	22.0-62.0	36.6 (11.6)	23.0-55.0	33.8 (13.4)	22.0-62.0
Height (m) [#]	1.72 (0.07)	1.59-1.89	1.75 (0.07)	1.67-1.89	1.69 (0.06)	1.59-1.76
Weight (kg) [#]	74.4 (17.6)	53.0-128.4	82.3 (20.8)	61.0-128.4	65.8 (6.9)	53.0-77.5
* $A_{Du} m^{-2\#}$	1.86 (0.22)	1.53-2.44	1.97 (0.24)	1.71-2.44	1.75 (0.11)	1.53-1.88
$VO_{2max} (L \cdot min^{-1})^{\#}$	3.41 (0.73)	2.30-5.10	3.72 (0.69)	2.43-5.10	3.06 (0.61)	2.30-4.02
$VO_{2max} (mL \cdot min^{-1} \cdot kg^{-1})$	46.7 (9.2)	29.7-60.6	46.5 (9.1)	32.8-59.5	47.0 (9.9)	29.7-60.6
$HR_{max} (bpm)$	190.4 (13.6)	161.0-212.0	194.9 (12.7)	175.0-212.0	185.5 (13.4)	161.0-205.0

mean (SD).

[#] Statistically significant differences between male and female at $p < 0.05$.

* Body surface area calculated by Dubois equation.

The subjects were asked to abstain from any vigorous exercise or sporting activity prior to the tests. They were tested in the lab on two occasions and a separate informed consent was obtained for each test. On the first occasion, a brief description of the necessary safety information, test procedures and apparatus was repeated both orally and in writing. They then performed a maximal aerobic capacity test on a treadmill to determine their individual maximal oxygen uptake (VO_{2max}). On the second visit, after a recovery period of at least 24 hours, the subjects performed the ascension test on the stair machine. They were given the opportunity to practice walking on the treadmill or climbing on the stair machine before the tests. Two researchers were available nearby at all times for safety purposes.

2.2. Maximal aerobic capacity test

In order to determine each subject's VO_{2max} , maximal aerobic capacity tests were carried out on a treadmill (Exercise™, x-track elite, Sweden). The subjects started with a 5-min rest followed by walking at $4 \text{ km} \cdot \text{h}^{-1}$ for 3 min and then running at $8 \text{ km} \cdot \text{h}^{-1}$ for 2 min. The speed was further increased every 2 min until the subject reached a comfortable pace and then continued running while the inclination was increased by 3% every 2 min until exhaustion

was reached (ACSM 2010). The highest VO_2 in $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ and HR values obtained during the $\text{VO}_{2\text{max}}$ test period were designated as the individual's $\text{VO}_{2\text{max}}$ and HR_{max} , respectively.

2.3. Stair ascending test

Subjects performed an ascending task on a stair machine (StairMaster, SM5, Vancouver, WA, USA) (Figure 2) with a step height of 20.5 cm and a depth of 25.0 cm. The StairMaster was selected for the task because it resembles ascending a long escalator (Arias et al. 2016). The subjects were allowed to hold onto the handrails during ascent. Individual subject's ascending SRs were determined at three levels based on their relative $\text{VO}_{2\text{max}}$ values in $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$: a $\text{VO}_{2\text{max}}$ of 60% for Level 1 (L1), 75% for Level 2 (L2), and 90% for Level 3 (L3) (Kuklane and Halder 2016). The subjects performed the ascent at each level and were allowed to rest between levels for two or five minutes following the test protocol described in the schematic flowchart in Figure 1. They were encouraged to keep on stepping for the given durations at each level, but were assured in advance that they could withdraw at any time. The presumption is that people in the general population will choose their maximal possible ascending speed to reach a safe place in an evacuation situation. Thus, it was only at L3 (90% of $\text{VO}_{2\text{max}}$) that the subjects were instructed to ascend for 5 min at the most or until exhaustion. They rated their perceived exertion on the Borg Scale after the test.

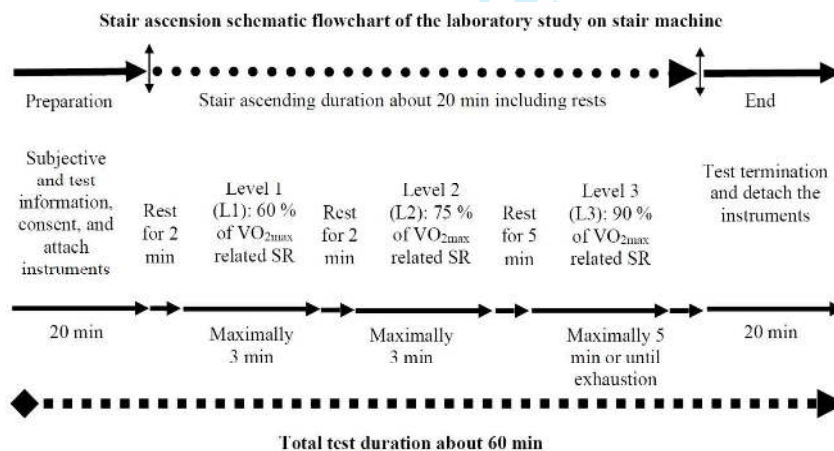


Figure 1. Schematic flowchart and protocol of the stair ascending test.

2.4. Instruments and subject preparation

The instruments included a heart rate (HR) transmitter buttoned to a chest belt and a wristwatch (RS400, Polar Electronics, Finland). A cardiopulmonary exercise testing system

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3 (Metamax II, Cortex Medical GmbH, Germany), consisting of a facemask with a volume
4 transducer fastened with a head cap, sampled the respiratory gasses every 10s. An EMG
5 biomonitor (Megawin ME6000-T16 Mega Electronics, Kuopio, Finland) recorded the raw
6 EMG at a sampling rate of 1024 Hz. The EMG system was fastened to the subjects' waists
7 with straps during the tests. Electromyography was recorded from the dominant lower limb
8 muscles including the knee extensors: vastus lateralis (VL) and rectus femoris (RF); and the
9 foot plantar flexors: gastrocnemius medialis (GM) and gastrocnemius lateralis (GL).

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15 The skin was cleaned with 70% isopropyl alcohol after scrubbing lightly with fine
16 sandpaper before applying the electrodes. EMG signals were obtained by using pre-gelled
17 bipolar (AgCl) surface electrodes in pairs (Ambu Neuroline-720, Ballerup, Denmark). Thigh
18 and calf muscles fibre arrangements were considered before positioning the electrodes over
19 the contracted muscle belly in line with the direction of the muscle fibres, with a centre-to-
20 centre distance of approximately 15-20 mm. The reference electrodes were attached to the
21 tubercle and shaft of the tibia and fibular head. The same investigator performed the
22 placement of electrodes following the guidelines of surface electromyography for the non-
23 invasive assessment of muscles (SENIAM) at www.seniam.org, Enschede, Netherlands
24 (Hermens et al. 2000). Clothing and shoes were not standardised; subjects were allowed to
25 wear their own sports clothes.
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50 **Figure 2.** A subject ascending on the StairMaster after full instrumentation.
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53 **2.5. Data collection and processing**

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55 Prior to the test, EMG recordings were also taken of the isometric MVC of the ankle plantar
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3 flexion (calf) and knee extension (quadriceps). The middle range of motion of the ankle and
4 knee joints were positioned so they could exert maximum isometric force. The MVC
5 durations were kept for 3-5 s.
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8 9 2.5.1. EMG data processing and normalization

10 The raw EMG signals were first filtered through a band-pass filter (20-499 Hz) (Merletti
11 1999). The *Megawin Software*, version 3.1-b10 was used. All the ascending durations (ADs)
12 from L1, L2 and L3 for each subject were divided into 10 equal-length periods in order to
13 achieve time normalization of the individual ADs. The ADs at L3 varied between subjects
14 depending on individual capacities. This normalization method was applied in order to
15 compare the dynamic muscle activities at each 10th percentile interval (Dingwell et al. 2008;
16 Maclsaac, Parker, and Scott 2001). The MDF in Hz was retrieved from an average spectrum
17 analysis using the calculation window. Root mean square averaging was applied to obtain
18 the average AMP in μV from each 10% period. Each average 10% AMP data set was
19 normalized by the average AMP recorded during the MVC tests of the respective muscles.
20 Due to excess noise from the EMG signals, the GM muscle AMP data from two participants,
21 and the RF and VL muscle AMP data from another participant were excluded from the
22 analyses.
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34 2.5.2. EMG data interpretation through MARC and MAIS

35 The muscle activity interpretation squares (MAIS) were developed and used to interpret the
36 dynamic EMG data during stair ascending on regular stairs (Halder et al. 2018). The MAIS are
37 based on the following *four* assumptions of EMG muscle activity (AMP and MDF) rate
38 changes (MARC) over the ADs. The first assumption is that an increase in both AMP and MDF
39 is an indication of *muscle force increase*. The second assumption is that an increase in AMP
40 and a decrease in MDF is an indication of *muscle fatigue*. The third assumption is that a
41 decrease in both AMP and MDF is an indication of decreasing *muscle force*. The fourth
42 assumption is that a decrease in AMP and an increase in MDF are an indication of *recovery*
43 from muscle fatigue (Cifrek et al. 2009). MARC were observed on the both AMP and MDF
44 values of the ten equal length divisions (10%) of the total ascending period (100%). The 10%
45 periodical average EMG activity during repeated movements of a task may provide an
46 estimation of fatigue based on the relative changes that occur in the MDFs and AMPs of the
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3 leg muscles (Asplund and Hall 1995). The averages of the MDF and the normalized AMP for
4 each equally divided 10% period were calculated to yield one data point, giving a total of 10
5 data points for each subject. These 10 periodical average AMP and MDF data points (10-
6 100%) and the changes between the unit times represent the MARC for each muscle during
7 ascension. Later, both the AMP and MDF MARC values were combined to obtain one final
8 point for each 10th percentile duration and that was presented into the MAIS.
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13 14 2.5.3. Calculation and statistics

15 The maximums (^{highest}) and means of the last 30 s (^{last 30 s}) of the cardiorespiratory
16 parameters, including HR, VO₂ and metabolic rate (M), were extracted from the data after
17 the initial sharp increase for all three ascending levels separately.
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21 The assumption of normality of the EMG values was not satisfied in the mixed model and
22 analysis of variance (ANOVA) tests. Thus, the Friedman's test of nonparametric-related
23 samples was performed to observe how the related muscle activities changed over time for
24 both the AMP and MDF. Independent *t* tests were performed to determine the statistical
25 significance of the physiological variables between genders.
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29 During an emergency evacuation, an ascending speed is expected to be close to the
30 individual's maximal capacity (on average about 90% of VO_{2max} related speed). Pronounced
31 muscle fatigue was not expected within the 3-min duration for low intensity tests at L1 and
32 L2 (60% and 75% of VO_{2max}) (Holmer and Gavhed 2007; ISO 2004). Accordingly, correlation
33 and regression analyses, and the MARC and MAIS were applied to L3 (90%) results where the
34 SRs were, as expected, relevant to an emergency and quick evacuation. Pearson's
35 correlation analyses were performed among the three muscle variables of AMP, MDF and
36 VO₂ at L3 to determine if the extent of the fixed speed can explain the changes in AMPs and
37 MDFs during the slow component increase of VO₂. Individual ADs were different at L3. All
38 physiological data, including VO₂, HR, M data, were also normalized to 0-100% periods
39 following the same procedure of EMG normalization.
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48 As stated in the previous section, 2.5.2, the averages of the parameter values were
49 calculated for each of the 10% normalized periods for each subject and then for all subjects.
50 In addition, the MARC representing average EMG AMPs and MDFs were calculated by the
51 following equation:
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$$\Delta = \frac{x_n - x_{n-1}}{\bar{t}/10}$$

where

Δ is change in a selected parameter over a normalized period;

x_n is the selected parameter value at a normalized time point n ;

x_{n-1} is the selected parameter value at a normalized time point $n-1$;

\bar{t} is the average duration in seconds for ascending at 90% of VO_{2max} SRs;

10 is the total number of normalized periods.

Statistical analyses were carried out in *Excel* (Microsoft Corporation, USA) and the *Statistical Package for the Social Science* (SPSS), version 22.0 (IBM Corporation, USA). A probability (p) value of ≤ 0.05 was considered to be statistically significance for all tests.

3. Results

3.1. Stair ascending capacity

All 25 participants managed to ascend for the two 3-min durations at the lower intensities at L1 and L2 without major cardiovascular strain and exertion. Notably, the % VO_{2max} were slightly higher than the targets based on VO_{2max} : 63% and 79%, respectively, for L1 and L2 (Table 2). Seventeen of the twenty-five participants managed to sustain ascending for the stipulated 5-min duration at L3 and they rated the SR as 'extremely hard', especially regarding leg exertion. The remaining eight quit between 2 and 4 minutes (Table 2). The mean (SD) perceived exertion measured on the Borg Scale at the end of the test was 19 (1). The % HR_{max} reached varied widely during exercising at these fixed SRs. The calculated mean (SD) M per step was 1.38 (0.59) $W \cdot m^{-2}$. Interestingly, the M and VO_2 per step were lowest during ascending at the highest SRs, and highest during low SRs at all three levels.

Table 2. Stair ascending capacity comparisons of three individual step rates for all subjects (N=25) with mean (SD).

Parameters	L1 (60% VO_{2max})	L2 (75% VO_{2max})	L3 (90% VO_{2max})
AD (s)	180.0 (0.0)	180.0 (0.0)	259.2 (68.7)
Ascending speed ($m \cdot s^{-1}$)	0.36 (0.09)	0.48 (0.09)	0.59 (0.10)
SR ($steps \cdot min^{-1}$)	66.1 (16.3)	88.3 (17.0)	109.4 (17.8)
V_{disp} ($m \cdot min^{-1}$)	13.2 (3.3)	17.7 (3.4)	21.9 (3.6)

V_{height reached} (m)	39.7 (9.8)	53.0 (10.2)	95.0 (30.8)
VO_{2last 30 s} (L·min⁻¹)	2.07 (0.49)	2.62 (0.61)	3.09 (0.64)
VO_{2highest} (L·min⁻¹)	2.13 (0.50)	2.68 (0.63)	3.18 (0.65)
VO_{2last 30 s} (mL·min⁻¹·kg⁻¹)	28.7 (6.1)	36.0 (6.9)	42.7 (7.9)
VO_{2highest} (mL·min⁻¹·kg⁻¹)	29.5 (6.18)	36.8 (6.8)	43.9 (7.8)
HR_{last 30 s} (bpm)	141.0 (15.9)	163.9 (14.5)	183.8 (12.5)
HR_{highest} (bpm)	142.0 (15.8)	165.5 (14.3)	184.9 (12.2)
M_{last 30 s} (W·m⁻²)	377.9 (73.2)	486.5 (86.4)	581.2 (92.4)
M_{highest} (W·m⁻²)	389.7 (74.4)	498.5 (87.4)	598.6 (91.7)
*%VO_{2max}	62.5 (5.1)	78.6 (6.6)	93.6 (6.1)
*%HR_{max}	74.3 (5.6)	86.8 (5.7)	96.9 (3.0)

*The highest values achieved for VO₂ and HR during either the treadmill VO_{2max} or the stair machine test was used to calculate the %VO_{2max} and %HR_{max}.

3.2. Comparisons between males and females

There were statistically significant gender differences in the anthropometric data including body weight ($p=.025$), height ($p=.016$), body surface area ($p=.009$) and absolute VO_{2max} values in L·min⁻¹ ($p=.019$) (Table 1). No stair ascending performances between genders at L3 showed a statistically significant difference except average absolute values in L·min⁻¹ for VO_{2last 30 s} and VO_{2highest}, $p=0.022$ and 0.014 , respectively. Moreover, the male participants' ADs were shorter than the females at L3 (Table 3).

Table 3. Stair ascending capacity comparisons between males (N=13) and females (N=12) at L3 (90% of VO_{2max}) with mean (SD).

Parameters	Male	Female	Significance (2 tailed)
AD (s)	235.4 (75.3)	285.0 (52.0)	0.070
Ascending speed (m·s⁻¹)	0.59 (0.09)	0.59 (0.11)	0.902
SR (steps·min⁻¹)	108.9 (16.2)	109.8 (20.2)	0.902
V_{disp} (m·min⁻¹)	21.8 (3.2)	22.0 (4.0)	0.902
V_{height reached} (m)	85.4 (30.1)	105.4 (29.1)	0.107
VO_{last 30 s} (L·min⁻¹)	3.36 (0.66)	2.79 (0.48)	0.022

VO_{2highest} (L·min⁻¹)	3.48 (0.66)	2.85 (0.48)	0.014
VO_{2last 30 s} (mL·min⁻¹·kg⁻¹)	41.8 (7.4)	43.6 (8.7)	0.589
VO_{2highest} (mL·min⁻¹·kg⁻¹)	43.2 (7.3)	44.6 (8.7)	0.670
HR_{last 30 s} (bpm)	185.8 (12.6)	181.6 (12.5)	0.413
HR_{highest} (bpm)	187.2 (12.1)	182.4 (12.2)	0.329
M_{last 30 s} (W·m⁻²)	600.7 (86.6)	560.0 (95.5)	0.280
M_{highest} (W·m⁻²)	621.7 (85.0)	573.5 (95.7)	0.196
*%VO_{2max}	92.5 (7.2)	94.8 (4.6)	0.347
*%HR_{max}	95.9 (3.4)	98.0 (2.0)	0.066

*The calculated average percentage reached the VO_{2highest} and HR_{highest} values during the StairMaster test in relation to the VO_{2max} and HR_{max} values from the treadmill test.

In the L1 exercise, the mean (SD) VO_{2highest} for the males and females reached 29.3 (6.0) and 29.7 (6.7) mL·min⁻¹·kg⁻¹ while the average HR_{highest} peaked at 139.9 (15.1) and 144.2 (16.8) bpm, respectively. The average M_{highest} values for men and women were 410.9 (71.9) and 366.7 (73.0) W·m⁻², respectively. At L2, the VO_{2highest} reached 36.2 (6.3) and 37.4 (7.5) mL·min⁻¹·kg⁻¹ for the males and females, respectively. The HR_{highest} peaked at 164.0 (16.4) and 167.2 (12.1) bpm during ascending at L2 for men and women, respectively. The average M_{highest} values for males and females reached 519.0 (88.7) and 476.4 (84.1) W·m⁻², respectively.

At L1, the average ascending speed, the calculated vertical height reached (V_{height reached}), and the vertical displacement (V_{disp}) were almost equal for males and females at 0.36 m·s⁻¹, 40 m, and 13 m·min⁻¹, respectively. In contrast at L2, the average ascending speeds for men and women were 0.47 vs 0.48 m·s⁻¹, respectively. The calculated mean value for the V_{height reached} was for men, 52.3 m and for women, 53.7 m. The V_{disp} was over 17.5 m·min⁻¹ for both genders in the 3-min test at 75%. The %HR_{max} was about 71% for men and 77% women at L1 (60%: 66 steps·min⁻¹ for both genders). Similarly, at L2 (75%: 87 steps·min⁻¹ for males and 89 steps·min⁻¹ for females) the percentages reached 84% and 90% of the HR_{max} levels for men and women, respectively, based on the VO_{2max} test.

3.3. Oxygen uptake (VO₂) at three SRs

The VO_2 values obtained from the three levels of ascending tests indicated that every cardiorespiratory steady state of VO_2 and its kinetics were related to each of the stair ascending intensity at the fixed rate. The levels of VO_2 increased as the stair ascending intensities increased from L1 to L2. The VO_2 values were on average below 30, above 35, and above 40 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, respectively, for 60% (L1), 75% (L2) and 90% (L3) of $\text{VO}_{2\text{max}}$ (Figure 3). At the L1 and L2 3-min tests, the cardiorespiratory steady state reflected in $\text{VO}_{2\text{ last } 30\text{ s}}$ values, accumulated at 90% of the total normalized ascending period and during the VO_2 slow components' increase. In contrast, the stable VO_2 started to accumulate after 70% of the total normalized ascending period at L3. This time was equal to 3.0 min after the onset of ascending.

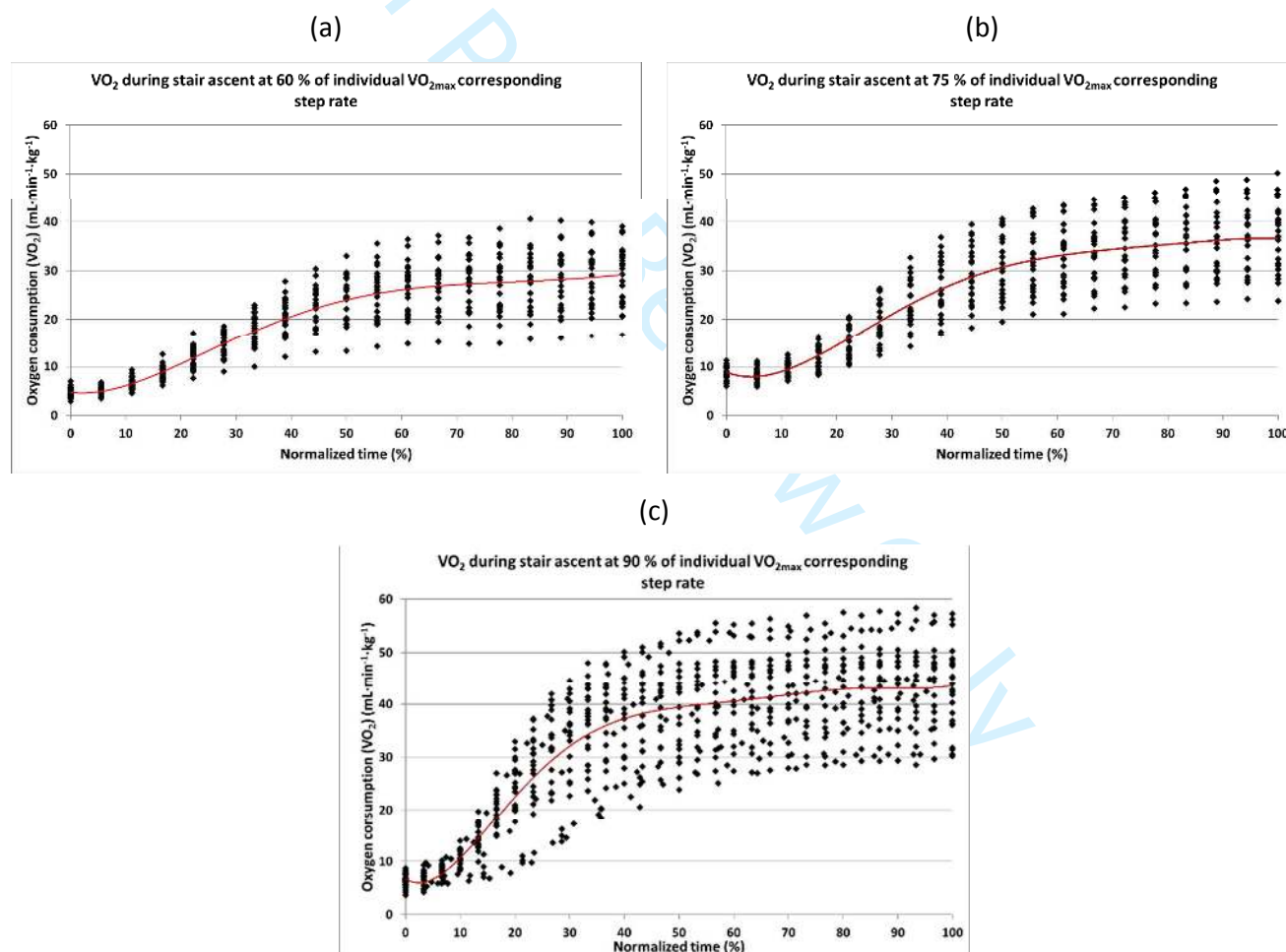


Figure 3. Average oxygen uptakes in normalized periods (0-100%) for all subjects (N=25) for 3 min each at L1 (a) and L2 (b), and a maximum of 5 min or until exhaustion at L3 (c). The average absolute ascending times were 3.0, 3.0 and 4.3 min at L1, L2 and L3, respectively.

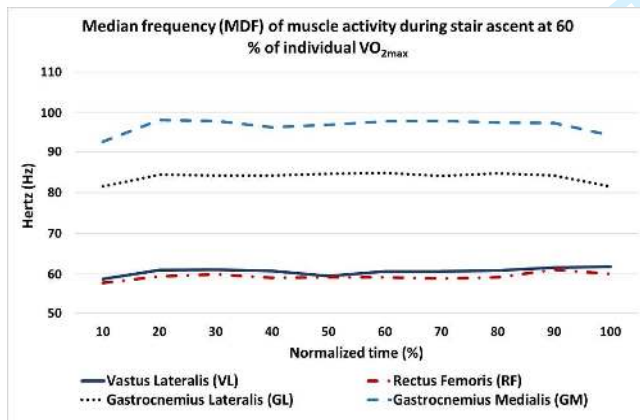
3.4. Changes over time in EMG MDF and AMP

The VL ($p=0.039$) and RF ($p=0.043$) MDF values differed significantly between their average normalized periods (10-100%) during ascending at L1 and L2, as shown in the Friedman's test, Figures 4(a) and 4(c). In contrast, the MDFs of the VL ($p<0.001$), RF ($p=0.009$) and GL ($p=0.011$) muscles decreased significantly over time (except GM) during the L3, intensive ascending exercise, Figure 4(e).

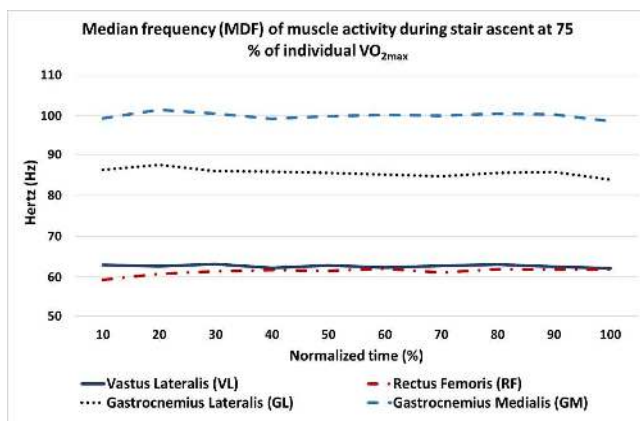
The EMG AMPs clearly showed an increase at the initial 10% to 20% periods for all muscles and at three levels. They reached a steady state and decreased at the end of ascending at L1 and L2, while there was a continuous increase over time during ascending at L3. However, the average AMPs for all of the four muscles increased significantly across the time normalized periods (10-100%) at all three levels (L1, L2 and L3, $p<0.05$), Figures 4(b), 4(d), and 4(f).

EMG MDFs

(a)

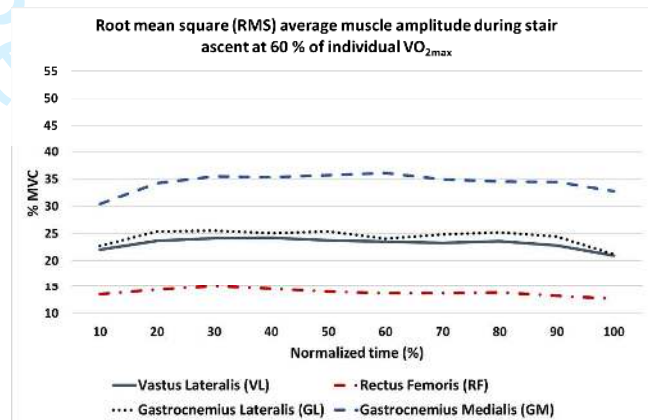


(c)

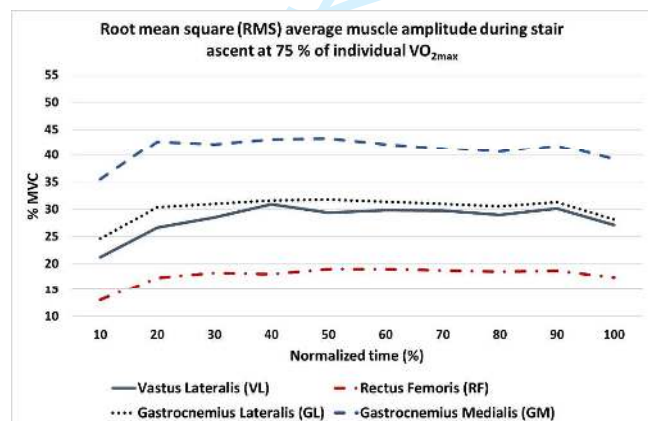


EMG AMPs

(b)



(d)



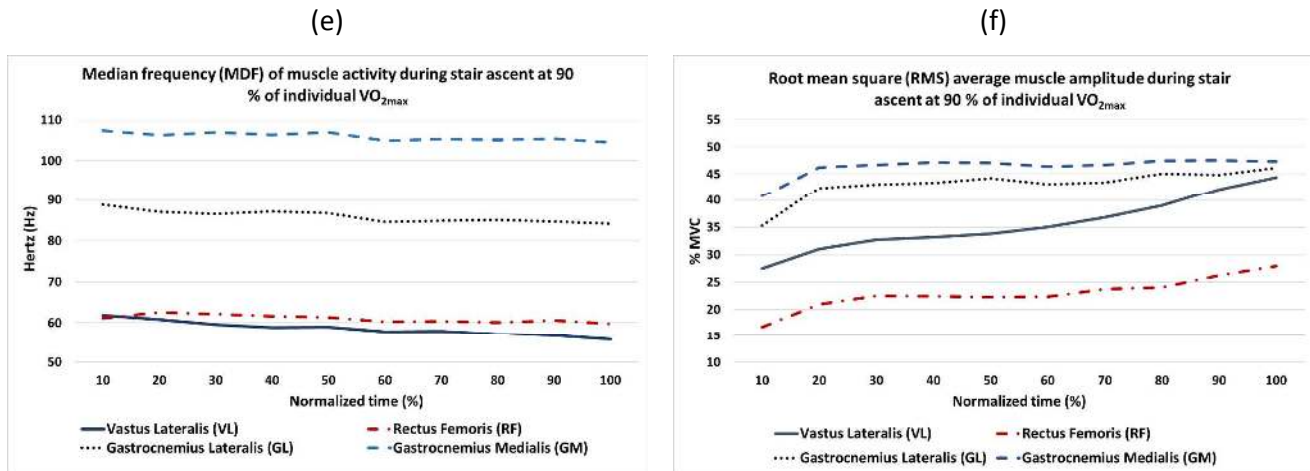
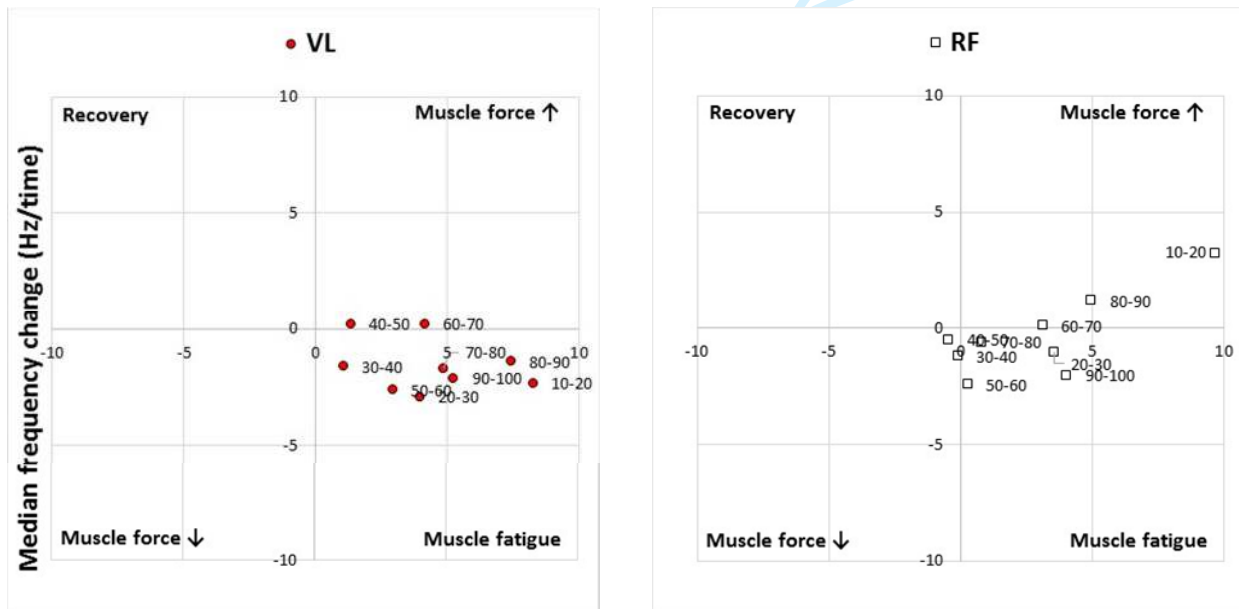


Figure 4. Average changes in EMG MDFs (left column: a, c, e) and normalized AMPs (right column: b, d, f) over the normalized (10-100%) periods at L1, L2, and L3, respectively.

3.5. Muscle activity rate changes (MARC) in muscle activity interpretation squares (MAIS)

All four muscles' AMP and MDF rate changes during the test at L3 showed a similar pattern in the MAIS. Most of the values aggregated between the *muscle force increase* and *muscle fatigue* squares of each muscle diagram (towards the right half of the diagrams in Figure 5). It is important to note that the end periods (90-100%) MARC values of the muscles were concentrated in the muscle fatigue square except for GM, which showed decreased muscle force (Figure 5).



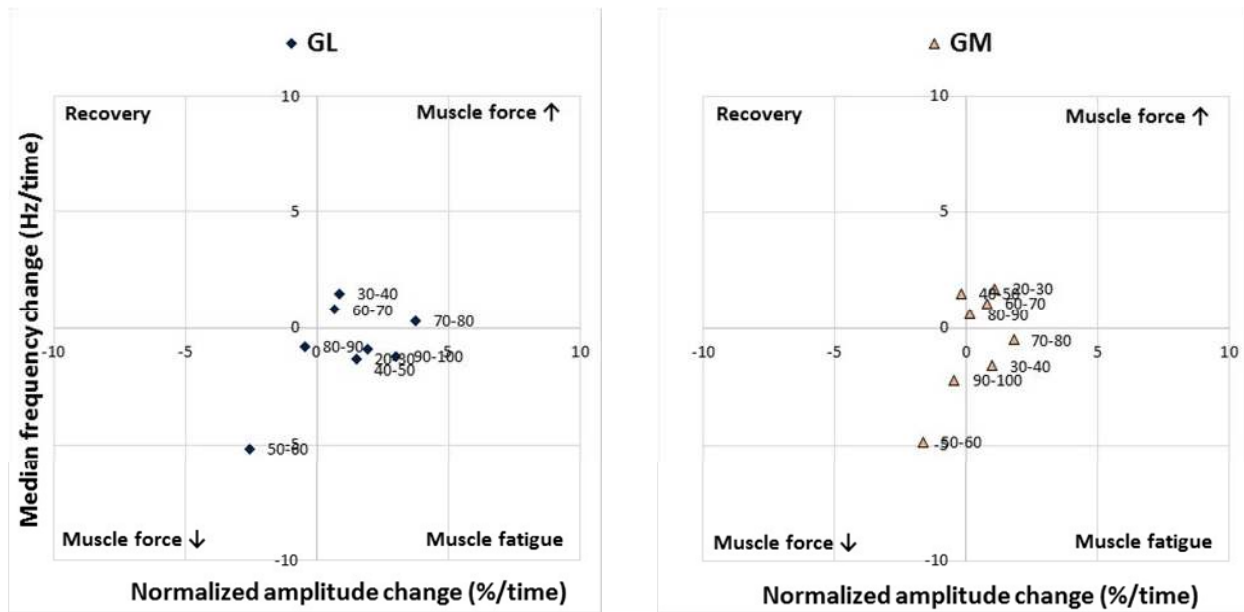


Figure 5. Muscle activity rate changes (MARC) for four muscles in normalized periods (10 - 100%) periods at 90% VO_{2max} (L3) in the muscle activity interpretation squares (MAIS).

4. Discussion

4.1. Stair ascending aerobic capacities at three speeds

The main finding of this study was that the average $VO_{2highest}$ and $HR_{highest}$ values reached $43.9 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ and 184.9 bpm during ascending at approximately 90% of VO_{2max} SR (L3), and the values were 94% VO_{2max} and 97% HR_{max} , respectively. However, the $VO_{2highest}$ was lower than the subjects' VO_{2max} ($46.7 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) (Tables 1 and 2). The average ascending duration was 4.32 min with an SR range between 68 and 133 $\text{steps}\cdot\text{min}^{-1}$ and the calculated vertical height reached 95 m. These data were used to develop an ascending evacuation model (Kuklane and Halder 2016).

The average $M_{highest}$ was about $600 \text{ W}\cdot\text{m}^{-2}$ during ascending at 90% of VO_{2max} SR. The observed $VO_{2highest}$ and calculated $M_{highest}$ ranges were between 30.7 to $58.3 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, and 423.8 to $764.4 \text{ W}\cdot\text{m}^{-2}$, respectively (Table 2). The calculated average $M_{highest}$ values were about $400 \text{ W}\cdot\text{m}^{-2}$ at 60% of VO_{2max} , which means that it is an activity that can be continued for up to 2 hours according to ISO 8996 (ISO 2004). The $M_{highest}$ achieved during the ascents at 75% of VO_{2max} (L2) (Table 2) are in agreement with the suggested M of about $475 \text{ W}\cdot\text{m}^{-2}$ (approximately 70% of VO_{2max}) for an activity lasting about 15-20 min (Holmer and Gavhed 2007). Holmer and Gavhed (2007) have also shown that people can manage an activity at

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3 this M for up to 5 min; in their study, the average M_{highest} reached $612 \text{ W}\cdot\text{m}^{-2}$, $\text{VO}_{2\text{highest}}$ to 44
4 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ and $\text{HR}_{\text{highest}}$ peaked at 179 bpm. In another ascending study involving a 5-min
5 activity on a different step machine with a similar SR of $112 \text{ steps}\cdot\text{min}^{-1}$, the average
6 $\text{VO}_{2\text{highest}}$ reached $42 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ and the $\text{HR}_{\text{highest}}$ peaked at 175 bpm (Butts, Dodge, and
7 McAlpine 1993). Notably, the present study's $\text{HR}_{\text{highest}}$ was higher than the values of the
8 previous two studies. The high HR indicates that the L3 workload appeared excessive for the
9 leg muscles, resulting in fatigue. Leg muscle fatigue and exhaustion may have forced the
10 subjects to discontinue during the 5-min long ascending, and LMF was presumably
11 responsible for lowering the $\text{VO}_{2\text{highest}}$ values more than their $\text{VO}_{2\text{max}}$, but equal to previously
12 studied high intensity simulated tasks. In a previous experiment on simulated firefighting
13 tasks, the $\text{VO}_{2\text{max}}$ rose to $44 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ (83% of $\text{VO}_{2\text{max}}$) in the process of rescuing six
14 victims and climbing six flights of stair for 5 min (von Heimburg, Rasmussen, and Medbo
15 2006).

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25 The males' average AD was shorter than the females' at L3. Most of the subjects were
26 males who quit before 5 min, showing that their significantly higher body mass made the
27 difference in their ability to sustain the critical power during stair ascending at 90% $\text{VO}_{2\text{max}}$.
28 The male participants' body mass ranged between 61 and 128 kg while the females' was
29 between 53 and 77.5 kg. The ascending distance ($V_{\text{height reached}}$) calculated for the female
30 participants was longer because they carried a low body mass resulting in a longer AD (Poole
31 et al. 2016). Moreover, there was a high variation in their selected SRs. The men's $\text{VO}_{2\text{max}}$
32 range was between 32.8 and $59.5 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, and women's between 30.7 and 60.6
33 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$. The M_{highest} for men were higher than that for women (Table 3). The
34 considerable differences in energy demands could lead to exhaustion in L3 (Table 2).
35 However, women reached the higher percentage of their $\text{VO}_{2\text{max}}$, 94.8 vs 92.5%, and HR_{max} ,
36 98.0 vs 95.9% compared to men at L3.

4.2. **Muscle activity EMG AMP and MDF**

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49 The analysis of muscle activity was a guide in evaluating how LMF in the legs affected the
50 stair ascending oxygen uptake and performance at the three ascending intensities, especially
51 L3. The AMPs increased significantly in all three controlled ascending speeds (Figures 4(b),
52 4(d), and 4(f)), and three muscles MDFs decreased significantly at L3 (Figure 4(e)), providing
53 strong evidence of LMF. The decrease in MDF results are supported by the progressive
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3 decreased MDF results found by Scheuermann, Tripse McConnell, and Barstow (2002) in fast
4 ramp increase cycling with a constant pedalling rate, suggesting that the MDF decrease was
5 associated with fatigue during the constant ascending pace.
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8 At L3, the muscle activity rate changes' (MARC) percentile points over time supported the
9 muscle fatigue results. Most of the MARC points, especially during the last 90-100% period,
10 were in the 'muscle fatigue' square in the muscle activity interpretation squares (MAIS). This
11 provided evidence of leg muscles fatigue during the test at 90% VO_{2max} SR (Figure 5). We
12 observed that some points corresponding to the starting periods were in the 'force increase'
13 square, which suggests that subjects were strong enough to exert a high force in the
14 beginning of the ascents. The MARC points shifted to the 'muscle fatigue' square after the
15 onset of fatigue while ascending was kept at a constant high speed with minimal possibilities
16 of postural adaptations. However, in the previous field study during ascending on the regular
17 stairs, the subjects tried to cope with fatigue by inclining forward and transferring their body
18 weight through their forearms to the handrails to reduce the leg muscles' workload (Halder
19 et al. 2018). The recruitment of additional muscle fibres may not have been possible during
20 high-intensity and constant ascents, and the decrease of muscle working efficiency from the
21 fibres already recruited may be associated with leg LMF, which reduced the ascending
22 tolerance (Cannon et al. 2011; Jones et al. 2011; Vanhatalo et al. 2011; Zoladz et al. 2008).
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34 The EMG results of the two lower SRs (L1 and L2) indicate that workloads and durations
35 were insufficient to cause fatigue, especially for the calf muscles. The leg muscular exertion
36 was high only for VL and RF muscles at 3-min test durations at L1 and L2, while MDFs
37 significantly shifted to lower frequencies, Figures 4(a) and 4(c) (Samuel et al. 2011). The EMG
38 AMPs showed a relationship to the constant ascending intensities and reflected the
39 workloads of the lower limb muscles measured at different intensities, Figures 4(b), 4(d),
40 and 4(f). A 3-5% higher percentage of muscle activations was required at L3 than in the two
41 lower SRs. Moreover, individual muscles had their own AMP and relative MDF levels to
42 comply with the ascending intensities (Figure 4).
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51 **4.3. Muscle activity and VO_2**

52 The average AMP increase was relatively stable after an initial sharp increase within one
53 minute. Each intensity of ascension progressively recruited the required fibres to maintain
54 the constant SR, Figures 4(b), 4(d), and 4(f). The ascending intensities were above the
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3 threshold for a prolonged activity that was supported by the 97% of VO_{2max} reached, which
4 required high velocity leg muscular movements, while the EMG AMP threshold reached 45%
5 of MVC during ascending. The greater use of fast, type II muscle fibres increases the energy
6 demand and causes a progressive, simultaneous VO_2 increase and later a relatively steady
7 state (Saunders et al. 2000), which was observed after the initial increase during the
8 continuation of ascent at 90% VO_{2max} SR (L3) (Figure 3). At higher work rates above the
9 ventilatory threshold, VO_2 did not reach a steady state immediately but continued to rise
10 slowly (Barstow 1994; Whipp and Wasserman 1972) as did lactate to the point of fatigue
11 (Roston et al. 1987). The VO_2 values were still increasing at the point of exhaustion or at the
12 end of the 5-min ascending test, while the muscles' force production was consistent for
13 maintaining the fixed SR. The pumping capacity of the heart reached its upper limit at about
14 97% of HR_{max} due to high and constant repetitive activities, which is evidence of reaching the
15 ventilatory threshold. The oxygen supply might be insufficient to meet the increasing energy
16 demands for the aerobic metabolism of the leg muscles, constraining work efficiency. The
17 body needed to recover by either slowing down the ascending speed or taking micropauses
18 in order to continue the ascent for a long duration. Ascending speed reductions or
19 micropauses were impossible in the machine-controlled SR where the subjects had no
20 control over their ascents.

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34 The anaerobic energy-yielding process dominated after the onset of ascents. It was
35 primarily dependent on the storage of adenosine tri-phosphate and creatine phosphate
36 (Costill, Wilmore, and Kenney 2012). When there is limited energy storage available in the
37 muscles, the aerobic energy process takes over the synthesis of new fuel on demand. The
38 delay of both VO_2 uptake and oxygen utilization in the body should be considered when
39 relating EMG to VO_2 . The progressive increase in AMP and decrease in MDF at L3 suggest an
40 association with fatigue (Scheuermann, Tripse McConnell, and Barstow 2002; Cifrek et al.
41 2009). Research documented that the AMP and spectral characteristics of the EMG signal
42 would increase over the duration of the VO_2 slow component (Sabapathy, Schneider, and
43 Morris 2005). During these high-intensity exercises, as more and more fast-twitch fibres
44 were recruited in order to maintain the same speed, the rate of oxygen uptake had to
45 increase. At the same time, the muscle fibres that became fatigued earlier in ascending
46 might continue to consume oxygen as they recover and this might also reduce efficiency and
47 contribute to the VO_2 slow component. The VO_2 slow component observed after
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3 stabilization with high AMP results indicated a progressive loss of muscle contractile
4 efficiency due to leg LMF (Jones et al. 2007; Cannon et al. 2011).
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6 The inability of the subjects to sustain energy transportation at a tolerable aerobic level in
7 the local leg muscles due to controlled and repetitive tasks is responsible for shortening the
8 ascending duration and causing an early cessation. The controlled and high SR resulted in
9 overall fatigue and exhaustion of the entire body due to lack of recovery (Vogiatzis et al.
10 1996), and inhibited the $VO_{2\text{highest}}$ from reaching the $VO_{2\text{max}}$ during ascents (Ben-Ezra and
11 Verstraete 1988). The cardiorespiratory capacity and natural anaerobic processes combined
12 caused LMF in the leg muscles and prevented subjects from reaching any of these limits in
13 the ascensions involving fixed and high SRs. Thus, the results of this study suggest that
14 evacuation at 90% intensity can be sustained for 2-6 min. It is necessary to carry out more
15 controlled studies at different predetermined SRs to further examine stair ascending
16 endurance, oxygen uptake, and muscle performance until exhaustion.
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27 5. Conclusions

28 Stair ascending capacity reached 94% and 97% of the subjects' average $VO_{2\text{max}}$ and HR_{max} ,
29 respectively, at 90% of $VO_{2\text{max}}$ (L3) at an average step rate (SR) of around 109.4 (17.8)
30 $\text{steps}\cdot\text{min}^{-1}$. The $VO_{2\text{highest}}$ registered $43.9\text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ during stair ascending tests. An
31 average, HR_{highest} peaked at 185 bpm and the metabolic rate reached about $600\text{ W}\cdot\text{m}^{-2}$,
32 indicating the maximal cardiorespiratory capacity. One-third of the subjects terminated the
33 ascension at L3 before reaching the stipulated test duration of 5-min, so that the average
34 ascending duration was 4.32 minutes. At L3, high repetitive muscle activity and controlled,
35 constant speed denied recovery, which caused an imbalance between the energy availability
36 and local demand that led to local muscle fatigue (LMF) in the legs. The significant increase
37 of EMG AMPs and decrease of MDFs evidenced LMF. High intensity ascents at controlled SRs
38 at 90% of $VO_{2\text{max}}$ or above could be sustained for 2 to 6 minutes on the stair machine,
39 depending on prerequisites such as body mass, step rate, etc. The points of the muscle
40 activity rate changes (MARC) appeared in the muscle fatigue area of the muscle activity
41 interpretation squares (MAIS). MARC and MAIS are useful for observing muscle activity
42 changes over time during dynamic tasks. The study results infer that the combined effects of
43 leg LMF and high cardiorespiratory demand limited the subjects' ascending tolerance and
44 consequently, forced them to stop their ascents on the stair machine.
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Oxygen uptake and muscle activity limitations during ascending on a stair machine

Amitava Halder^{1*}, Chuansi Gao¹, Michael Miller² & Kalev Kuklane¹

¹ Chuansi Gao, Associate Professor, Division of Ergonomics and Aerosol Technology, Department of Design Sciences, Lund University, Box 118, 221 00 Lund, Sweden. E-mail: Chuansi.Gao@design.lth.se. Phone: +46 46222 3206.

² Michael Miller, Department of Health Sciences, Faculty of Medicine, Lund University, Box 117, 221 00 Lund, Sweden. E-mail: Michael.Miller@med.lu.se. Phone: +46 70 910 1191.

¹ Kalev Kuklane, Associate Professor, Division of Ergonomics and Aerosol Technology, Department of Design Sciences, Lund University, Box 118, 221 00 Lund, Sweden. E-mail: Kalev.Kuklane@design.lth.se. Phone: +46 46222 7833.

*Corresponding author:

Amitava Halder

Division of Ergonomics and Aerosol Technology, Department of Design Sciences, Lund University, Box 118, 221 00 Lund, Sweden. E-mail: Amitava.Halder@design.lth.se. Phone: +46 46 2228005.

Running Head: Stair climbing physiological limiting factors

Disclosure statement: The authors declare that no competing interests exist.

Funding Source: Swedish Fire Research Board (Brandforsk) and Swedish Transport Administration (Trafikverket).

Acknowledgments: The work was sponsored by the Swedish Fire Research Board (Brandforsk) and the Swedish Transport Administration (Trafikverket). The sponsors had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. The authors appreciate the useful contributions made by the project leaders, Karl Fridolf and Enrico Ronchi, from the Division of Fire Safety Engineering, and the cooperation partners, Mattias Delin from DeBrand Sverige AB and Johan Norén from Brand & Riskingenjörerna AB. Finally, we acknowledge Eileen Deaner for editing the language.

Oxygen uptake and muscle activity limitations during ascending on a stair machine

ABSTRACT

This laboratory study examined human stair ascending capacity and constraining factors including legs' local muscle fatigue (LMF) and cardiorespiratory capacity. Twenty-five healthy volunteers, mean age 35.3 years, with maximal oxygen uptake (VO_{2max}) of $46.7 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, and maximal heart rate of 190 bpm, ascended on a stair machine at 60% and 75% (3 min each), and 90% of VO_{2max} (5 min or until exhaustion). The VO_2 , HR and electromyography (EMG) of the leg muscles were measured. The average $VO_{2highest}$ reached $43.9 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, and $HR_{highest}$ peaked at 185 bpm at 90% of VO_{2max} step rate (SR). EMG amplitudes significantly increased at all three levels, $p < 0.05$, and median frequencies decreased mostly at 90% of VO_{2max} SR evidencing leg LMF. Muscle activity interpretation squares were developed and effectively used to observe changes over time, confirming LMF. The combined effects of LMF and cardiorespiratory constraints reduced ascending tolerance and constrained the duration to 4.32 minutes.

Practitioner Summary

To expedite ascending evacuation from high-rise buildings and deep underground structures, it is necessary to consider human physical load. This study investigated the limiting physiological factors and muscle activity rate changes (MARC) used in the muscle activity interpretation squares (MAIS) to evaluate leg local muscle fatigue (LMF). LMF and cardiorespiratory capacity significantly constrain human stair ascending capacities at high, constant step rates.

Keywords: Stair climbing, Ascending capacity, Oxygen consumption, Electromyography, Muscle fatigue

Abbreviations

HR_{max}	Maximum heart rate reached during maximal aerobic capacity test (bpm)
$HR_{last\ 30\ s}$	Average heart rate during the last 30 seconds of each ascending exercise (bpm)

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3	HR _{highest}	Maximum heart rate reached during ascending test (bpm)
4	MAIS	Muscle activity interpretation <u>squares</u>
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6	MARC	Muscle activity rate <u>changes</u>
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8	M _{highest}	Maximum metabolic rate reached during ascending test ($W \cdot m^{-2}$)
9		
10	M _{last 30 s}	Average metabolic rate during the last 30 seconds of each ascending exercise
11		($W \cdot m^{-2}$)
12		
13	V _{disp}	Vertical displacement ($m \cdot min^{-1}$)
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15	V _{height reached}	Vertical height reached (m)
16		
17	VO _{2max}	Maximum oxygen uptake reached during maximal aerobic capacity test
18		($L \cdot min^{-1}$, $mL \cdot min^{-1} \cdot kg^{-1}$)
19		
20	VO _{2highest}	Maximum oxygen uptake reached during stair ascending test
21		
22	VO _{2last 30 s}	Average oxygen uptake during the last 30 seconds of each ascending exercise
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24	%VO _{2max}	The average VO _{2highest} during the stair ascending test that reached the
25		percentage of VO _{2max}
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27	%HR _{max}	The average HR _{highest} during the stair ascending test that reached the
28		percentage of HR _{max}
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1. Introduction

Stair ascension is a physically challenging activity requiring both cardiorespiratory endurance and leg muscle power (Macdonald et al. 2007). Serious concerns in evacuation research include the physiological limitations, maximum capacities and durations in climbing stairs. Non-stop prolonged ascending can be required in an emergency evacuation to reach a safe refuge level from deep underground structures, such as subways and in high-rise buildings (Lam et al. 2014; Ronchi et al. 2015; Delin et al. 2016). From both the performance and evacuation perspectives, it is impossible for a person to continue ascending with the same maximum speed for a long duration. Emergency stair ascent requires strong repetitive leg muscle activity to carry the entire body weight. Generally, cardiorespiratory constraints limit human physiological performance. However, the effects of local muscle fatigue (LMF) due to a repetitive activity can further reduce the ascending capacity before the cardiorespiratory capacity limits are reached (Cheng and Rice 2013).

Several field and laboratory studies have assessed ascending capacity by measuring heart rate (HR), blood pressure and oxygen uptake (VO₂), and have estimated energy costs in

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3 preferred and prescribed speeds on different stair machines (Bassett et al. 1997; Butts,
4 Dodge, and McAlpine 1993; O'Connell et al. 1986; Teh and Aziz 2002; Lam et al. 2014). On a
5 step mill, the relative VO_2 values observed were 26, 32, 38 and 46 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ during
6 ascending for 5 minutes at 60, 77, 95, and 112 $\text{steps}\cdot\text{min}^{-1}$, respectively (Butts, Dodge, and
7 McAlpine 1993). Another study used gradual increments of step rates (SRs) every two
8 minutes on a step ergometer and obtained a lower $\text{VO}_{2\text{max}}$ than when running on a treadmill,
9 suggesting a contribution of leg LMF (Ben-Ezra and Verstraete 1988). The onset of fatigue
10 may have constrained the capacity and kept the VO_2 lower than the subjects' maximal levels,
11 indicating another possible performance constraining factor.
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18 Electromyography (EMG) studies have reported that muscle activity while ascending was
19 significantly higher than descending as the calf muscles worked proportionately at a higher
20 level than the shin muscles during ascension on regular stairs. (Eteraf Oskouei et al. 2014).
21 One study on an inclined treadmill demonstrated that greater ankle and knee extensor
22 activity was required for propulsion during a double-step stance phase compared to a single-
23 step (Gottschall, Aghazarian, and Rohrbach 2010). Scheuermann, Tripse McConnell, and
24 Barstow (2002) showed that both EMG and VO_2 measurements were used to observe
25 physiological responses during cycling where the EMG median frequency (MDF) decreased
26 during fast ramp cycling ($64 \text{ W}\cdot\text{min}^{-1}$), while it remained relatively constant at slow ramp
27 cycling ($8 \text{ W}\cdot\text{min}^{-1}$) at the same pedaling cadence of 70 cycles per minute. The increase of
28 amplitude (AMP) was related to the work rate increase. Another study showed the level of
29 muscle fatigue using the ratio of muscle maximum voluntary contraction (MVC) to AMP at
30 the beginning and end of repetitive work (Oksa, Ducharme, and Rintamaki 2002). However,
31 the observation of muscle activity, including the development of fatigue over time during
32 stair ascending evacuation at high intensity exercise, was not studied.
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45 Therefore, the laboratory study presented in this paper aimed to observe changes in both
46 the AMP and MDF over time in order to evaluate the development of muscle fatigue during
47 constant pace ascents on a stair machine. This was accomplished based on the muscle
48 activity rate changes (MARC) presented in the muscle activity interpretation squares (MAIS)
49 (Halder et al. 2018), which in turn are based on Cifrek et al.'s (2009) four possible
50 assumptions of muscle activity during any kind of work. Running and cycling physiological
51 responses have been examined using both EMG and VO_2 , but there is a lack of research on
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3 leg muscle fatigue in prolonged stair ascension. The measurements of leg muscle EMG and
4 VO_2 presented here are a complementary and novel approach to better observe and assess
5 fatigue that can constrain human ascending capacity during an evacuation. Thus, the overall
6 aim of the laboratory study was to explore stair ascending physiological limitations and
7 capacity by measuring VO_2 , HR and leg muscle EMG during ascending on a stair machine.
8 Specifically, the study investigated the extent to which the effects of LMF and VO_2 constrain
9 human ascending endurance during simulated urgent evacuation at 90% of VO_{2max} SR.
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16 **2. Methods**

17 **2.1. Subjects**

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19 The non-invasive methods and procedures used in this study comply with the Declaration of
20 Helsinki. The study was approved by the Regional Ethics Board in Lund, Sweden (Dnr.
21 2014/54). The subjects, representing a varied population with regards to age, gender and
22 body build, were recruited through announcements in the social media. To determine their
23 eligibility, the subjects completed a questionnaire that covered basic information including
24 history of disease and disabilities and medications. Twenty-five healthy subjects without any
25 musculoskeletal problems were selected for the study. They received both verbal and
26 written information about the test procedures during the recruiting period and before the
27 tests. Table 1 presents the subjects' anthropometrics, gender and VO_{2max} data with means
28 and standard deviations (SD).
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Table 1. Anthropometric, gender and maximum aerobic capacity (VO_{2max}) data of the total number of subjects (N=25), and for the males (N=13) and females (N=12) separately with

Parameters	Total subjects		Male		Female	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Age (years)	35.3 (12.3)	22.0-62.0	36.6 (11.6)	23.0-55.0	33.8 (13.4)	22.0-62.0
Height (m) [#]	1.72 (0.07)	1.59-1.89	1.75 (0.07)	1.67-1.89	1.69 (0.06)	1.59-1.76
Weight (kg) [#]	74.4 (17.6)	53.0-128.4	82.3 (20.8)	61.0-128.4	65.8 (6.9)	53.0-77.5
* $A_{Du} m^{-2\#}$	1.86 (0.22)	1.53-2.44	1.97 (0.24)	1.71-2.44	1.75 (0.11)	1.53-1.88
$VO_{2max} (L \cdot min^{-1})^{\#}$	3.41 (0.73)	2.30-5.10	3.72 (0.69)	2.43-5.10	3.06 (0.61)	2.30-4.02
$VO_{2max} (mL \cdot min^{-1} \cdot kg^{-1})$	46.7 (9.2)	29.7-60.6	46.5 (9.1)	32.8-59.5	47.0 (9.9)	29.7-60.6
$HR_{max} (bpm)$	190.4 (13.6)	161.0-212.0	194.9 (12.7)	175.0-212.0	185.5 (13.4)	161.0-205.0

mean (SD).

[#] Statistically significant differences between male and female at $p < 0.05$.

* Body surface area calculated by Dubois equation.

The subjects were asked to abstain from any vigorous exercise or sporting activity prior to the tests. They were tested in the lab on two occasions and a separate informed consent was obtained for each test. On the first occasion, a brief description of the necessary safety information, test procedures and apparatus was repeated both orally and in writing. They then performed a maximal aerobic capacity test on a treadmill to determine their individual maximal oxygen uptake (VO_{2max}). On the second visit, after a recovery period of at least 24 hours, the subjects performed the ascension test on the stair machine. They were given the opportunity to practice walking on the treadmill or climbing on the stair machine before the tests. Two researchers were available nearby at all times for safety purposes.

2.2. Maximal aerobic capacity test

In order to determine each subject's VO_{2max} , maximal aerobic capacity tests were carried out on a treadmill (Exercise™, x-track elite, Sweden). The subjects started with a 5-min rest followed by walking at $4 \text{ km} \cdot \text{h}^{-1}$ for 3 min and then running at $8 \text{ km} \cdot \text{h}^{-1}$ for 2 min. The speed was further increased every 2 min until the subject reached a comfortable pace and then continued running while the inclination was increased by 3% every 2 min until exhaustion

was reached (ACSM 2010). The highest VO_2 in $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ and HR values obtained during the $\text{VO}_{2\text{max}}$ test period were designated as the individual's $\text{VO}_{2\text{max}}$ and HR_{max} , respectively.

2.3. Stair ascending test

Subjects performed an ascending task on a stair machine (StairMaster, SM5, Vancouver, WA, USA) (Figure 2) with a step height of 20.5 cm and a depth of 25.0 cm. The StairMaster was selected for the task because it resembles ascending a long escalator (Arias et al. 2016). The subjects were allowed to hold onto the handrails during ascent. Individual subject's ascending SRs were determined at three levels based on their relative $\text{VO}_{2\text{max}}$ values in $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$: a $\text{VO}_{2\text{max}}$ of 60% for Level 1 (L1), 75% for Level 2 (L2), and 90% for Level 3 (L3) (Kuklane and Halder 2016). The subjects performed the ascent at each level and were allowed to rest between levels for two or five minutes following the test protocol described in the schematic flowchart in Figure 1. They were encouraged to keep on stepping for the given durations at each level, but were assured in advance that they could withdraw at any time. The presumption is that people in the general population will choose their maximal possible ascending speed to reach a safe place in an evacuation situation. Thus, it was only at L3 (90% of $\text{VO}_{2\text{max}}$) that the subjects were instructed to ascend for 5 min at the most or until exhaustion. They rated their perceived exertion on the Borg Scale after the test.

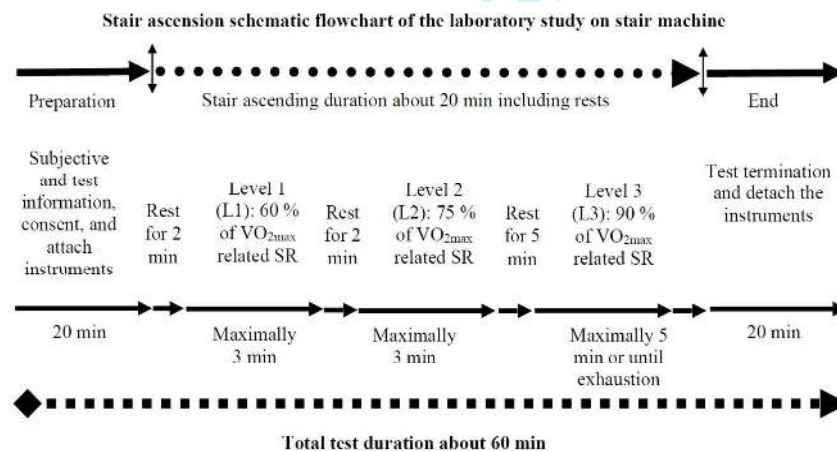


Figure 1. Schematic flowchart and protocol of the stair ascending test.

2.4. Instruments and subject preparation

The instruments included a heart rate (HR) transmitter buttoned to a chest belt and a wristwatch (RS400, Polar Electronics, Finland). A cardiopulmonary exercise testing system

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3 (Metamax II, Cortex Medical GmbH, Germany), consisting of a facemask with a volume
4 transducer fastened with a head cap, sampled the respiratory gasses every 10s. An EMG
5 biomonitor (Megawin ME6000-T16 Mega Electronics, Kuopio, Finland) recorded the raw
6 EMG at a sampling rate of 1024 Hz. The EMG system was fastened to the subjects' waists
7 with straps during the tests. Electromyography was recorded from the dominant lower limb
8 muscles including the knee extensors: vastus lateralis (VL) and rectus femoris (RF); and the
9 foot plantar flexors: gastrocnemius medialis (GM) and gastrocnemius lateralis (GL).

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11 The skin was cleaned with 70% isopropyl alcohol after scrubbing lightly with fine
12 sandpaper before applying the electrodes. EMG signals were obtained by using pre-gelled
13 bipolar (AgCl) surface electrodes in pairs (Ambu Neuroline-720, Ballerup, Denmark). Thigh
14 and calf muscles fibre arrangements were considered before positioning the electrodes over
15 the contracted muscle belly in line with the direction of the muscle fibres, with a centre-to-
16 centre distance of approximately 15-20 mm. The reference electrodes were attached to the
17 tubercle and shaft of the tibia and fibular head. The same investigator performed the
18 placement of electrodes following the guidelines of surface electromyography for the non-
19 invasive assessment of muscles (SENIAM) at www.seniam.org, Enschede, Netherlands
20 (Hermens et al. 2000). Clothing and shoes were not standardised; subjects were allowed to
21 wear their own sports clothes.
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50 **Figure 2.** A subject ascending on the StairMaster after full instrumentation.

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53 **2.5. Data collection and processing**

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55 Prior to the test, EMG recordings were also taken of the isometric MVC of the ankle plantar
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3 flexion (calf) and knee extension (quadriceps). The middle range of motion of the ankle and
4 knee joints were positioned so they could exert maximum isometric force. The MVC
5 durations were kept for 3-5 s.
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8 9 2.5.1. EMG data processing and normalization

10 The raw EMG signals were first filtered through a band-pass filter (20-499 Hz) (Merletti
11 1999). The *Megawin Software*, version 3.1-b10 was used. All the ascending durations (ADs)
12 from L1, L2 and L3 for each subject were divided into 10 equal-length periods in order to
13 achieve time normalization of the individual ADs. The ADs at L3 varied between subjects
14 depending on individual capacities. This normalization method was applied in order to
15 compare the dynamic muscle activities at each 10th percentile interval (Dingwell et al. 2008;
16 Maclsaac, Parker, and Scott 2001). The MDF in Hz was retrieved from an average spectrum
17 analysis using the calculation window. Root mean square averaging was applied to obtain
18 the average AMP in µV from each 10% period. Each average 10% AMP data set was
19 normalized by the average AMP recorded during the MVC tests of the respective muscles.
20 Due to excess noise from the EMG signals, the GM muscle AMP data from two participants,
21 and the RF and VL muscle AMP data from another participant were excluded from the
22 analyses.
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34 2.5.2. EMG data interpretation through MARC and MAIS

35 The muscle activity interpretation squares (MAIS) were developed and used to interpret the
36 dynamic EMG data during stair ascending on regular stairs (Halder et al. 2018). The MAIS are
37 based on the following *four* assumptions of EMG muscle activity (AMP and MDF) rate
38 changes (MARC) over the ADs. The first assumption is that an increase in both AMP and MDF
39 is an indication of *muscle force increase*. The second assumption is that an increase in AMP
40 and a decrease in MDF is an indication of *muscle fatigue*. The third assumption is that a
41 decrease in both AMP and MDF is an indication of decreasing *muscle force*. The fourth
42 assumption is that a decrease in AMP and an increase in MDF are an indication of *recovery*
43 from muscle fatigue (Cifrek et al. 2009). MARC were observed on the both AMP and MDF
44 values of the ten equal length divisions (10%) of the total ascending period (100%). The 10%
45 periodical average EMG activity during repeated movements of a task may provide an
46 estimation of fatigue based on the relative changes that occur in the MDFs and AMPs of the
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3 leg muscles (Asplund and Hall 1995). The averages of the MDF and the normalized AMP for
4 each equally divided 10% period were calculated to yield one data point, giving a total of 10
5 data points for each subject. These 10 periodical average AMP and MDF data points (10-
6 100%) and the changes between the unit times represent the MARC for each muscle during
7 ascension. Later, both the AMP and MDF MARC values were combined to obtain one final
8 point for each 10th percentile duration and that was presented into the MAIS.

14 2.5.3. Calculation and statistics

15 The maximums (^{highest}) and means of the last 30 s (^{last 30 s}) of the cardiorespiratory
16 parameters, including HR, VO₂ and metabolic rate (M), were extracted from the data after
17 the initial sharp increase for all three ascending levels separately.

21 The assumption of normality of the EMG values was not satisfied in the mixed model and
22 analysis of variance (ANOVA) tests. Thus, the Friedman's test of nonparametric-related
23 samples was performed to observe how the related muscle activities changed over time for
24 both the AMP and MDF. Independent *t* tests were performed to determine the statistical
25 significance of the physiological variables between genders.

29 During an emergency evacuation, an ascending speed is expected to be close to the
30 individual's maximal capacity (on average about 90% of VO_{2max} related speed). Pronounced
31 muscle fatigue was not expected within the 3-min duration for low intensity tests at L1 and
32 L2 (60% and 75% of VO_{2max}) (Holmer and Gavhed 2007; ISO 2004). Accordingly, correlation
33 and regression analyses, and the MARC and MAIS were applied to L3 (90%) results where the
34 SRs were, as expected, relevant to an emergency and quick evacuation. Pearson's
35 correlation analyses were performed among the three muscle variables of AMP, MDF and
36 VO₂ at L3 to determine if the extent of the fixed speed can explain the changes in AMPs and
37 MDFs during the slow component increase of VO₂. Individual ADs were different at L3. All
38 physiological data, including VO₂, HR, M data, were also normalized to 0-100% periods
39 following the same procedure of EMG normalization.

48 As stated in the previous section, 2.5.2, the averages of the parameter values were
49 calculated for each of the 10% normalized periods for each subject and then for all subjects.
50 In addition, the MARC representing average EMG AMPs and MDFs were calculated by the
51 following equation:

$$\Delta = \frac{x_n - x_{n-1}}{\bar{t}/10}$$

where

Δ is change in a selected parameter over a normalized period;

x_n is the selected parameter value at a normalized time point n ;

x_{n-1} is the selected parameter value at a normalized time point $n-1$;

\bar{t} is the average duration in seconds for ascending at 90% of VO_{2max} SRs;

10 is the total number of normalized periods.

Statistical analyses were carried out in *Excel* (Microsoft Corporation, USA) and the *Statistical Package for the Social Science* (SPSS), version 22.0 (IBM Corporation, USA). A probability (p) value of ≤ 0.05 was considered to be statistically significance for all tests.

3. Results

3.1. Stair ascending capacity

All 25 participants managed to ascend for the two 3-min durations at the lower intensities at L1 and L2 without major cardiovascular strain and exertion. Notably, the % VO_{2max} were slightly higher than the targets based on VO_{2max} : 63% and 79%, respectively, for L1 and L2 (Table 2). Seventeen of the twenty-five participants managed to sustain ascending for the stipulated 5-min duration at L3 and they rated the SR as 'extremely hard', especially regarding leg exertion. The remaining eight quit between 2 and 4 minutes (Table 2). The mean (SD) perceived exertion measured on the Borg Scale at the end of the test was 19 (1). The % HR_{max} reached varied widely during exercising at these fixed SRs. The calculated mean (SD) M per step was 1.38 (0.59) $W \cdot m^{-2}$. Interestingly, the M and VO_2 per step were lowest during ascending at the highest SRs, and highest during low SRs at all three levels.

Table 2. Stair ascending capacity comparisons of three individual step rates for all subjects (N=25) with mean (SD).

Parameters	L1 (60% VO_{2max})	L2 (75% VO_{2max})	L3 (90% VO_{2max})
AD (s)	180.0 (0.0)	180.0 (0.0)	259.2 (68.7)
Ascending speed ($m \cdot s^{-1}$)	0.36 (0.09)	0.48 (0.09)	0.59 (0.10)
SR ($steps \cdot min^{-1}$)	66.1 (16.3)	88.3 (17.0)	109.4 (17.8)
V_{disp} ($m \cdot min^{-1}$)	13.2 (3.3)	17.7 (3.4)	21.9 (3.6)

$V_{\text{height reached}}$ (m)	39.7 (9.8)	53.0 (10.2)	95.0 (30.8)
$VO_{2\text{last 30 s}}$ ($L \cdot \text{min}^{-1}$)	2.07 (0.49)	2.62 (0.61)	3.09 (0.64)
$VO_{2\text{highest}}$ ($L \cdot \text{min}^{-1}$)	2.13 (0.50)	2.68 (0.63)	3.18 (0.65)
$VO_{2\text{last 30 s}}$ ($\text{mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$)	28.7 (6.1)	36.0 (6.9)	42.7 (7.9)
$VO_{2\text{highest}}$ ($\text{mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$)	29.5 (6.18)	36.8 (6.8)	43.9 (7.8)
$HR_{\text{last 30 s}}$ (bpm)	141.0 (15.9)	163.9 (14.5)	183.8 (12.5)
HR_{highest} (bpm)	142.0 (15.8)	165.5 (14.3)	184.9 (12.2)
$M_{\text{last 30 s}}$ ($W \cdot \text{m}^{-2}$)	377.9 (73.2)	486.5 (86.4)	581.2 (92.4)
M_{highest} ($W \cdot \text{m}^{-2}$)	389.7 (74.4)	498.5 (87.4)	598.6 (91.7)
*% $VO_{2\text{max}}$	62.5 (5.1)	78.6 (6.6)	93.6 (6.1)
*% HR_{max}	74.3 (5.6)	86.8 (5.7)	96.9 (3.0)

*The highest values achieved for VO_2 and HR during either the treadmill $VO_{2\text{max}}$ or the stair machine test was used to calculate the % $VO_{2\text{max}}$ and % HR_{max} .

3.2. Comparisons between males and females

There were statistically significant gender differences in the anthropometric data including body weight ($p=.025$), height ($p=.016$), body surface area ($p=.009$) and absolute $VO_{2\text{max}}$ values in $L \cdot \text{min}^{-1}$ ($p=.019$) (Table 1). No stair ascending performances between genders at L3 showed a statistically significant difference except average absolute values in $L \cdot \text{min}^{-1}$ for $VO_{2\text{last 30 s}}$ and $VO_{2\text{highest}}$, $p=0.022$ and 0.014 , respectively. Moreover, the male participants' ADs were shorter than the females at L3 (Table 3).

Table 3. Stair ascending capacity comparisons between males (N=13) and females (N=12) at L3 (90% of $VO_{2\text{max}}$) with mean (SD).

Parameters	Male	Female	Significance (2 tailed)
AD (s)	235.4 (75.3)	285.0 (52.0)	0.070
Ascending speed ($\text{m} \cdot \text{s}^{-1}$)	0.59 (0.09)	0.59 (0.11)	0.902
SR ($\text{steps} \cdot \text{min}^{-1}$)	108.9 (16.2)	109.8 (20.2)	0.902
V_{disp} ($\text{m} \cdot \text{min}^{-1}$)	21.8 (3.2)	22.0 (4.0)	0.902
$V_{\text{height reached}}$ (m)	85.4 (30.1)	105.4 (29.1)	0.107
$VO_{\text{last 30 s}}$ ($L \cdot \text{min}^{-1}$)	3.36 (0.66)	2.79 (0.48)	0.022

VO_{2highest} (L·min⁻¹)	3.48 (0.66)	2.85 (0.48)	0.014
VO_{2last 30 s} (mL·min⁻¹·kg⁻¹)	41.8 (7.4)	43.6 (8.7)	0.589
VO_{2highest} (mL·min⁻¹·kg⁻¹)	43.2 (7.3)	44.6 (8.7)	0.670
HR_{last 30 s} (bpm)	185.8 (12.6)	181.6 (12.5)	0.413
HR_{highest} (bpm)	187.2 (12.1)	182.4 (12.2)	0.329
M_{last 30 s} (W·m⁻²)	600.7 (86.6)	560.0 (95.5)	0.280
M_{highest} (W·m⁻²)	621.7 (85.0)	573.5 (95.7)	0.196
*%VO_{2max}	92.5 (7.2)	94.8 (4.6)	0.347
*%HR_{max}	95.9 (3.4)	98.0 (2.0)	0.066

*The calculated average percentage reached the VO_{2highest} and HR_{highest} values during the StairMaster test in relation to the VO_{2max} and HR_{max} values from the treadmill test.

In the L1 exercise, the mean (SD) VO_{2highest} for the males and females reached 29.3 (6.0) and 29.7 (6.7) mL·min⁻¹·kg⁻¹ while the average HR_{highest} peaked at 139.9 (15.1) and 144.2 (16.8) bpm, respectively. The average M_{highest} values for men and women were 410.9 (71.9) and 366.7 (73.0) W·m⁻², respectively. At L2, the VO_{2highest} reached 36.2 (6.3) and 37.4 (7.5) mL·min⁻¹·kg⁻¹ for the males and females, respectively. The HR_{highest} peaked at 164.0 (16.4) and 167.2 (12.1) bpm during ascending at L2 for men and women, respectively. The average M_{highest} values for males and females reached 519.0 (88.7) and 476.4 (84.1) W·m⁻², respectively.

At L1, the average ascending speed, the calculated vertical height reached (V_{height reached}), and the vertical displacement (V_{disp}) were almost equal for males and females at 0.36 m·s⁻¹, 40 m, and 13 m·min⁻¹, respectively. In contrast at L2, the average ascending speeds for men and women were 0.47 vs 0.48 m·s⁻¹, respectively. The calculated mean value for the V_{height reached} was for men, 52.3 m and for women, 53.7 m. The V_{disp} was over 17.5 m·min⁻¹ for both genders in the 3-min test at 75%. The %HR_{max} was about 71% for men and 77% women at L1 (60%: 66 steps·min⁻¹ for both genders). Similarly, at L2 (75%: 87 steps·min⁻¹ for males and 89 steps·min⁻¹ for females) the percentages reached 84% and 90% of the HR_{max} levels for men and women, respectively, based on the VO_{2max} test.

3.3. Oxygen uptake (VO₂) at three SRs

The VO_2 values obtained from the three levels of ascending tests indicated that every cardiorespiratory steady state of VO_2 and its kinetics were related to each of the stair ascending intensity at the fixed rate. The levels of VO_2 increased as the stair ascending intensities increased from L1 to L2. The VO_2 values were on average below 30, above 35, and above 40 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, respectively, for 60% (L1), 75% (L2) and 90% (L3) of $\text{VO}_{2\text{max}}$ (Figure 3). At the L1 and L2 3-min tests, the cardiorespiratory steady state reflected in VO_2 last 30 s values, accumulated at 90% of the total normalized ascending period and during the VO_2 slow components' increase. In contrast, the stable VO_2 started to accumulate after 70% of the total normalized ascending period at L3. This time was equal to 3.0 min after the onset of ascending.

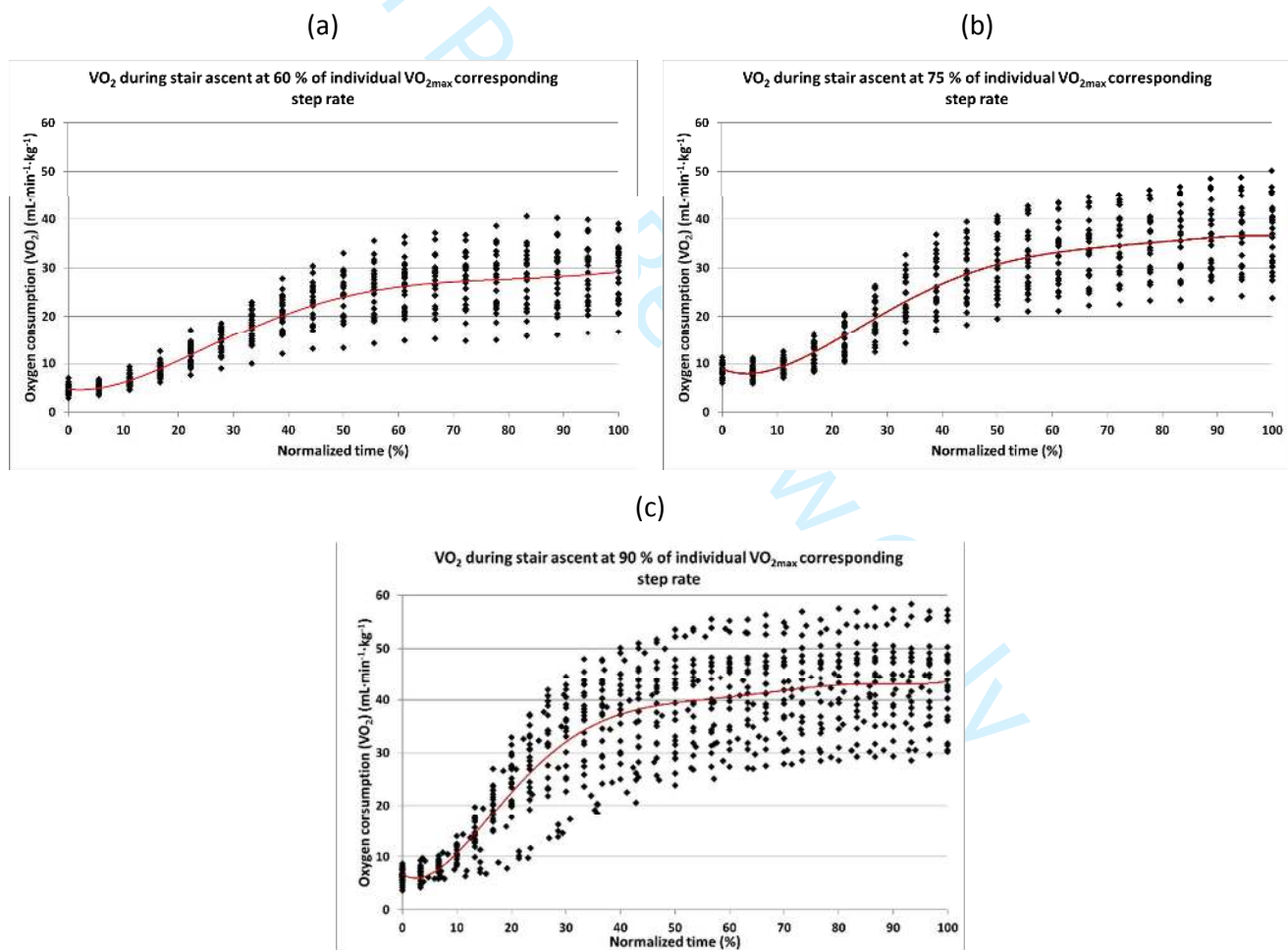


Figure 3. Average oxygen uptakes in normalized periods (0-100%) for all subjects ($N=25$) for 3 min each at L1 (a) and L2 (b), and a maximum of 5 min or until exhaustion at L3 (c). The average absolute ascending times were 3.0, 3.0 and 4.3 min at L1, L2 and L3, respectively.

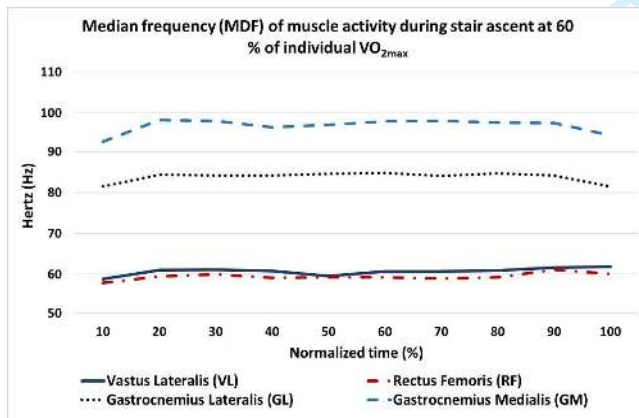
3.4. Changes over time in EMG MDF and AMP

The VL ($p=0.039$) and RF ($p=0.043$) MDF values differed significantly between their average normalized periods (10-100%) during ascending at L1 and L2, as shown in the Friedman's test, Figures 4(a) and 4(c). In contrast, the MDFs of the VL ($p<0.001$), RF ($p=0.009$) and GL ($p=0.011$) muscles decreased significantly over time (except GM) during the L3, intensive ascending exercise, Figure 4(e).

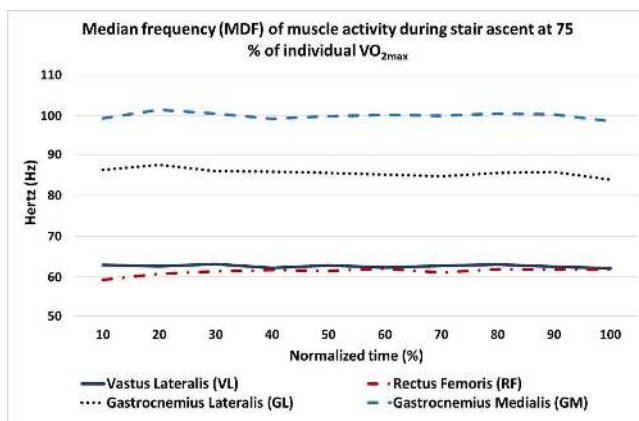
The EMG AMPs clearly showed an increase at the initial 10% to 20% periods for all muscles and at three levels. They reached a steady state and decreased at the end of ascending at L1 and L2, while there was a continuous increase over time during ascending at L3. However, the average AMPs for all of the four muscles increased significantly across the time normalized periods (10-100%) at all three levels (L1, L2 and L3, $p<0.05$), Figures 4(b), 4(d), and 4(f).

EMG MDFs

(a)

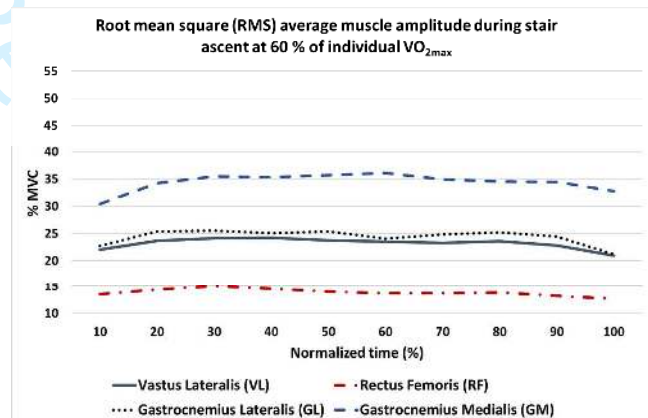


(c)

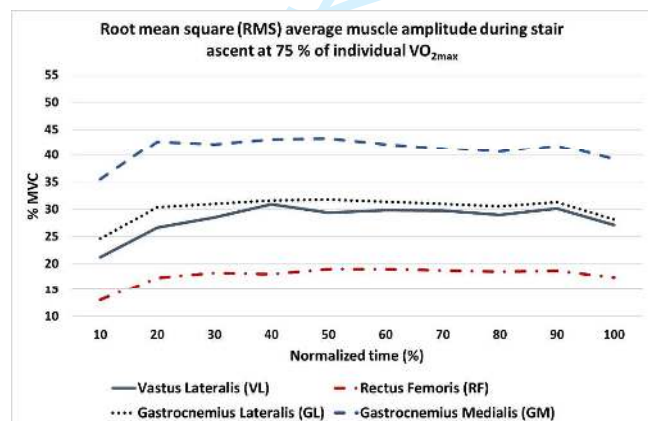


EMG AMPs

(b)



(d)



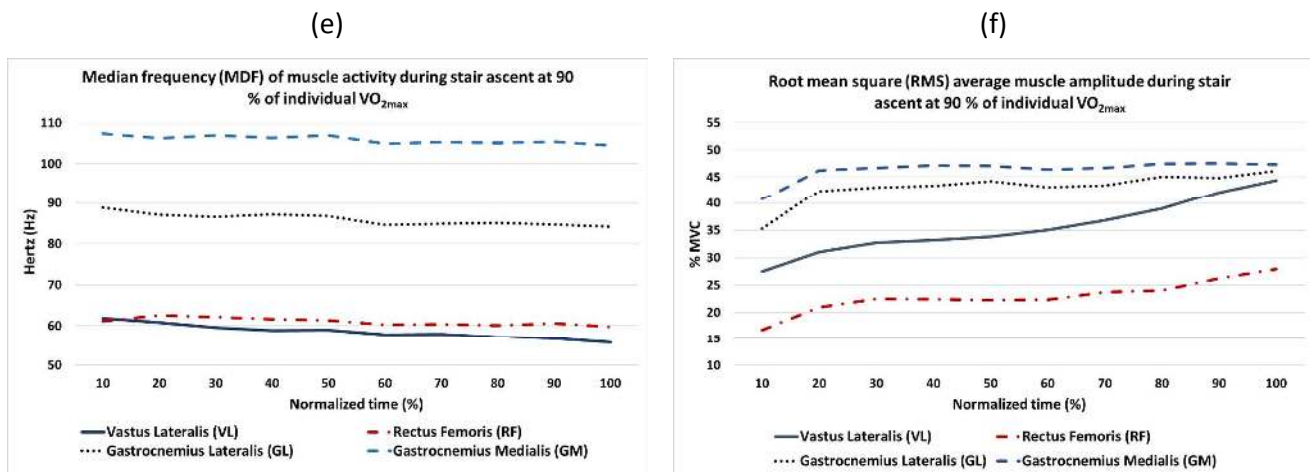
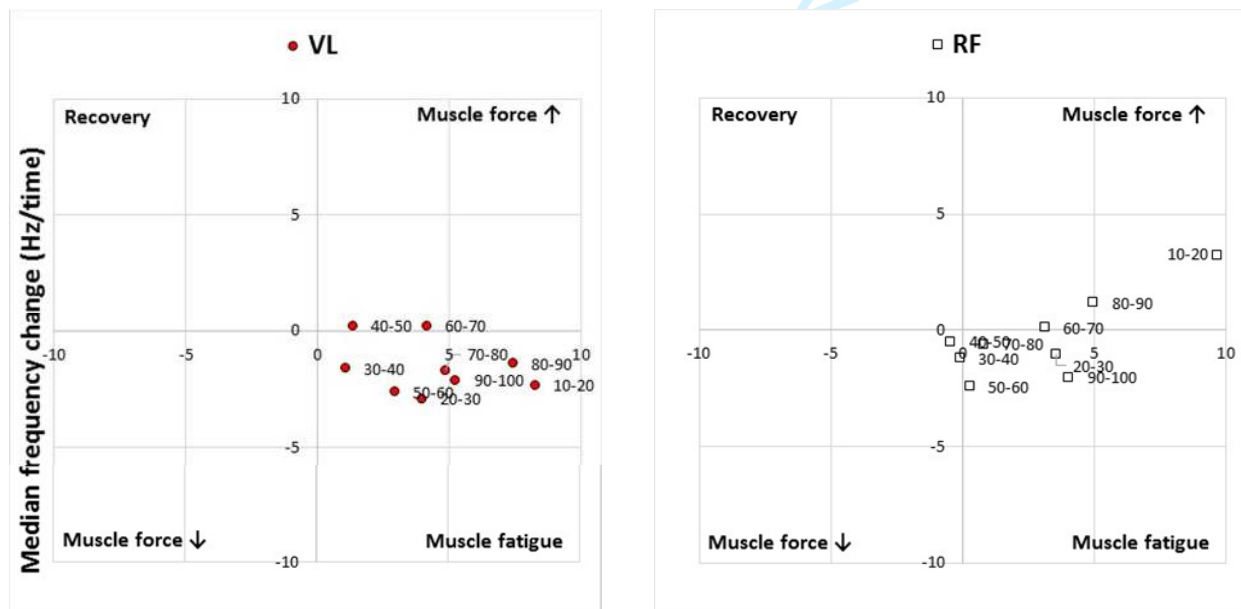


Figure 4. Average changes in EMG MDFs (left column: a, c, e) and normalized AMPs (right column: b, d, f) over the normalized (10-100%) periods at L1, L2, and L3, respectively.

3.5. Muscle activity rate changes (MARC) in muscle activity interpretation squares (MAIS)

All four muscles' AMP and MDF rate changes during the test at L3 showed a similar pattern in the MAIS. Most of the values aggregated between the *muscle force increase* and *muscle fatigue* squares of each muscle diagram (towards the right half of the diagrams in Figure 5). It is important to note that the end periods (90-100%) MARC values of the muscles were concentrated in the muscle fatigue square except for GM, which showed decreased muscle force (Figure 5).



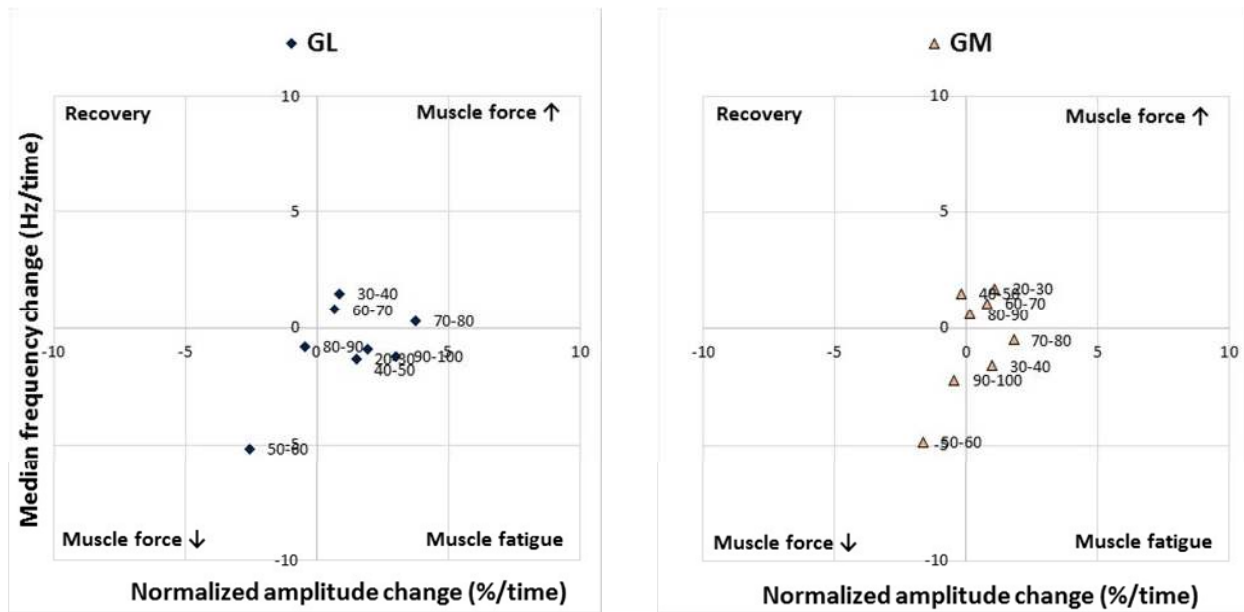


Figure 5. Muscle activity rate changes (MARC) for four muscles in normalized periods (10 - 100%) periods at 90% VO_{2max} (L3) in the muscle activity interpretation squares (MAIS).

4. Discussion

4.1. Stair ascending aerobic capacities at three speeds

The main finding of this study was that the average $VO_{2highest}$ and $HR_{highest}$ values reached $43.9 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ and 184.9 bpm during ascending at approximately 90% of VO_{2max} SR (L3), and the values were 94% VO_{2max} and 97% HR_{max} , respectively. However, the $VO_{2highest}$ was lower than the subjects' VO_{2max} ($46.7 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) (Tables 1 and 2). The average ascending duration was 4.32 min with an SR range between 68 and 133 $\text{steps}\cdot\text{min}^{-1}$ and the calculated vertical height reached 95 m. These data were used to develop an ascending evacuation model (Kuklane and Halder 2016).

The average $M_{highest}$ was about $600 \text{ W}\cdot\text{m}^{-2}$ during ascending at 90% of VO_{2max} SR. The observed $VO_{2highest}$ and calculated $M_{highest}$ ranges were between 30.7 to $58.3 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, and 423.8 to $764.4 \text{ W}\cdot\text{m}^{-2}$, respectively (Table 2). The calculated average $M_{highest}$ values were about $400 \text{ W}\cdot\text{m}^{-2}$ at 60% of VO_{2max} , which means that it is an activity that can be continued for up to 2 hours according to ISO 8996 (ISO 2004). The $M_{highest}$ achieved during the ascents at 75% of VO_{2max} (L2) (Table 2) are in agreement with the suggested M of about $475 \text{ W}\cdot\text{m}^{-2}$ (approximately 70% of VO_{2max}) for an activity lasting about 15-20 min (Holmer and Gavhed 2007). Holmer and Gavhed (2007) have also shown that people can manage an activity at

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3 this M for up to 5 min; in their study, the average M_{highest} reached $612 \text{ W}\cdot\text{m}^{-2}$, $\text{VO}_{2\text{highest}}$ to 44
4 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ and $\text{HR}_{\text{highest}}$ peaked at 179 bpm. In another ascending study involving a 5-min
5 activity on a different step machine with a similar SR of $112 \text{ steps}\cdot\text{min}^{-1}$, the average
6 $\text{VO}_{2\text{highest}}$ reached $42 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ and the $\text{HR}_{\text{highest}}$ peaked at 175 bpm (Butts, Dodge, and
7 McAlpine 1993). Notably, the present study's $\text{HR}_{\text{highest}}$ was higher than the values of the
8 previous two studies. The high HR indicates that the L3 workload appeared excessive for the
9 leg muscles, resulting in fatigue. Leg muscle fatigue and exhaustion may have forced the
10 subjects to discontinue during the 5-min long ascending, and LMF was presumably
11 responsible for lowering the $\text{VO}_{2\text{highest}}$ values more than their $\text{VO}_{2\text{max}}$, but equal to previously
12 studied high intensity simulated tasks. In a previous experiment on simulated firefighting
13 tasks, the $\text{VO}_{2\text{max}}$ rose to $44 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ (83% of $\text{VO}_{2\text{max}}$) in the process of rescuing six
14 victims and climbing six flights of stair for 5 min (von Heimburg, Rasmussen, and Medbo
15 2006).

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25 The males' average AD was shorter than the females' at L3. Most of the subjects were
26 males who quit before 5 min, showing that their significantly higher body mass made the
27 difference in their ability to sustain the critical power during stair ascending at 90% $\text{VO}_{2\text{max}}$.
28 The male participants' body mass ranged between 61 and 128 kg while the females' was
29 between 53 and 77.5 kg. The ascending distance ($V_{\text{height reached}}$) calculated for the female
30 participants was longer because they carried a low body mass resulting in a longer AD (Poole
31 et al. 2016). Moreover, there was a high variation in their selected SRs. The men's $\text{VO}_{2\text{max}}$
32 range was between 32.8 and $59.5 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$, and women's between 30.7 and 60.6
33 $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$. The M_{highest} for men were higher than that for women (Table 3). The
34 considerable differences in energy demands could lead to exhaustion in L3 (Table 2).
35 However, women reached the higher percentage of their $\text{VO}_{2\text{max}}$, 94.8 vs 92.5%, and HR_{max} ,
36 98.0 vs 95.9% compared to men at L3.

4.2. **Muscle activity EMG AMP and MDF**

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49 The analysis of muscle activity was a guide in evaluating how LMF in the legs affected the
50 stair ascending oxygen uptake and performance at the three ascending intensities, especially
51 L3. The AMPs increased significantly in all three controlled ascending speeds (Figures 4(b),
52 4(d), and 4(f)), and three muscles MDFs decreased significantly at L3 (Figure 4(e)), providing
53 strong evidence of LMF. The decrease in MDF results are supported by the progressive
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3 decreased MDF results found by Scheuermann, Tripse McConnell, and Barstow (2002) in fast
4 ramp increase cycling with a constant pedalling rate, suggesting that the MDF decrease was
5 associated with fatigue during the constant ascending pace.
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8 At L3, the muscle activity rate changes' (MARC) percentile points over time supported the
9 muscle fatigue results. Most of the MARC points, especially during the last 90-100% period,
10 were in the 'muscle fatigue' square in the muscle activity interpretation squares (MAIS). This
11 provided evidence of leg muscles fatigue during the test at 90% VO_{2max} SR (Figure 5). We
12 observed that some points corresponding to the starting periods were in the 'force increase'
13 square, which suggests that subjects were strong enough to exert a high force in the
14 beginning of the ascents. The MARC points shifted to the 'muscle fatigue' square after the
15 onset of fatigue while ascending was kept at a constant high speed with minimal possibilities
16 of postural adaptations. However, in the previous field study during ascending on the regular
17 stairs, the subjects tried to cope with fatigue by inclining forward and transferring their body
18 weight through their forearms to the handrails to reduce the leg muscles' workload (Halder
19 et al. 2018). The recruitment of additional muscle fibres may not have been possible during
20 high-intensity and constant ascents, and the decrease of muscle working efficiency from the
21 fibres already recruited may be associated with leg LMF, which reduced the ascending
22 tolerance (Cannon et al. 2011; Jones et al. 2011; Vanhatalo et al. 2011; Zoladz et al. 2008).
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34 The EMG results of the two lower SRs (L1 and L2) indicate that workloads and durations
35 were insufficient to cause fatigue, especially for the calf muscles. The leg muscular exertion
36 was high only for VL and RF muscles at 3-min test durations at L1 and L2, while MDFs
37 significantly shifted to lower frequencies, Figures 4(a) and 4(c) (Samuel et al. 2011). The EMG
38 AMPs showed a relationship to the constant ascending intensities and reflected the
39 workloads of the lower limb muscles measured at different intensities, Figures 4(b), 4(d),
40 and 4(f). A 3-5% higher percentage of muscle activations was required at L3 than in the two
41 lower SRs. Moreover, individual muscles had their own AMP and relative MDF levels to
42 comply with the ascending intensities (Figure 4).
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51 **4.3. Muscle activity and VO_2**

52 The average AMP increase was relatively stable after an initial sharp increase within one
53 minute. Each intensity of ascension progressively recruited the required fibres to maintain
54 the constant SR, Figures 4(b), 4(d), and 4(f). The ascending intensities were above the
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3 threshold for a prolonged activity that was supported by the 97% of VO_{2max} reached, which
4 required high velocity leg muscular movements, while the EMG AMP threshold reached 45%
5 of MVC during ascending. The greater use of fast, type II muscle fibres increases the energy
6 demand and causes a progressive, simultaneous VO_2 increase and later a relatively steady
7 state (Saunders et al. 2000), which was observed after the initial increase during the
8 continuation of ascent at 90% VO_{2max} SR (L3) (Figure 3). At higher work rates above the
9 ventilatory threshold, VO_2 did not reach a steady state immediately but continued to rise
10 slowly (Barstow 1994; Whipp and Wasserman 1972) as did lactate to the point of fatigue
11 (Roston et al. 1987). The VO_2 values were still increasing at the point of exhaustion or at the
12 end of the 5-min ascending test, while the muscles' force production was consistent for
13 maintaining the fixed SR. The pumping capacity of the heart reached its upper limit at about
14 97% of HR_{max} due to high and constant repetitive activities, which is evidence of reaching the
15 ventilatory threshold. The oxygen supply might be insufficient to meet the increasing energy
16 demands for the aerobic metabolism of the leg muscles, constraining work efficiency. The
17 body needed to recover by either slowing down the ascending speed or taking micropauses
18 in order to continue the ascent for a long duration. Ascending speed reductions or
19 micropauses were impossible in the machine-controlled SR where the subjects had no
20 control over their ascents.

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22 The anaerobic energy-yielding process dominated after the onset of ascents. It was
23 primarily dependent on the storage of adenosine tri-phosphate and creatine phosphate
24 (Costill, Wilmore, and Kenney 2012). When there is limited energy storage available in the
25 muscles, the aerobic energy process takes over the synthesis of new fuel on demand. The
26 delay of both VO_2 uptake and oxygen utilization in the body should be considered when
27 relating EMG to VO_2 . The progressive increase in AMP and decrease in MDF at L3 suggest an
28 association with fatigue (Scheuermann, Tripse McConnell, and Barstow 2002; Cifrek et al.
29 2009). Research documented that the AMP and spectral characteristics of the EMG signal
30 would increase over the duration of the VO_2 slow component (Sabapathy, Schneider, and
31 Morris 2005). During these high-intensity exercises, as more and more fast-twitch fibres
32 were recruited in order to maintain the same speed, the rate of oxygen uptake had to
33 increase. At the same time, the muscle fibres that became fatigued earlier in ascending
34 might continue to consume oxygen as they recover and this might also reduce efficiency and
35 contribute to the VO_2 slow component. The VO_2 slow component observed after
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3 stabilization with high AMP results indicated a progressive loss of muscle contractile
4 efficiency due to leg LMF (Jones et al. 2007; Cannon et al. 2011).

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6 The inability of the subjects to sustain energy transportation at a tolerable aerobic level in
7 the local leg muscles due to controlled and repetitive tasks is responsible for shortening the
8 ascending duration and causing an early cessation. The controlled and high SR resulted in
9 overall fatigue and exhaustion of the entire body due to lack of recovery (Vogiatzis et al.
10 1996), and inhibited the $VO_{2\text{highest}}$ from reaching the $VO_{2\text{max}}$ during ascents (Ben-Ezra and
11 Verstraete 1988). The cardiorespiratory capacity and natural anaerobic processes combined
12 caused LMF in the leg muscles and prevented subjects from reaching any of these limits in
13 the ascensions involving fixed and high SRs. Thus, the results of this study suggest that
14 evacuation at 90% intensity can be sustained for 2-6 min. It is necessary to carry out more
15 controlled studies at different predetermined SRs to further examine stair ascending
16 endurance, oxygen uptake, and muscle performance until exhaustion.
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27 **5. Conclusions**

28 Stair ascending capacity reached 94% and 97% of the subjects' average $VO_{2\text{max}}$ and HR_{max} ,
29 respectively, at 90% of $VO_{2\text{max}}$ (L3) at an average step rate (SR) of around 109.4 (17.8)
30 $\text{steps}\cdot\text{min}^{-1}$. The $VO_{2\text{highest}}$ registered $43.9 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ during stair ascending tests. An
31 average, HR_{highest} peaked at 185 bpm and the metabolic rate reached about $600 \text{ W}\cdot\text{m}^{-2}$,
32 indicating the maximal cardiorespiratory capacity. One-third of the subjects terminated the
33 ascension at L3 before reaching the stipulated test duration of 5-min, so that the average
34 ascending duration was 4.32 minutes. At L3, high repetitive muscle activity and controlled,
35 constant speed denied recovery, which caused an imbalance between the energy availability
36 and local demand that led to local muscle fatigue (LMF) in the legs. The significant increase
37 of EMG AMPs and decrease of MDFs evidenced LMF. High intensity ascents at controlled SRs
38 at 90% of $VO_{2\text{max}}$ or above could be sustained for 2 to 6 minutes on the stair machine,
39 depending on prerequisites such as body mass, step rate, etc. The points of the muscle
40 activity rate changes (MARC) appeared in the muscle fatigue area of the muscle activity
41 interpretation squares (MAIS). MARC and MAIS are useful for observing muscle activity
42 changes over time during dynamic tasks. The study results infer that the combined effects of
43 leg LMF and high cardiorespiratory demand limited the subjects' ascending tolerance and
44 consequently, forced them to stop their ascents on the stair machine.
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Response to the comments from honourable editor

Oxygen uptake and muscle activity limitations during ascending on a stair machine

Dear Editor,

Thank you so much indeed for giving us several chances to improve this paper. I really appreciate your efforts and time that you have given for reading the manuscript carefully. As I said before, the suggestions given by you and this editorial process are educational for me, which will definitely help me to develop my writing skill in future.

We have considered all the comments and modified the paper accordingly. I would like to thank you once more for that. I have uploaded both revised manuscript and the 'marked copy' of the manuscript. In the marked copy of the manuscript, the changes that have been made are "underlined".

Sincerely,
Amitava

Authors' responses are given below as ANS after each comment

11-Mar-2018

Dear Amitava

Oxygen uptake and muscle activity limitations during ascending on a stair machine

Your revised paper has now been considered, with the conclusion that further attention is needed to the following points:

I have done more than what I am supposed to do, and I hope that you could also do so. Although the writing has been improved, there are few problems. I hope that you can seek help from your co-authors. They are supposed to help you.

ANS: Thank you so much for spending your valuable time to read the paper and for the suggestions to improve it. I have gotten helps from my co-authors and another native English speaker who is fluent in scientific writing in different fields.

Page 2 line 15, a comma is missing right after "bpm".

ANS: A comma has been added

Page 2 line 37, I think this word "used" should be put right after "(MARC)".

ANS: I have modified it.

Page 3 line 37, "in" should be removed.

ANS: I am not so sure. I think that if we put the word "used" right after "(MARC)" then we might need "in" after "used".

Page 3 line 56, I think that there should be a "have" right before "estimated".

ANS: Yes, you are right.

Page 4 line 48, please replace "It does so" by "It was accomplished". This should be a past tense.

ANS: I have replaced.

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3 Page 6 line 21, please insert as least one blank line here to separate the table form the text. Please
4 do the same on page 13.

5 **ANS: One blank line has been inserted in the suggested places.**

6 Page 6 line 28, "subjects" should be removed.

7 **ANS: Oh sure, thanks.**

8 Page 7 line 8, "per minute" should be removed.

9 **ANS: Yes, It can be removed and I have done it.**

10 Page 9 line 15, "values" should be removed.

11 **ANS: It has been deleted.**

12 Page 9 line 47, it is not clear whether it is a data point per subject and totally 10 data points per
13 subject.

14 **ANS: The sentence has been re-written.**

15 Page 9 lines 54 to 56, I think that this sentence should be moved to the beginning of the paragraph.

16 **ANS: The sentence has been moved.**

17 Page 10 line 22, please replace "and" with "during" or "for".

18 **ANS: I have used "for".**

19 Page 11 lines 23 and 27, what are the numbers in the parentheses? Likewise in many places.

20 **ANS: They are "mean (SD)". We have modified the sentence.**

21 Page 11 line 27, I think that you should mention the trend before this sentence before you
22 mentioned "the opposite trend". Opposite to what?

23 **ANS: The sentence is modified by deleting the "the opposite trend".**

24 Page 13 line 45, rather than "related", why not mention that VO₂ increased as the stair ascending
25 intensities increased.

26 **ANS: The step rate was always fixed in each ascending intensity, which was not changing in**
27 **time. We had chosen to start with a low level (L1). VO₂ increased as the stair ascending**
28 **intensities increased from level 1 to level 3.**

29 I have updated the sentences and the reference has been given in text now

30 (<https://www.ncbi.nlm.nih.gov/pubmed/10368878>), which describes the specific oxygen
31 uptake (VO₂) kinetics in detail.

32 Page 14 line 45, "in left column" should be removed.

33 **ANS: It has been removed.**

34 Page 15 lines 3 and 5, "in right column" should be removed.

35 **ANS: Please see above**

36 Page 16 line 18, in this caption, you need to insert something like "respectively".

37 **ANS: I have inserted "respectively" in the end.**

38 Page 17 line 33, rather than using a symbol, please use the word "approximately".

39 **ANS: Okay, it is done.**

40 Page 19 lines 20 to 24, it is not clear whether this sentence described what Halder et al. observed in
41 the previous study or the current study.

42 **ANS: I have updated the sentence and I hope that it is clear now.**

43 Page 19 line 42, "in right column" should be removed.

44 **ANS: It has been deleted.**